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Integrated rural and urban agricultural systems for the sustainability transition towards the bioeconomy

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The term 'bioeconomy' was formulated as antonym to the economic system based on unlimited growth, which exceeds the planetary boundaries and is contradictory to the natural law of entropy (Bonauiti, 2015).
The counteracting natural law of syntropy may provides the guiding principles
of natural order and organisation of agricultural systems
for a sustainable increase in biomass production for the bioeconomy.

(Chapter 5.3.3 - Sustainable agroecologic intensification, p. 170)

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List of acronyms

4F's	– Food, Feed, Fibre, Fuel
AHP	– Analytical Hierarchy Process
BfN	– Bundesamt für Naturschutz
BMBF	– Bundesministerium für Bildung und Forschung
BMEL	– Bundesministerium für Ernährung und Landwirtschaft
BMELV	– Bundesministerium für Ernährung, Landwirtschaft und Verbraucherschutz
BNEF	– Bloomberg New Energy Finance
BP	– British Petroleum
CAP	– Common Agricultural Policy
CHP	– Combined Heat and Power
C	– Carbon
CO_2	– Carbon Dioxide
$CO_{2\text{-eq.}}$	– Carbon Dioxide Equivalent
COP21	– 21st United Nations Framework Convention on Climate Change
DLR	– Deutsches Zentrum für Luft- und Raumfahrt
DWEA	– Department for Water and Environmental Affairs
e.g.	– exempli gratia (for example)
EC	– European Commission
EJ	– Exajoule
EU	– European Union
EIA	– Energy Information Administration
ESVD	– Ecosystem Services Valuation Database
FAO	– Food and Agriculture Organization
Fig	– Figure
FORMAS	– The Swedish Research Council for Environment, Agricultural Sciences and Spatial Planning
GHG	– Greenhouse Gas
ha	– Hectare
IAASTD	– International Assessment of Agricultural Knowledge, Science and Technology for Development
IEA	– International Energy Agency
IFRES	– Integrated Food and Renewable Energy System
IIASA	– International Institute for Applied Systems Analysis
INR	– Indian Rupee

IoT	– Internet of Things
IRENA	– International Renewable Energy Agency
IREPA	– Integrated Renewable Energy Potential Assessment
Kcal	– Kilocalorie
kW	– Kilowatt
LED	– Light emitting diode
LPG	– Liquefied Petroleum Gas
m	– Meter
m^2	– Square Meter
N	– Nitrogen
MCDA	– Multi-Criteria Decision Analysis
MLP	– Multi-Level Perspective
MNRE	– Ministry of New and Renewable Energy
MW	– Megawatt
NASA SMSE	– National Aeronautics and Space Administration Surface Meteorology and Solar Energy
NBS	– Nature-based Solution
NEO	– NASA Earth Observations
NGO	– Non-governmental Organisation
NPP	– Net Primary Productivity
O_2	– Oxygen
OECD	– Organisation for Economic Co-operation and Development
PE	– Polyethylene
pH	– Potential of hydrogen
PLA	– Participatory Learning and Action
RE	– Renewable Energy
REI4P	– Renewable Energy Independent Power Producer Procurement Programme
REN21	– Renewable Energy Policy Network for the 21st Century
REPA	– Renewable Energy Potential Assessment
RET	– Renewable Energy Technology
s	– Second
SDG	– Sustainable Development Goals
SI	– Sustainable Intensification
SMART	– Simple Multi-Attribute Rating Technique
t	– Tonne

Tab.	– Table
TEEB	– The Economics of Ecosystems and Biodiversity
UNCTAD	– United Nations Conference on Trade and Development
UNDP	– United Nations Development Programme
UNEP / GI-Rec	– United Nations Environment Programme / Global Initiative for Resource Efficient Cities
UN DESA	– United Nations Department of Economic and Social Affairs
US	– United States
TEEB	– The Economics of Ecosystems and Biodiversity
WASA	– Wind Atlas South Africa
WEC	– World Energy Council
Wp	– Watt Peak
yr.	– Year
ZAR	– South African Rand

Abstract

The goal of the bioeconomy is a fundamental transition of both the economy and society towards sustainability. Replacing fossil resources by biomass for the provision of food, feed, fibre and fuel/energy (the 4F's) will result in a substantial increase in demand for agricultural products in the next decades. The consequent intensification of agricultural production, however, needs to be achieved while also alleviating the societal challenges of the 21st century, including climate change, biodiversity loss, reduction in ecosystem services, land degradation, urbanisation and food waste. Today, agriculture is in the ambivalent position of being both part of the problem and part of the solution, rendering 'business as usual' not an option for the future. The bioeconomy provides a knowledge-based, cross-sectoral and systemic pathway to increase agricultural production and involves all relevant stakeholders along biobased value chains in the sustainability transition.

The overall objective of this interdisciplinary thesis is to investigate the contribution that three selected bioeconomic approaches can make to the sustainable intensification of agricultural production. It is based on four studies that together encompass the growing urban population on the demand side and the numerous smallholder family farmers in countries of the global South on the supply side. It is in these countries that the largest potentials for increasing agricultural productivity and renewable energy (RE) production are to be found.

The first study develops the 'Integrated Renewable Energy Potential Assessment' (IREPA) approach for harnessing these potentials through the creation of 'Integrated Food and RE Systems' (IFRES). It involves the large number of smallholder farmers in the development of the bioeconomy. The IREPA methodology comprises bottom-up RE potential assessment, participatory learning and action research, and multi-criteria decision analysis. It is applied and evaluated in two case studies in rural South Africa and India. In both studies, locally appropriate renewable energy technologies (RET) for implementation into smallholder agricultural systems are identified. The case studies reveal the further necessity of participatory, bottom-up approaches to integrating local stakeholders in project planning and decision making, in order to support sustainable rural livelihoods and agricultural development in the growing bioeconomy.

The second study uses IREPA to explore smallholders' perception of agricultural RE production. Social, environmental, technical, institutional and economic factors are analysed to identify drivers of and barriers to RE implementation into smallholder agricultural systems. The results show that mainly environmental factors, in particular climate change impacts, motivate smallholders to adapt their production systems and produce RE, while social factors (social cohesion, gender aspects, increased well-being, food and water security, etc.) determine the actual change. The barrier of high upfront investment costs can be eliminated by falling RET prices, the development of novel rural RE business models and institutional support involving smallholders in rural RE projects. In addition, the growing smartphone penetration rate in rural areas enables 'do-it-yourself' RET, including operation and maintenance, based on open-access online information. Such insights are crucial for the targeted formulation of agricultural development policies and thus the involvement of relevant stakeholders in the sustainability transition towards a bioeconomy.

The third study addresses the biomass demand side. It investigates the characteristics of urban gardening in Germany and its potential to encourage sustainable consumer behaviour based on a review of 657 urban gardening project websites and a subsequent online survey involving 380 project participants. The results reveal that urban gardens generate multiple social, environmental and economic benefits for sustainable city development. They create diverse social communities that actively promote sustainable consumer behaviour by (unintentionally) applying a number of methods known to encourage pro-environmental behaviour. Hence, urban gardens are transformative spaces that actively involve the growing urban population in the societal transition towards a bioeconomy.

In the context of sustainable intensification of biomass production in rural areas, the fourth study investigates the contribution of environmental service assessment and monetization in agricultural systems, using the example of the perennial biomass crop miscanthus for biofuel production. The valorisation makes the multiple environmental services - such as soil fertility improvement, carbon sequestration, water and air purification - tangible. This can incentivise payments to farmers for the provision of these public goods. Enhancing and utilising environmental services through nature-based solutions and agroecologic practices is a promising pathway to sustainable intensification, providing a shift from input-based towards process-based agricultural systems.

Finally, it can be concluded that integrated approaches which connect different production systems, disciplines and stakeholders are central for the development of the bioeconomy:

- The integration of sustainable technologies, such as RE, into agricultural systems requires case-based research and participation of local stakeholders in project planning and decision making. In addition, the perspective of local stakeholders is crucial for targeted policy formulation.
- The integration of the growing urban population in the sustainability transition towards the bioeconomy can be supported by urban gardening. The local production of food in cities and urban areas has been found to promote sustainable consumer behaviour.
- The integration of nature-based solutions into agricultural systems enhances environmental service provision and supports the sustainability transformation from input-based towards process-based agricultural biomass production.

The approaches discussed in this thesis can support the sustainable intensification of agriculture, serve to re-connect the perspectives of rural producers and urban consumers, and enable the involvement of large portions of society in the sustainability transition towards the bioeconomy.

Zusammenfassung

Die Bioökonomie strebt die grundlegende Nachhaltigkeitstransformation von Wirtschaft und Gesellschaft an. Deren fossile Ressourcenbasis wird dabei durch Biomasse ersetzt. Dies führt zu einem deutlichen Anstieg des Bedarfs an landwirtschaftlichen Produkten als Nahrungs- und Futtermittel sowie für die stoffliche und energetische Nutzung. Die dafür notwendige Intensivierung der landwirtschaftlichen Produktion muss allerdings gleichzeitig dazu beitragen die gesellschaftlichen Herausforderungen des 21. Jahrhunderts zu lösen: Klimawandel, Verringerung von Biodiversität und Ökosystemdienstleistungen, Bodendegradierung, Urbanisierung und Lebensmittelverschwendung. Die vorherrschenden Produktionssysteme sind sowohl Teil der Lösung als auch Teil des Problems, ein ‚Weiter wie bisher' ist keine Option. Zur nachhaltigen Produktionssteigerung bietet die Bioökonomie eine wissensbasierte, sektorübergreifende und systemische Herangehensweise, die alle relevanten Akteure entlang biobasierter Wertschöpfungsketten einbezieht.

Ziel dieser interdisziplinären Dissertation ist die Untersuchung und Weiterentwicklung von drei bioökonomischen Ansätzen, im Rahmen von vier Studien, um die Bereitstellung landwirtschaftlicher Produkte zu steigern und dabei die wachsende urbane Bevölkerung auf der Nachfrageseite und auf der Angebotsseite die zahlreichen Kleinbauern in Ländern des Globalen Südens einzubeziehen.

In diesen Ländern existieren sowohl die größten Potenziale zur landwirtschaftlichen Intensivierung als auch zur Produktion erneuerbarer Energien (EE). Zur Nutzung dieser Potentiale wurde in der ersten Studie der Ansatz der ‚Integrierten Bewertung des Potenzials erneuerbarer Energien' (IREPA) entwickelt, um die Integration von EE-Technologien in kleinbäuerliche Agrarsysteme zu fördern und dabei die große Anzahl an Kleinbauern in die Entwicklung der Bioökonomie einzubeziehen. Die IREPA-Methode besteht im Wesentlichen aus einer bottom-up-Bewertung des EE-Potentials, partizipativer Lern- und Aktionsforschung sowie Multikriterienanalyse. Damit konnten Kleinbauern in zwei Fallstudien in Südafrika und Indien dabei unterstützt werden geeignete EE-Technologien für ihre Produktionssysteme zu ermitteln. Die Integration lokaler Akteure in Projektplanung und Entscheidungsfindung ist wichtig zur Förderung nachhaltiger Lebensgrundlagen und landwirtschaftlicher Entwicklung in der wachsenden Bioökonomie.

In der zweiten Studie wurden soziale, ökologische, technische, institutionelle und wirtschaftliche Faktoren ermittelt um Hindernisse und Treiber für die Implementierung von EE-Technologien in kleinbäuerliche Agrarsysteme zu identifizieren. Ökologische Faktoren, insbesondere die Auswirkungen des Klimawandels, motivieren Kleinbauern dazu, ihr Produktionssystem anzupassen und erneuerbare Energien zu produzieren, während soziale Faktoren (wie bspw. soziale Strukturen, Gender-Aspekte, gesteigertes Wohlbefinden, Versorgungssicherheit mit Nahrungsmittel und Wasser) bestimmen was tatsächlich umgesetzt wird. Stark gesunkene Preise von EE-Technologien, neuartige Geschäftsmodelle für deren Vertrieb im ländlichen Raum sowie die institutionelle Unterstützung von Kleinbauern durch

Einbeziehung in EE-Projekte beseitigen das Hindernis hoher Investitionskosten mehr und mehr. Die steigende Smartphone-Verbreitung bietet Zugang zu Informationen und Anleitungen, wodurch EE-Technologien auch im Selbstbau installiert und betrieben werden können. Einblicke wie diese sind entscheidend für die Formulierung zielgerichteter, landwirtschaftlicher Entwicklungsstrategien und die Einbindung relevanter Akteure in die Nachhaltigkeitstransformation zur Bioökonomie.

In der dritten Studie wurden urbane Gartenprojekte in Deutschland charakterisiert um deren Potential zur Förderung eines nachhaltigen Konsumentenverhaltens zu untersuchen. Dafür wurden zunächst die Webseiten von 657 urbanen Gartenprojekten analysiert und anschließend eine online Umfrage mit 380 urbanen Gärtner*innen durchgeführt. Urbane Gärten bieten vielfältige soziale, ökologische und wirtschaftliche Vorteile für eine nachhaltige Stadtentwicklung. Die diversen sozialen Gartengemeinschaften fördern ein nachhaltiges Konsumentenverhalten, indem (unbeabsichtigt) mehrere Methoden angewandt werden, die bekanntermaßen umweltfreundliches Verhalten fördern. Urbane Gärten stellen daher transformative Räume dar, die die wachsende urbane Bevölkerung in den gesellschaftlichen Wandel zur Bioökonomie einbeziehen.

In der vierten Studie wurde der Ansatz der Bewertung und Monetarisierung von Umweltdienstleistungen in Agrarsystemen und dessen Beitrag zur Förderung der nachhaltigen Produktionsintensivierung am Fallbeispiel der mehrjährigen Biomassepflanze Miscanthus für die Biokraftstoffproduktion untersucht. Durch die Monetarisierung werden Umweltdienstleistungen wie bspw. Bodenfruchtbarkeit, CO_2-Sequestrierung sowie Wasser- und Luftreinigung, greifbar. Dies schafft Anreize um Landwirte für die Bereitstellung dieser Gemeingüter auch zu vergüten. Die gezielte Förderung von Umweltdienstleistungen mittels agrarökologischer Praktiken und naturbasierter Lösungen ist ein aussichtsreicher Ansatz, um von einer Input-basierten hin zu einer Prozess-basierten Intensivierung der Agrarproduktion zu gelangen.

Letztendlich lässt sich aus den vier Studien dieser Arbeit schließen, dass integrative Ansätze, die Verbindungen zwischen Produktionssystemen, Disziplinen und beteiligten Akteuren schaffen, von zentraler Bedeutung für die Entwicklung der Bioökonomie sind:

- Die Integration nachhaltiger Technologien, wie EE, in landwirtschaftliche Systeme erfordert fallbezogene Forschungsansätze und die Beteiligung lokaler Akteure in der Projektplanung und Entscheidungsfindung. Für die Entwicklung zielgerichteter, bioökonomischer Politikstrategien bildet die Perspektive lokaler Akteure eine wichtige Grundlage.
- Die Integration der wachsenden urbanen Bevölkerung in die Nachhaltigkeitstransformation zur Bioökonomie wird durch das urbane Gärtnern unterstützt, indem ein nachhaltiges Konsumentenverhalten gefördert wird.

- Die Integration naturbasierter Lösungen in landwirtschaftliche Produktionssysteme fördert die Bereitstellung von Umweltdienstleistungen und unterstützt dadurch die Nachhaltigkeitstransformation von der Input-basierten zur Prozess-basierten Landwirtschaft.

Die drei Ansätze dieser Arbeit können wichtige Beiträge zur nachhaltigen Intensivierung der Landwirtschaft leisten und durch die (Wieder-)Verbindung ländlicher Produzenten und urbaner Verbraucher, diese großen Bevölkerungsgruppen in die Nachhaltigkeitstransformation zur Bioökonomie einbeziehen.

1. General Introduction

Agricultural production needs to substantially increase to meet the future demand for food, feed, fibre and fuel (energy) (4F's) in the growing bioeconomy. The driving forces for the increase in demand for agricultural products are outlined in Chapter 1.1. and include population growth, affluent human development and the transition to a bioeconomy, where fossil resources are replaced by biobased resources. At the same time, the required increase in agricultural production needs to be achieved by tackling the global challenges of the 21st century (Chapter 1.2.), caused to a large extent by unsustainable agricultural practices (Chapter 1.3) and the overexploitation of fossil resources. The title of the last 'International Assessment of Agricultural Knowledge, Science and Technology for Development' (IAASTD) in 2009, *'Agriculture at the crossroads'* illustrates the ambivalence of the current situation, with agriculture being part of the solution as well as part of the problem, rendering 'business as usual' no option for the future (McIntyre, 2009).

The bioeconomy addresses these global challenges based on a holistic and cross-sectoral perspective considering social, environmental and economic sustainability for the interdisciplinary development of resource-efficient, biobased value nets (Chapter 1.4).

Replacing fossil resources with biomass requires a structural change of the resource base, from the rather centralized exploitation of coal, oil and natural gas at a few locations through almost monopolistic corporations (Lennon et al., 2019), towards the decentralised production of biomass for the 4F's as well as renewable energy (RE) by millions of farmers (Arndt et al., 2019; Wirth et al., 2018). At the same time new biobased products and energy forms are emerging that must be accepted by consumers and consumed sustainably (Wirth et al., 2018). Hence both producers and consumers need to be addressed, involved and connected to solve the great challenges of the 21st century (Arndt et al., 2019; Lennon et al., 2019; Wirth et al., 2018). In this thesis three bioeconomic approaches are investigated and developed further:

- *Chapter 2:* The Integrated Renewable Energy Potential Assessment (IREPA) has been developed for bottom-up renewable energy potential assessment in countries of the South. In two case studies locally appropriate renewable energy technologies (RET) were selected, based on the participatory IREPA methodology, thereby involving smallholder farmers in the sustainability transition towards the bioeconomy.

- *Chapter 3:* Urban agriculture brings agricultural production systems into growing cities, connecting producers and consumers, and creating awareness of sustainable consumer behaviour and sustainable agricultural production.

- *Chapter 4:* The assessment of environmental services in agricultural systems illustrates the multifunctionality of agriculture. The monetization of these services provided for society makes them tangible, the beneficiaries accountable and incentivises farmers to adopt more sustainable agricultural practices.

How these approaches can inform and support the sustainability transition in agriculture and society for the development of the bioeconomy is discussed in Chapter 5. An innovative concept is subsequently outlined that integrates both different agricultural and RE production systems as well as the producer and consumer perspective along the rural-urban gradient for a sustainable supply of the agricultural products for the 4F's and RE in future.

1.1. Drivers of the increase in global biomass demand

The United Nations Department of Economics and Social Affairs (UN DESA) estimates that 9.6 billion people will live on the planet in 2050 (and 10.9 billion in 2100) (UN DESA, 2013). Furthermore, in the past decades, countries of the South have made substantial progress in lifting the Human Development Index (HDI), a measure of health, education and economic achievements (Malik, 2013). Emerging economies, including China, Brazil, India and South Africa, performed particularly well. The average per capita income rose across all countries between 1990 and 2012, with the highest annual growth rates in China (+9%) and Sub-Saharan Africa (+5% from 2003 to 2008). India and China even managed to double their economic output per capita (Malik, 2013). As these countries constitute the largest populations in the world, more people are affected by this development than by the industrial revolution (Malik, 2013). The relationship between per capita intake of crop calories and protein, and the per capita gross domestic product is temporally consistent (Tilman et al., 2011). Consequently, the demands for processed food, meat and dairy products, fish and vegetable oils are foreseen to rise considerably to 3130 kcal per person and day in 2050. The demand for cereals (food and feed) is expected to increase from 2.1 billion tonnes in 2009 to a global production level of about 3.0 billion tonnes in 2050 (FAO, 2009a; Godfray et al., 2010).
Therefore, the projected population growth together with affluent human development will demand a substantial increase in global agricultural food production of about 70% by 2050 (and of about 100% in Africa) (FAO, 2009a; Godfray et al., 2010).

In addition to the increase in demand for food and feed, the depletion of fossil resources will also increase the biomass demand for fibre (biomass for biobased products) and fuel (energy) (FAO, 2009a; OECD, 2009). Moriarty and Honnery (2012) reviewed and analysed projections of the future global energy demand from several international energy agencies (e.g. IEA, WEC, EIA, IIASA) and the energy industry (e.g. BP, Shell). By 2050, the global primary energy consumption will reach levels between 770 EJ and 1175 EJ (985 EJ – 1740 EJ in 2100) (Moriarty and Honnery, 2012). This represents an increase between 21% to 55% compared to the global primary energy consumption of 533 EJ in 2013 (BP, 2014). According to the International Energy Agency (IEA), 93% of the projected demand increase originates from non-OECD countries, while OECD countries show little to no further growth in energy consumption (IEA, 2010). Considering this, Moriarty and Honnery (2012) assumed the 2008 energy consumption level of OECD countries as a global benchmark for energy sufficiency. Supposing that all populations on the planet will have reached this level by 2050, the global primary energy demand would be as high as 1748 EJ in 2050 (Moriarty and Honnery, 2012). Consequently, the global primary energy production needs to increase by 31% to 70% until 2050 (Moriarty and Honnery, 2012).

Bioenergy already supplied 47 EJ in 2007 (FAO, 2009c) and 53 EJ in 2010 (IRENA, 2014) globally. The largest share of this biomass was used as traditional biofuel in 2010, the major energy source for cooking and heating in countries of the South (IRENA, 2014). The bioenergy consumed in the manufacturing industry (15%), in the transport sector (9%) and the power and district heating sector (8%) sum up to 32% (IRENA, 2014). IRENA projects the bioenergy demand to double (97 EJ) or almost triple (147 EJ) until 2030, increasing its share in the global primary energy supply to about 20% in 2030 (from 10% in 2010) and in the global RE supply to about 60% in 2030 (53% in 2010) (IRENA, 2014).

In addition to energy, multiple materials, chemicals and daily life products need to be produced from biomass, because of the depleting fossil resource base. Such biobased products comprise, among others, fibre-based materials, bio-plastics and bio-polymers, surfactants, bio-solvents, bio-lubricants, ethanol and other chemicals, pharmaceutical products like vaccines, enzymes, and cosmetics (Taskforce on bio-based products of European Commission, 2007). In 2010, chemical companies were the most important players in this emerging market sector, producing already 8-10% of various chemical substances from biomass (Calliope et al., 2013). In 2011, 247 companies produced 3.5 million tonnes biopolymers. This represents 1.5% of the total global polymer production and is expected to grow to 3% in 2020 (12 million tonnes) (nova-Institute, 2013). The biotechnology sector is expected to contribute 2.7% to the gross domestic product (GDP) of OECD countries in 2030 (OECD, 2009). For comparison, the agricultural sector had a share of 3.7% on the global GDP in 2011 (Statista, 2020).

Hence, it is predicted that the growing world population and prosperous human development will require:

± 70% more biomass for food and feed until 2050 (FAO, 2009a),

± 100-200% more biomass for bioenergy until 2030 (IRENA, 2014),

± 29% more biomass for biopolymers until 2020 (nova-Institute, 2013), based on the perpetuation of the current utilisation levels of biomass for food and feed in 2009, biomass for bioenergy in 2010 and biomass for biobased products in 2013.

Most of this biomass needs to be supplied from agriculture (FAO, 2009a, 2009c; IRENA, 2014; nova-Institute, 2013). At present, however, agriculture is confronted with several global challenges that require fundamental adaptations of agricultural production systems.

1.2. Global challenges of the 21st century affecting agriculture

The tremendous increase in agricultural biomass production for the 4F's need to be achieved by not only coping with, but simultaneously solving the global challenges of the 21st century, which impact on and/or are caused to a large extend by agriculture:

I. Climate change force adaptions of the agricultural production systems according to the changing conditions on local, regional and global level (Smith et al., 2007). At the same time, the share of greenhouse gas (GHG) emissions from agriculture on the global anthropogenic GHG emissions was about 11% in 2010 with further increase expected. The annual growth rate of agricultural GHG emissions between 1990 and 2010 was 0.9% (Smith et al., 2014).

II. Biodiversity loss leading to the sixth global mass extinction caused by human resource exploitation, habitat fragmentation, invasive species introduction, pathogen distribution, eradicating species directly and changing climate (Barnosky et al., 2011),

III. Reduction in ecosystem service provision with a value of $ 20.2 trillion between 1997 ($ 145 trillion/yr.) and 2011 ($ 125 trillion/yr.). Main causes include deforestation of tropical forests and the depletion of wetlands for gaining arable land (Costanza et al., 2014) - 15 out of 24 relevant ecosystems for human survival are in degradation and / or are used unsustainably (Millennium Ecosystem Assessment, 2005);

IV. Land degradation, 24% of global land area had the status 'in degradation' in 2008 due to erosion, mismanagement and desertification (Bai et al., 2008), affecting cropland to 38% (McIntyre, 2009)

V. Urbanisation trend, 70% of global population will live in cities and metropolitan areas in 2050 compared to 49% in 2009 (FAO, 2009a; Statista, 2018a). Fewer farmers need to feed more people, requiring a further increase in labour efficiency (Fuglie et al., 2012).

VI. Food losses and wastes – about one-third of food produced (in terms of weight) is lost within the value chain and wasted by the consumers (Gustavsson et al., 2011);

Finding solutions for coping with and solving these challenges needs to be integral part of future agricultural and bioeconomic development and requires a closer look at the drivers of agricultural development in the past and their potential contribution in future. This allows for the identification of potential starting points and stakeholder groups to be integrated in the sustainability transition towards the bioeconomy.

1.3. Agriculture's path to the crossroad

After World War II and the Green Revolution in the 1960s, agricultural productivity multiplied due to scientific and technological achievements "*The general model has been to continuously innovate, reduce farm gate prices and externalize costs*" (McIntyre 2009, p. 3). This transformed agriculture from mainly smallholder family farming towards intensive, specialised, large-scale, industrial production systems, mainstreaming what has been introduced previously on colonial plantations (McIntyre, 2009).

Drivers of agricultural productivity growth in past and their future role

The emerging system of what is today considered 'conventional agriculture' made and makes efficient use of mechanisation, fertilizers, pesticides, irrigation and high-yielding varieties to achieve high crop yields at low farm-gate prices (Fuglie, 2012; McIntyre, 2009). The main drivers for agricultural productivity and output growth (on average 2.39% annually) from 1961 to 1990 (Fuglie, 2012) were input (e.g. energy, fertilizer, pesticides) and capital increases, conducive agricultural policies, area expansion, irrigation technologies and considerable breeding advancements. The yield gains achieved by these measures, lead to a production increase of the major food crops, like e.g. for soy (31%), maize (68%), rice (87%) and wheat (100%) between 1980 and 2002 (Cassman and Grassini, 2020). After that period, however, input intensification reached its limits. Between 1991 to 2009, the annual average productivity and output growth of 2,35% was achieved through improving the total factor productivity through knowledge, skills and management developments (Fuglie, 2012).

One important aspect in this process is the increase in the cropping intensity, allowing for more than one crop to be harvested on the same land within one year (Bruinsma, 2009; OECD-FAO, 2009). Between 1961/63 and 2006/07, the harvested area expanded by 229.5 million hectares, while the total agricultural land expanded by 135.6 million hectares only. Hence, almost half of the increase in the harvested area was due higher copping intensity (OECD-FAO, 2009). Globally, higher cropping intensities explained 9% of the crop production increase between 1961 and 2005. Until 2050, is expected that higher cropping intensities can contribute about 14% to the agricultural production increase (Bruinsma, 2009; OECD-FAO, 2009).

However, if the intensification of the cropping system is not appropriately managed and takes place at the expense of the fallow or through agricultural land expansion, it will accelerate soil fertility depletion, biodiversity losses and climate change (Bruinsma, 2009; Cassman and Grassini, 2020).

Conversely, between 2002 and 2014, land expansion became a main driver of the production increase of the main food crops with 85% for soy, 66% for maize, 43% for rice and 17% for wheat (Cassman and Grassini 2020). The expansion of agricultural land is a highly contested issue for achieving a higher biomass supply (Cassman and Grassini, 2020; FAO, 2009b; OECD, 2009; OECD-FAO, 2009; UNCTAD, 2013). The total suitable land for rain-fed agriculture (moderate to very well suitable) was estimated to be about 4.2 billion hectares globally. Out of these, 1.6 billion are already under cultivation, leaving 2.6 billion hectares theoretically available. However, this potentially arable land includes forests (45%), protected areas (12%) and urban areas (3%), leaving effectively 1.56 billion ha for agricultural production (Bruinsma, 2009; FAO, 2009b; OECD, 2009; OECD-FAO, 2009). This estimation, however, includes several other constraints and land-use competitions: (i) the increasing demand for pasture land for the growing livestock production (OECD-FAO, 2009); (ii) the land-use competition with biomass for biobased products and bioenergy (OECD-FAO, 2009); (iii) the location of 90% of these land areas in just two regions, South America and Sub-Saharan Africa (Bruinsma, 2009), with often limited accessibility or other non-agricultural uses (FAO, 2009b) and currently rather low agricultural productivity (OECD-FAO, 2009); (iv) an overestimation of the land, based on the method defining areas suitable (when at least one crop could provide a minimum yield, e.g. olive trees in North Africa) without considering whether staple crops could actually be grown (Bruinsma, 2009); (v) areas with high ecological fragility (e.g. wetlands), low soil fertility, toxicity and a high incidence of diseases (Bruinsma, 2009).

Taking these aspects into account, about 9% of the land is potentially suitable for the expansion of agriculture (about 70 million hectares) (Bruinsma, 2009). While about 120 million hectare can be gained in countries of the South, about 50 million hectare are lost in countries of the North due to continuing degradation, economic unviability and sealing for human infrastructure (Bruinsma, 2009).

Soil fertility depletion and land degradation are increasing due to unsustainable agricultural practices. In 2008, 38% of the cropland was already degraded, while salinization affected about 10% of the irrigated land (McIntyre, 2009). Despite the 8-times increase in fertilizer use in the past four decades (UNCTAD, 2013), soil nutrient depletion affects 59% of the harvested area in terms of N, 85% in terms of P and 90% in terms of K (McIntyre, 2009). At the same time, nutrient losses causing eutrophication of terrestrial and aquatic ecosystems are projected to increase 2.4 to 2.7 times until 2050 (Tilman et al., 2001).

Consequently, the approaches that have multiplied agricultural productivity since the end of the Second World War have only limited potential to further increase agricultural biomass production for the 4F's by 2050 by:

- ± 9% through agricultural land expansion (Bruinsma, 2009),
- ± 14% through higher cropping intensities (Bruinsma, 2009).

Furthermore, the drivers of agricultural development in the past are known to continuously degrade cropland, deplete soil nutrients and water resources, fragment habitats, decrease biodiversity, deprive ecosystem services and accelerate climate change (McIntyre, 2009; OECD, 2009; OECD-FAO, 2009; UNCTAD, 2013).

Hence, new agricultural approaches and production systems are required that not only focus on increasing biomass production, but at the same time substantially reduce the negative environmental impacts of agriculture. For the future, improved farm management and technology, knowledge and skills developments and innovative agricultural concepts need to enhance the total factor productivity (Fuglie, 2012) at a projected rate of 1.1% annually until 2050 (Bruinsma, 2009) for supplying sufficient and sustainable biomass for the 4F's to meet the future demand in the growing bioeconomy.

Smallholder family farms

The largest potentials for increasing agricultural biomass productivity are located in those regions of the world that have not been reached by the scientific and technological advancements of the past. These areas include parts of South East Asia, Latin America and Sub-Saharan Africa (Bruinsma, 2009; OECD-FAO, 2009). In these areas smallholder family farming is predominant and agriculture constitutes the main source of rural livelihoods. Globally, a large number of 475 million smallholder family farms exist (Graeub et al., 2016). For the 'UNs' International Year of Family Farming 2014' these types of farms were analysed, revealing the characteristics and the diversity of these farms. This corrected the anecdotal figures of smallholder managing 80% of the agricultural land and producing 80% of the global food from the previous FAO report on the 'State of Food and Agriculture' (FAO, 2014b). Graeub et al. (2016) revealed, based on newer agricultural census data, that family farms (with varying definitions in size across countries and regions) constitute 98% of all farms and hold 53% of the agricultural land, thus producing at least 53% of the global food. Most family farms are located in Asia (99%), Africa (97%) and Europe (97%). In Asia family farms hold 98% of the land. In Europe, North and Central America and Africa it is between 67-69% of the land. In terms of food production, the importance of smallholder family farms varies considerably across regions. European and Asian smallholder family farms achieve surplus production (114% and 112%, respectively). In Africa as well as in North and Central America 64% and 60%, respectively, of the food produced in these regions stems from smallholder family farms, while South Americas' family farmers provide only 36% of the regions' food (Graeub et al., 2016).

These values represent a very conservative estimation, likely underestimating the real share of food produced in the smallholder family farms given the inverse productivity-size relationship in agriculture (Barrett et al., 2010; Graeub et al., 2016). In contrast to the economies of scale theory, the productivity per land area is empirically measured generally higher on small farms compared to large farms (Barrett et al., 2010). The hypothesis of a potentially higher soil fertility on small farms was tested and discarded as explanation, while village and household-level market imperfections (e.g. non-tradeable endowments, variations in transaction costs on local level) can explain about one-third of the inverse relationship (Barrett et al., 2010). Taking the still largely un-explained inverse productivity-size relationship into account, leads to the assumption that the actual share of smallholder family farms on the global food supply is considerably higher than 53% (Graeub et al., 2016).

Finally, Graeub et al. (2016) point out that there is no definition of smallholder family farms according to the size of their land. The term family farm and smallholder farm is often used interchangeably. The often used 2 ha or 10 ha boundaries for a smallholder farm are not meaningful, as the size of a smallholder farm and thus the country-specific definition (if any) varies considerably (Jayne et al., 2010). In Nicaragua and Peru, for example, a smallholder farm can be as large as 60ha (Graeub et al., 2016) while in India and Africa 47% and 57% of smallholders, respectively, hold less than 0.5ha (FAO, 2014b). This updated analysis of the characteristics of smallholder family farms provides accurate figures about the importance of this large population group for supplying biomass for the 4F's and for solving the great challenges of the 21st century. Therefore, the general point of view on smallholder family farms in political debates made a U-turn from smallholder family farms being part of the poverty and food security problem towards these farms being a central component for the solution of these problems (FAO, 2014b, 2009a; Graeub et al., 2016; McIntyre, 2009) and thus need to be considered as important population group for the development of the global bioeconomy.

The IAASTD report highlighted the multifunctionality of agriculture referring to biomass for the 4F's, the provision of ecosystem services, the landscape structure and the socio-cultural heritage, and concluded that future agricultural development requires a holistic and systems-oriented approach, as introduced by the global development of the bioeconomy.

1.4. Bioeconomic solutions for sustainable agricultural biomass production

The basic premise of both, the agricultural development (FAO, 2014b, 2009a; McIntyre, 2009; OECD-FAO, 2009) and the bioeconomy development is (BMBF, 2010; BMELV, 2013; EC, 2012; FORMAS, 2012; OECD, 2009) that 'business as usual' is no option for the future. The Earth Overshoot Day, the day when humans have consumed more resources than the earth can reproduce within one year, was reached between 3rd and 5th August for the years 2011 to 2016 (Overshootday.org, 2020). Hence human society and economy live for about five months of the year at the expense of natural ecosystems and future generations. This refers to the initial meaning of the term *bioeconomics* by Zeman in the late 1960s. The term was subsequently taken up by the economist Georgescu-Roegen in the 1970s (Bonauiti, 2015), who argued that unlimited economic growth is incompatible with the natural laws, in particular the thermodynamic law of entropy (Bonauiti, 2015), and that economic activities have to take place within the planetary boundaries (Bonauiti, 2015; Steffen et al., 2015).

The transition from a fossil-based towards a bio-based economy provides a fundamental paradigm shift of the economy and the society (BMBF, 2010; EC, 2012). The bioeconomy re-emerged from the biotechnology sector defined by the OECD "a*s an economy that uses renewable bioresources, efficient bioprocesses and eco-industrial clusters to produce sustainable bioproducts, jobs and income*" (OECD, 2004, p. 5). Sustainable, biobased development requires the coverage and integration of multiple economic sectors, the revitalisation of rural areas as well as the creation and utilisation of new knowledge facilitated by coordinating strategies and policies (OECD, 2004; Patermann and Aguilar, 2018). Sustainably produced biomass, together with advancements in bioprocess engineering, will be key in solving the challenges of the 21st century and will form the basis for the future economy (EU, 2007). Increasing the biomass production to meet the future demand requires a highly productive and sustainable primary sector as its backbone. Thereby, a strong focus lies on countries of the South (OECD, 2009), where the main increase in biomass production will take place (OECD-FAO, 2009).

Subsequently, the EU regarded the cross-cutting nature of the bioeconomy as a "*unique opportunity to comprehensively address inter-connected societal challenges such as food security, natural resource scarcity, fossil resource dependence and climate change, while achieving sustainable economic growth*" (EC, 2012, p. 3). Until today, 49 countries had developed dedicated or bioeconomy-related strategies (the latter focusing on individual sectors or aspects of the bioeconomy) (Bioökonomie.de, 2021; German Bioeconomy Council, 2018), with the following being among the pioneers: the OECD and the EU as well as USA, Canada, Australia, Germany, Finland and Sweden (Staffas et al., 2013). The main targets, areas of innovations and approaches in these strategies for solving the global challenges of the 21st century are:

- The global dimension of the bioeconomy supports international agreements and cooperation, which is required because of international value chains in a globalized world (ACIL Tasman, 2008; EC, 2012; FORMAS, 2012; Luoma et al., 2011; OECD, 2009);
- The systemic integration of all relevant sectors that produce, utilise or develop biobased resources (plants, animals, microorganisms, organic waste) including agriculture and forestry, landscaping, fishery and aquacultures, plant and animal breeding as well as the food, beverage, wood, pulp and paper, leather, textile, pharma, chemistry and the (bio-)energy industry (ACIL Tasman, 2008; BioteCanada, 2009; BMBF, 2010; BMELV, 2013; EC, 2012; FORMAS, 2012; OECD, 2009);
- The interdisciplinary perspective for strengthening the inter- and cross-sectoral cooperation between these sectors (ACIL Tasman, 2008; BioteCanada, 2009; BMBF, 2010; BMELV, 2013; EC, 2012; FORMAS, 2012; Luoma et al., 2011; OECD, 2009; White House, 2012);

- Participation and collaboration across all relevant stakeholders from governments, industry, research and civil society (ACIL Tasman, 2008; BioteCanada, 2009; BMBF, 2010; BMELV, 2013; EC, 2012; Luoma et al., 2011; White House, 2012);
- Informing and engaging with society and end-users about product sustainability, consumption patterns and lifestyles (BMELV, 2013; EC, 2012; FORMAS, 2012; Luoma et al., 2011);
- The planning, design and assessment of biobased value chains based on the sustainability paradigm of decoupling human development and economic growth from the expense of environmental and ecosystem services degradation (BioteCanada, 2009; BMBF, 2010; BMELV, 2013; EC, 2012; FORMAS, 2012; OECD, 2009);
- The circular resource use, rendering organic wastes and residues valuable feedstocks for biobased products, while aiming at the elimination of waste disposal. Therein, cities are considered circular bioeconomy hubs, strengthening the productive re-use of the substantial amounts of urban organic wastes (EC, 2018);
- The holistic value chain perspective across all biomass utilisation pathways (4F's) (BMBF, 2010), through
    - the cascading utilisation of biobased resources (biorefinery concept) to foster synergies between individual processes, sectors and actors within biobased value chains in order to increase resource-use efficiency (BMBF, 2010; BMELV, 2013),
    - the assessment and consideration of social, environmental and economic sustainability (BMELV, 2013; FORMAS, 2012; OECD, 2009);
- The prioritisation of food production over other biomass utilisation pathways for achieving global food and nutrition security (BMBF, 2010; BMELV, 2013);
- The strong investment in research and innovation (ACIL Tasman, 2008; BioteCanada, 2009; BMBF, 2010; BMELV, 2013; EC, 2012; FORMAS, 2012; OECD, 2009);
- Knowledge and skill development with rapid deployment as major driver of the bioeconomy (ACIL Tasman, 2008; BMBF, 2010; BMELV, 2013, 2013; EC, 2012; White House, 2012) e.g. through multi-disciplinary education programmes (EC, 2012) and training of professionals (BMELV, 2013).

These bioeconomy developments provide a comprehensive and international pathway with guidelines for increasing the biomass supply, making its production and consumption more sustainable while mitigating and solving the global challenges of the 21st century.

1.5. Bioeconomy-inspired solutions for the global challenges of the 21st century

In this thesis three approaches for supporting the sustainability transition to the bioeconomy have been investigated and developed further, addressing both the supply and the demand side.

1.5.1. Integration of renewable energy production into smallholder farming systems

Agriculture is one of largest energy consumer and thus GHG emitter globally (FAO, 2011). At the same time, the large population group of smallholder farmers in rural areas countries of the South often lack access to modern, clean and affordable energy. The integration of RE generation into agricultural production systems provides the opportunity to produce food and clean energy at the same time (FAO, 2014a). Integrated food and renewable energy systems (IFRES) (i) combine the production of biomass for food and energy on the same land e.g. through inter- und multiple-cropping of food and energy crops and / or (ii) maximise the use of synergies between crop production, livestock keeping, aquaculture and (multiple) RET by maximising the utilisation of residues and by-products (FAO, 2014a) in circular or cascading production systems.

Hence, access to modern energy for agricultural operations can enhance productivity (FAO, 2010), e.g. through mechanisation of field management, running irrigation pumps, harvest and post-harvest processes and improved storage (FAO, 2011). Higher productivity in combination with reduced losses can increase household incomes and supports food and energy self-sufficiency and security. In addition, multiple other social, environmental and economic benefits can be achieved through RE production and utilisation in rural farming households:

⇒ first, the reduced indoor-air-pollution provides better health for the household members (especially women) (Mangoyana and Smith, 2011);

⇒ second, the often time-consuming task of fuel collection (wood, manure, crop residues) can be replaced with other (social or productive) activities (Mangoyana and Smith, 2011);

⇒ third, the substitution of traditional energy sources reduces deforestation and associated losses of biodiversity and ecosystem services and / or provides the possibility to utilise crop residues and manure (if used as energy source before) for soil fertility improvement (Duku et al., 2011);

⇒ fourth, fossil energy (e.g. LPG, petroleum, kerosene, fossil-based grid electricity) can be replaced thus reducing household GHG emissions (Mangoyana and Smith, 2011);

⇒ fifth, RE self-production can be realised at a lower price per energy unit compared to prevailing energy sources, thus saving financial resources (Mangoyana and Smith, 2011);

⇒ sixth, the overall natural resource-use efficiency is increased, when making productive use of sun, wind, water, geothermal and/or bioenergy in addition to food and feed production (FAO, 2014a),

⇒ seventh, the production of RE on farm level may creates synergies and supports other productive tasks, e.g. utilisation of residual heat of biogas generators for harvest drying, or allows for mechanisation, e.g. of flour milling and other food processing (Mangoyana and Smith, 2011).

Hence, the integration of RE into smallholder farming systems is a key driver of agricultural development, poverty alleviation and sustainable rural livelihoods (FAO, 2011; Kaygusuz, 2012). The design and implementation of locally appropriate RET provides a promising option to sustainably intensify overall productivity of agricultural systems in countries of the South, where the highest agricultural productivity gains can be achieved (Bruinsma, 2009; OECD-FAO, 2009).
However, despite the ample benefits, the success rate of RE projects is rather low, as reported for Sub-Saharan Africa (36%) (Barry et al., 2011) and Thailand (40%) (Green, 2004). Reasons for this include a centralized planning process focusing on techno-economic factors, the imposition of unfamiliar technologies (Amigun et al., 2011; Dent et al., 2012), while often neglecting the local socio-cultural context (García and Bartolomé, 2010).
The exploration of the local context and the integration of smallholder famers in a participatory approach to RET planning and selection can support the identification of locally appropriate RET that match both the local renewable resource base and the role of energy in peoples' lives. Hence, a participatory, bottom-up approach can reach the large number of smallholder farmers and involve them in the sustainability transition towards the bioeconomy focusing on resource-use efficiency, agricultural productivity and socio-economic benefits for sustainable rural livelihoods in countries of the South. The 'Integrated Renewable Energy Potential Assessment' (IREPA) approach was applied in two case studies rural South Africa and India has been developed further as part of this thesis.
-> Chapter 2.1 and Chapter 2.2 of this thesis

1.5.2. Urban gardening – a driver of the societal transition towards the bioeconomy?

The participation and the involvement of all relevant stakeholders across disciplines and sectors are central for the bioeconomy development (EC, 2018, 2012; Staffas et al., 2013). This implies the engagement of society, as end-users and consumers, in sustainable natural resource through the consumer behaviour (BMELV, 2013). Therefore, the transition towards the bioeconomy can only become reality, when the concept is fully understood and taken up by the civil society in form of commitment for sustainable consumer behaviour (BMBF, 2014; EC, 2012; EU, 2007). The EU as well as the German bioeconomy strategies emphasise (i) the support of research and development of social innovations by the private and the public sector (BMBF, 2010; BMELV, 2013; EC, 2018, 2012), and (ii) that biotechnological research and development always needs to be accompanied by a socio-economic assessment including the normative dimensions of social processes and political support (BMBF, 2014). Considering the urbanisation trend, the growing urban population needs to be involved in the development of the bioeconomy.
In 2012, cities and metropolitan areas inhabited 53% of the world's population (72% in Europe) (Statista, 2018b) and consumed about 75%-80% of natural resources and energy on 2-3% of the global

land area (Hoballah and Peter, 2012; UNEP/GI-REC, 2017). The urbanisation trend will raise the urban population to about 70% by 2050 (Statista, 2018a) and likewise the natural resource consumption. Cities and metropolitan areas can be considered an urban metabolism of complex socio-technical and socio-ecological processes (Musango et al., 2017). These include flows of materials, energy, information and people with the aim of meeting the diverse needs of the cities' inhabitants. In addition, the cities' impacts on its (global) catchment area needs to be taken into account (Musango et al., 2017).

In view of this mega trend, cities and metropolitan areas take a key role in both the development of the bioeconomy and the design of sustainable biobased value chains for the future. Urban areas harbour an enormous potential for the increase in the resource-use efficiency and at the same time a reduction of the impacts on environment and climate (Musango et al., 2017). The European Commission (EC) highlights cities as circular bioeconomy hubs, emphasising the need of re-using the large quantities of organic wastes as feedstock for various biobased products (EC, 2018).

Urban agriculture has developed into a global trend. Urban food and biomass production in commercial high-tech, indoor production systems (= urban farming) or in individual or community gardens on available public and private areas (= urban gardening) becomes more and more part of the urban lifestyles globally (Chatterjee et al., 2020; Kalantari et al., 2018; Paganini and Lemke, 2020; Wille et al., 2017). Sustainable urban agriculture can become a key-concept for the bioeconomy, allowing for biomass production (especially food) and the enhancement of ecosystem services, thereby re-integrating agriculture and natural ecosystems into the nowadays largely segregated consumer and producer relationship (Hoballah and Peter, 2012). The bioeconomy and urban agriculture have in common that they are both based on natural ecosystems, material flows and natural cycles of formation and breakdown processes. In particular, urban gardening can re-connect urban consumers with natural processes through the production of food and biomass in cities. The urban gardening trend can thus raise awareness among the growing urban population about sustainable agricultural production and sustainable consumer behaviour. Therefore, the potential contribution of urban gardening for engaging the growing urban population in the sustainability transition towards the bioeconomy has been investigated based on a comprehensive characterisation of urban community gardeners in Germany.

-> Chapter 3 of this thesis

1.5.3. Sustainable agricultural production systems through environmental service valuation

Deforestation and the drainage of wetlands for the expansion of agricultural land are the major drivers for the decline of biodiversity and the vital services ecosystems provide for society (Costanza et al., 2014). Ecosystem services are categorised in *provisioning* (e.g. biomass for the 4F's), *regulating* (e.g.

climate regulation, pest and disease regulation, pollination, water and air purification) and *cultural* services (e.g. recreation, education, landscape aesthetics) (Costanza et al., 2014; Costanza et al., 1997; Millennium Ecosystem Assessment, 2005) on national to global level (Dauber and Miyake, 2016). After the first assessment of the global value of ecosystem services in 1997 (Costanza et al., 1997), these categories became the widely accepted measure for the state of the ecosystems and the changes over time (Millennium Ecosystem Assessment, 2005), leading to the foundation of the UN programme '*The Economics of Ecosystems and Biodiversity*' (TEEB, 2010). The European Biodiversity Strategy to 2020, for example, prompted the member states to map, assess and integrate ecosystem service values into the national accounting (EC, 2011). The bioeconomy strategies of Sweden, Finland, Germany, the EU and Canada explicitly highlight the importance of ecosystem services and the urgent need to sustain and increase them (BioteCanada, 2009; BMELV, 2013; EC, 2012; FORMAS, 2012; Luoma et al., 2011).

Also agricultural systems provide multiple ecosystem services, in addition to the provision of biomass for the 4F's. These include e.g. CO_2 sequestration, nutrient cycling, pollination, diverse habitats and the structure of the regional landscape (FAO, 2016; Matzdorf et al., 2010). According to (Matzdorf et al., 2010), ecosystem services provided by agricultural landscapes, and thus being subject to human management and service inputs from other ecosystems, should be referred to as 'environmental service' to distinguish between natural and human-managed services. Agricultural systems directly impact on the surrounding ecosystems. The landscape change through agriculture implies changes in the ecosystem service provision of these natural areas (TEEB, 2010). The valorisation of environmental services in agricultural systems thus provides a suitable measure to assess these multiple services in order to evaluate and subsequently improve the overall sustainability of agricultural systems (Jungmeier, 2016). Moreover, in agriculture the (intentional) avoidance of negative impacts on the adjacent and wider ecosystems should be assessed and taken into account (Jungmeier, 2016).

Assessing environmental services on local level can support the design of sustainable agricultural systems e.g. by informing crop selection (annual and perennial crops) and crop rotations (e.g. in terms of nutrient dynamics and water use). In this way agricultural systems can be designed that encourage beneficial environmental services, like for example carbon sequestration and soil fertility, natural pest and disease control, pollination and water retention (FAO, 2016). Consequently, the overall system performance and the resource-use efficiency can be enhanced, while material inputs (fertilizers, pesticides, irrigation) and the associated negative impacts on the environment can be reduced (FAO, 2016). The enhancement of environmental services can gradually build up productivity and thus have great potential for reclaiming degraded areas (FAO, 2016) and ameliorating marginal land facing biophysical or economic constraints (van Orshoven et al., 2014).

As part of this thesis, a conceptual case study about the production of miscanthus as feedstock for an isobutanol biorefinery in the Federal State of Brandenburg (Germany) was carried out to evaluate whether environmental service valorisation can support the sustainable biomass production in agricultural systems. Environmental services applicable to this agricultural production system have been explored and subsequently monetised to make these 'externalities' tangible and thus the providers and beneficiaries accountable.

-> Article 4 of this thesis

1.6. Aims of this study

The biomass demand for food, (+70%) (FAO, 2009a), fibre (+29%) (nova-Institute, 2013), bioenergy (100-200%) (IRENA, 2014) and the total energy demand (31-55%) (Moriarty and Honnery, 2012) are projected to grow considerably in the upcoming decades. Increasing the supply of both biomass and RE, however, is troubled by the global challenges of the 21st century. Coping with these challenges and finding solutions for higher biomass and RE production requires holistic, knowledge-based and system-oriented approaches across disciplines and national borders, involving all relevant stakeholder groups. The bioeconomy provides strategies for the development of sustainable, biobased value nets spanning from the production of biobased resources and RE in agricultural systems over its conversion to the marketing and consumption of biobased products.

In this interdisciplinary thesis the contributions of integrated rural and urban agricultural systems for the sustainability transition towards the bioeconomy are investigated, focusing on the sustainable increase in biomass and RE production by addressing both the demand and supply side (Fig. 1), based on:

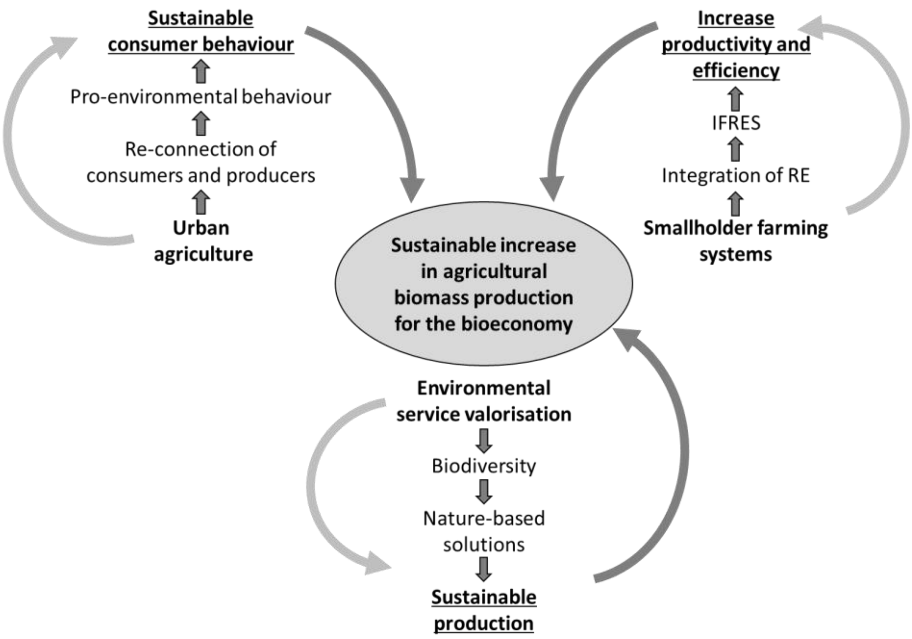

Figure 1: Graphical outline of this thesis: The role of smallholder farming systems in countries of the South, urban agriculture and environmental service valorisation for the sustainability transition towards the bioeconomy

- The increased production of biomass and renewable energy in smallholder farming systems in countries of the South – based on the research questions:
  (1) How to assess the renewable energy potential and select appropriate renewable energy technologies for implementation into smallholder agricultural systems in emerging economies?
  (2) How are renewable energy technologies perceived by smallholder farmers and which are the drivers and barriers for their implementation?

- The role of urban agriculture for food production and the societal transition towards the bioeconomy by fostering a sustainable consumer behaviour – based on the research question:
  (3) How can urban agriculture contribute to a sustainable food and biomass supply for the bioeconomy?

- The food-energy-environment trilemma of increasing the biomass production while sustaining and enhancing ecosystem services – based on the research question:
  (4) How can the implementation of sustainable biomass production systems be supported by the assessment and valorisation of environmental services?

These research questions are explored in the following four scientific articles of this thesis. Subsequently, the implications of the research findings are discussed based on the state of the art in the respective fields of research. Finally, the individual topics are connected by sketching concepts and solutions for the sustainable intensification of rural and urban agricultural production for the growing bioeconomy.

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2. Integrated Renewable Energy Potential Assessment (IREPA)

2.1 Integrated assessment of renewable energy potential: approach and application in rural South Africa

In this chapter first the need for and the development of the IREPA approach is explained, based on a comprehensive review of renewable energy (RE) and biomass potential assessment studies, the selection factors for locally appropriate renewable energy technologies (RET) and participatory impact assessment as well as decision making methods.
In the second part, the results of the first IREPA application in a rural South African community is presented and discussed with regard to the applicability of the approach in practice. Finally, the policy implications of participatory, bottom-up RET selection are discussed in contrast to the centralized, top down RE policy in South Africa.

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Integrated assessment of renewable energy potential: Approach and application in rural South Africa

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ABSTRACT

This paper presents the development and application of the Integrated Renewable Energy Potential Assessment (IREPA), employing a three-pronged approach: (i) literature review of renewable energy potential assessment methodologies, renewable energy technology (RET) selection factors and impact assessment methods; (ii) discussions with academic peers from natural and social sciences, and the private energy engineering sector; (iii) evaluation of the IREPA methodology through case-study research in a rural community in South Africa. Locally relevant social, institutional, environmental and techno-economic factors were explored through mutual knowledge exchange with smallholders and subsequently applied for appropriate RET selection. Three barriers to participatory decision-making were revealed: i) lack of knowledge ofrenewable energy among smallholders; ii) insufficient practical information dissemination in IREPA; iii) abstract nature of the analytical hierarchy process. The adaptions recommended by this research would render IREPA a suitable bottom-up approach for the assessment and effective implementation of RET, stimulating socio-economic development in rural areas.

1. Introduction

Improving access to clean and modern energy is high on the policy agenda of many developing and emerging economies (Hailu, 2012) and essential to the post-2015 development agenda (UNECOSOC, 2014). Extension of the electricity grid to rural areas where most of the energy-poor households live is technically challenging and often not economically viable due to the low density and dispersed structure of rural settlements (Cherni et al., 2007). Decentralized, renewable energy (RE) systems (solar-, wind-, hydro-, geothermal and bioenergy) can increase access to modern energy in rural areas, (Cherni et al., 2007; Kaygusuz, 2012). By the end of 2015, 146 countries had adopted RE support policies. More than two thirds of these countries are developing countries or emerging economies (REN21, 2016).

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The highest technical potential for solar, wind and biomass energy (about 983 EJ) has been found for the African continent (De Vries et al., 2007). This is almost twice the 2013 total global annual primary energy consumption of 533 EJ (BP, 2014). Currently, modern RE accounts for only 1.5% of the total African primary energy supply, which is based to 51% on fossil fuels and nuclear power and to 47% on solid biofuels such as wood and charcoal (IRENA-DBFZ, 2013).

In South (Africa energy is mainly generated from coal (87.5%). Solid biofuels account for 9.4%, while other RE have a share of 1.3% (OECD/IEA, 2016). Since the abolishment of the Apartheid various electrification programmes have been implemented, e.g. *White Paper on Energy Policy* (estd. 1998), *Integrated National Electrification Programme* (estd. 2001) and *Integrated Resource Plan* (estd. 2011) (DoE SA, 2013). Between 1996 and 2014 5.7 million households were connected to the grid. This transformed the electrification rate in the Transkei (Eastern Cape) from more than 80% un-electrified households in 1996 (DoE SA, 2013) to 82.3% electrified households in 2015 (Stats SA, 2015). For further rural electrification off-grid renewable energy technologies (RET) are proposed, in particular in the former homeland areas in KwaZulu Natal and the Eastern Cape, the two provinces with the highest off-grid potential in South Africa (DoE SA, 2013).

Currently, RE development in South Africa is directed by the *Renewable Energy Independent Power Producer Procurement Programme (REI4P)* (DoE SA, 2015). The REI4P is based on a competitive bidding process for RE supply contracts, focusing on large-scale RE-production (> 1MW). In the first three years, the programme has had considerable success. The number of electricity producers has increased from one to 64 and RE electricity prices have decreased. However, the socio-economic development targets of the REI4P, including human capital building as well as job and enterprise creation in rural areas, have not been achieved (Walwyn and Brent, 2015). This shows the limitations of centralized, top-down approaches to reaching remote rural areas and stimulating socio-economic development. In rural areas, RET planned according to techno-economic considerations by external experts often fail to meet the expectations of a long-term and sustainable energy supply (Hailu, 2012; Wang et al., 2009).

The implementation of RE depends on the complex interaction of social, institutional, environmental, technical and economic factors that determine the adaptability of a technology to the local socio-cultural context (Barry et al., 2011; García and Bartolome, 2010; Kaygusuz, 2012). The involvement of stakeholders is therefore an important condition for successful RE implementation.

Smallholder farmers - defined here as farms with less than 10 ha, often less than 1 ha (Jayne et al., 2010) - manage more than 80% of the natural resources in rural areas (IAASTD, 2009). Therefore smallholders are the stakeholders that should primarily be addressed in RE potential assessments (REPA) and RE implementation programmes in rural areas.

This study presents an innovative methodology to REPA in smallholder farming systems. The "Integrated Renewable Energy Potential Assessment" (IREPA) was developed with the purpose of integrating the above-mentioned factors in a participatory, bottom-up approach to select locally appropriate RET for the assessment of the renewable energy implementation potential (REIP). For the methodological development, a three-pronged approach was applied. First, current methodologies used for REPA were analysed with emphasis on social, institutional, environmental and techno-economic factors. In addition, appropriate methodologies for participatory research, impact assessment and decision-making were reviewed. Second, IREPA was developed based on the results from the previous step, additionally informed by discussions with academic peers and the private energy sector. Third, findings from case-study research in the Eastern Cape Province of South Africa are presented, testing whether IREPA is applicable in this specific context.

2. Methodology

2.1. Development of the IREPA approach

2.1.1. Literature review

Current approaches for REPA were analysed, taking only methodologies into account that assessed the ***theoretical, geographical, technical, economic*** and ***implementation*** potential categories as defined by Hoogwijk (2004) and Resch et al. (2008).

In addition, literature on RE case studies was reviewed to explore the social, institutional, environmental, technical and economic factors considered important for RET selection. For the identification of these factors at the local level *Participatory Learning and Action* (PLA)[1] research methods are essential and are therefore included in the literature review (Chambers, 1994; Hart, 2008).

Further, social and environmental impact assessment as well as multi-criteria decision analysis (MCDA) methods were reviewed, drawing on the MCDA reviews of Hailu (2012), Taha and Daim (2013) and Wang et al. (2009), to identify a suitable methodology for assessing the impacts of RET on people's livelihoods and to select locally appropriate RETs in the IREPA.

2.1.2. Discussions with academic peers and the private sector

The results of the literature review were discussed with academic peers from the disciplines agricultural sciences, agricultural economics and social sciences, and with energy engineers from the research and development department on future renewable power technologies of ALSTOM (Schweiz) AG. This enabled an inter- and transdisciplinary research perspective.

[1] PLA comprise a wide range of approaches including *Participatory Rural Appraisal (PRA), Rapid Rural Appraisal (RRA), Participatory Learning Methods (PALM), Participatory Action Research (PAR), Farming Systems Research (FSR), and others* (Hart, 2008).

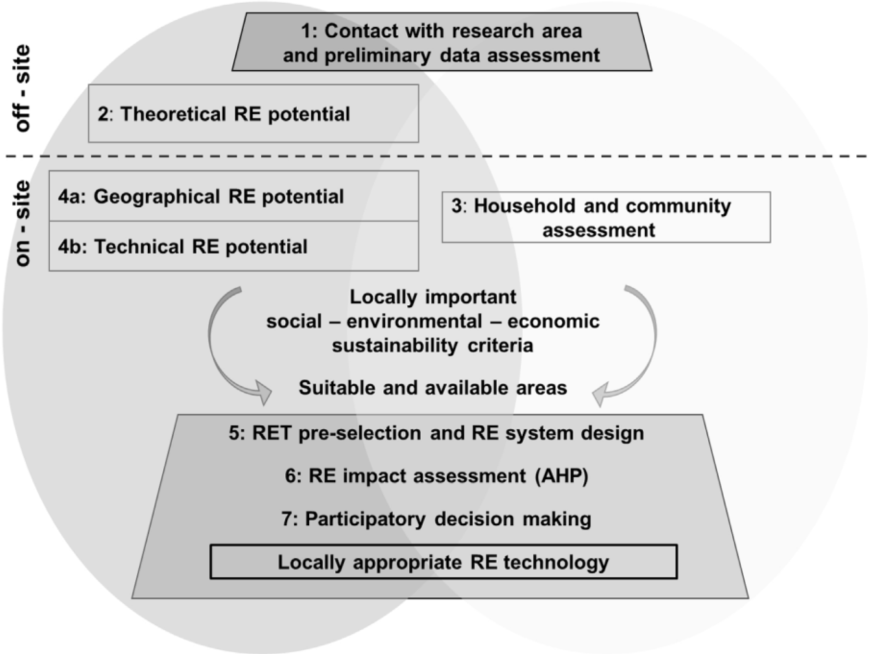

Fig. 1. Methodology of the Integrated Renewable Energy Potential Assessment (IREPA).

2.2. *Application and evaluation of IREPA in a rural community in South Africa*

2.2.1. *IREPA-Methodology*

IREPA integrates the techno-economic perspective of energy engineering (trapezoidal box), the bio-physical perspective of natural science (grey circle) for REPA assessment, and the socio-cultural perspective of social science (light grey circle), aiming at applying a participatory, bottom-up approach for appropriate RET selection and REIP assessment (Fig. 1):

Step 1: contact with research area and preliminary data assessment

Contact to the research area and local partners (e.g. local government representatives, research institutions, NGOs, village chiefs, farmers, etc.) is established to engage in a process of information exchange about the local context. For the participatory aspect of IREPA, it is important to have a local contact person in order to gain access to and build up trust with the community where research is conducted (Amigun et al., 2011; Wüstenhagen et al., 2007).

Step 2: theoretical renewable energy potential (ThREP)

The *ThREP* for solar-, wind-, hydro-, geothermal and bioenergy is assessed according to the REP categories defined by Hoogwijk (2004) and Resch et al. (2008). The bio-physical renewable resource (RR) availability is evaluated by drawing on global and national statistical databases covering the researched area (Table 1) as suggested by Angelis-Dimakis et al. (2011).

Step 3: household and community assessment

For IREPA participatory research methods are applied to assess the household and community characteristics and subsequently identify social, institutional, environmental, technical and economic factors for the selection of locally appropriate RET. For interview design IREPA draws on the *Sustainable Livelihoods Framework* (SLF) (Scoones, 1998), *Environmental Impact Assessment* (Finnveden et al., 2003; UNEP, 2008) and *Social Impact Assessment* (Amezaga et al., 2010) (section 3.3). The following PLA research methods were applied:

- *Open-ended, semi-structured interviews* with households (n = 18, five male, thirteen female) to explore socio-demographic and -economic characteristics as well as perceptions regarding the role of energy in people's lives. The questionnaire was evaluated in a pilot survey with a group of women (n = 9) from a nearby agricultural training project who had similar socio-economic characteristics.

Table 1
Data sources for the assessment of the local renewable resource base at Mgwenyana.

Renewable Resource	Data Sources
Solar	HelioClim-3 Database of Solar Irradiance
Wind	Wind Atlas for South Africa (WASA)
Hydro	Department of Water and Environmental Affairs (DWEA), South Africa
Biomass	NASA Earth Observations (NEO); Local Biomass Inventory Analysis
Geothermal	Banks and Schäffler, 2006

Table 2
Key-informants interviewed during the Household and Community Assessment at Mgweynana.

Name	Affiliation
Luke Boshier	Founder and director of "Centre for Appropriate Rural Technology" (CART)
Dianne van der Walt	Member of CART, Permaculture expert and teacher
Khaya (*surname unknown*)	Project staff of CART
David Philips	Founder and director of "People Empowered Preserved Earth" (PEPE)
Vujani Mgcotyelwa	Member of the Traditional Council of Mgwenyana

- *Key-informant interviews* (n = 5) with four development practitioners of CART and PEPE (three male, one female) and one male member of the traditional council of Mgwenyana (Table 2).
- *Focus Group Discussions* with above-mentioned key informants, community members participating in the partner organisations's project (two male, fourteen female) and two members of the traditional council (one male, one female).
- *Transect walks* through the community accompanied by *informal interviews* with community members.
- *Direct and participant observation* - field records in the form of written notes, photographs and videos were taken during the interviews, transect walks and while working together with community members in the project.
- *Living in the community* and performing regular daily tasks including fetching water and firewood, preparing food on an open fire and gardening contributed to a better understanding of the community members' daily routine.
- *Visits to four rural development projects* - a former CART project in *Sicambeni* (community about 40 km from Mgwenyana); *Sisonke Eco-school* in Port St. Johns; *Growing the Future* project in Grootbos and *Green Pop* in Cape Town, providing insights into development work in similar settings.
- *Review of secondary sources* including project reports of CART and PEPE.

These PLA methods provided detailed qualitative and quantitative data on local livelihoods. For analysis of qualitative data, the information was transcribed and coded in order to categorize, generalize and interpret it (Creswell, 2009 p. 184ff). The emerging data were cross-checked to obtain reliable data employing triangulation of different data sources (Fig. 2) (Creswell, 2009).

Quantitative data were processed using MSO Excel 2007 performing descriptive statistics. Percentages, averages and ranges were calculated (Creswell, 2009).

The results were structured drawing on the *Sustainable Livelihoods Framework* (SLF) (Scoones, 1998). The tool enables understanding and characterising people's livelihoods with the aim of retaining factors that determine the role of energy in people's livelihoods. The SLF focuses on people's assets (human, social, physical, natural and financial) and the livelihood strategies adopted to achieve certain livelihood outcomes. Attention is drawn to core influences that shape people's assets: (i) the *Vulnerability Context* describes the external environment that affects the wider availability of assets based on *trends* (e.g. demographics, resource and technology use, etc.), *shocks* (e.g. diseases, natural disasters, etc.) and *seasonality* (e.g. prices, agricultural production, employment etc.) over which people have limited or no control; (ii) *Transforming Structures and Processes* represent institutions, organisations, policies and legislation that influence livelihoods from a household to international level and from private to public spheres, and that determine access e.g. to decision-making bodies and capital (including terms of exchange between different types of capital) and returns (economic or otherwise) from any livelihood strategy (DFID, 1999).

The emerging data were compared with RET selection factors derived from the literature (section 3.2). Subsequently, the ten most important factors were selected based on the frequency with which a factor was mentioned in the household and key-informant interviews. These factors reflect the aims and requirements to be met by a RET for it to be appropriate in a particular local context, and are regarded as *local RET sustainability criteria*.

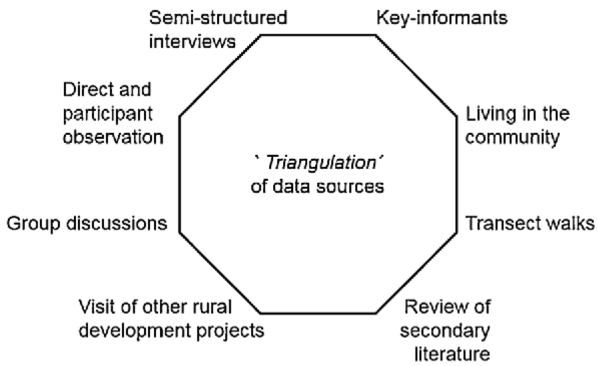

Fig. 2. Triangulation of multiple data and information sources (based on Creswell, 2009).

Table 3
Brief overview of social, institutional, environmental, technical and economic factors determining renewable energy potentials.

REP category [a]	Definition [a]	Determining factors	Description of factors
Theoretical	Physical renewable resource availability	*Bio-physical*	Climatic, geographical and geological conditions in the research area (Hoogwijk, 2004; Resch et al., 2008)
Geographical	Suitable areas for harnessing renewable resources	*Bio-physical, technical*	Power density: - e.g. Solar power density: > 120 W m^{-2} on ground (Hoogwijk, 2004) - e.g. Average wind speed: > 4 m s^{-1} at 10 m height (Kumar et al.,2010) - e.g. Average wind power density: > 400 W m^{-2} at 30 m height (De Vries et al., 2007) Occurance of surface water and height gradient (Resch et al., 2008) Biomass as scarce resource in semi-arid and arid areas (water = limiting factor) (Smeets et al., 2007) Areas with geothermal sources and drilling depth (Resch et al., 2008)
		Environmental	Incompatible land cover (Hoogwijk, 2004, De Vries et al., 2007)
Technical	Availability of suitable areas	*Social*	Current land-use patterns (Smeets et al., 2007) Social acceptance of RE - (lack of) knowledge about RE (Hoogwijk, 2004)
		Social, environmental, economic, institutional	Competition with other land and resource uses (Moriarty and Honnery, 2012), espically for bioenergy (Smeets et al., 2007)
		Environmental, technical	Accessibility (Smeets et al., 2007) and available infrastructure (Moriarty and Honnery, 2012)
		Institutional	RE policy support (Resch et al., 2008)
	Technical conversion efficiency	*Technical, economic, environmental, social*	Type and characteristics of selected RET (De Vries et al., 2007)
Economical	Investment costs Energy production costs Interest rate	*Institutional, social, economic*	Public and private investments/procurement (Gross et al., 2003) RE policy support (Resch et al., 2008) and fiscal incentives e.g. feed-in-tariffs, tax exemptions, and others; RE portfolio standards (Gross et al., 2003)
Implementation	***Social, institutional, environmental, technical and economic factors***		

[a]Based on: De Vries et al., 2007; Hoogwijk, 2004; Resch et al., 2008.

Furthermore, in this step special emphasis is placed on the assessment of suitable and available biomass resources (including land for energy crops) for energy production. In addition, the system boundary (spatial extension of the community) is defined.

Step 4a: geographical renewable energy potential (GREP)

Bio-physical data on RRs within the system boundary (incl. temporal patterns) are employed to assess suitable areas for RE generation. For this purpose local power densities are evaluated based on threshold values for technical utilisation (Table 3, section 3.1). RR with power densities below the threshold values are excluded from the assessment. The bioenergy potential is assessed in a biomass inventory analysis. This is based on the exploration available biomass resources (agricultural residues, organic kitchen waste, animal and human excreta, etc.), performed in step 3.

Step 4b: technical renewable energy potential (TREP)

From the suitable areas identified, those areas available for RE generation are selected according to the local RET sustainability criteria. The conversion efficiencies of locally available RET are also included to assess the TREP.

Step 5: RET pre-selection and energy system design

Suitable RET are pre-selected based on the *TREP* and the local RET sustainability criteria. RET options are pre-selected and planned by the researchers considering the availability of required materials and technology devices including their prices. For planning the whole RE generation value chain is considered by drawing on LCA's cradle-to-grave perspective (Keam and McCormick, 2008).

Step 6: energy system impact assessment

Local appropriateness of the proposed RETs is assessed by considering the impacts on the daily life of household members and on the environment. To select the most appropriate RET, the *Analytical Hierarchy Process* (AHP) is applied (Saaty, 1990). In the AHP, each proposed RET is evaluated using quantitative and qualitative selection criteria. First, the local RET sustainability criteria are arranged in pairs. Local participants rate the importance of the two criteria based on a scale of 1 to 9, where 1 indicates equal importance and 9 absolute importance over the other. Second, each participant compares the proposed RETs, arranged in pairs, with each other and with respect to each sustainability criterion. The pair comparisons allow for the computation of a decision matrix. Based on participant ratings, the eigenvector of (i) each sustainability criterion and (ii) of each RET is calculated using matrix algebra. The eigenvector expresses the priority of each participant (Saaty, 1990).

Finally, two rankings are obtained. The first states the importance of each sustainability criterion. The second reveals the most appropriate RET, either at community level, when taking all participant rankings into account, or at household level, when taking an individual ranking into account.

Step 7: participatory decision-making process

Finally, the AHP ranking is presented to the households and/or community in a *Focus Group Discussion*. The expenses and requirements for the achievement of individual benefits associated with a particular RET are considered by calculating *benefit:cost*, *benefit:labour* and *benefit:land area* ratios (Saaty, 1990). With full information at hand, local participants can ideally take the final decision for one or a combination of RETs.

2.2.2. *Case study area*

IREPA was applied in the rural community of Mgwenyana (31°55′ S; 29°23′ E) in the Eastern Cape province of South Africa from August to December 2012. Mgwenyana consists of four villages with a total of 9568 inhabitants in 736 homesteads. The four villages - *Masemeni*, *Kunduna*, *Mahkuzani* and *Mputshane* - cover an area of about 12.75 km^2 along the hillsides of the *Mngazi River* valley from 207 to 395 m above sea level. The climate is subtropical with a mean annual temperature of about 18–19 °C (Moyo et al., 2010). Average annual precipitation is 735 mm, characterised by a distinct rainy and dry season (DWEA, 2012).

Research was conducted in cooperation with the non-governmental organisations *Centre for Appropriate Rural Technology* (CART) and *People Empowered Preserved Earth* (PEPE). CART was approached by the traditional leaders to assist the community in utilizing their assets and natural resources in a sustainable way. Community development initiated by the local chief family provides a very suitable setting for applying the bottom-up IREPA.

2.2.3. Monitoring and evaluation

Monitoring and evaluation (M&E) of the IREPA methodology took place continually throughout the application in field research, according to the guideline of the *Monitoring and Evaluation in Energy for Development International Working Group* (M&EED IWG, 2012). For each IREPA step a causal chain was established that links the required inputs (e.g. permission to stay in and research the community) to the activity undertaken (e.g. application of PLA methods) and to the outputs (e.g. factors concerning the role of energy in people's lives), allowing for an evaluation of whether the expected outputs of each IREPA step had been achieved. If an IREPA step is not applied successfully, this M&E approach provides information on the area of failure, e.g. a missing input or the inapplicability of an applied method to achieve the expected output.

3. Results

The first section presents the results of the thematic literature reviews and discussions with academic peers and the private sector, which led to the development of IREPA. The second section provides insights from IREPA case study research.

3.1. Renewable energy potential assessment methodologies

The assessment of the *theoretical, geographical, technical, economic* and *implementation potential* is based on the factors summarized in Table 3.

The *theoretical* and *geographical potential* depends primarily on the bio-physical RR availability at a given location (incl. annual patterns), as well as environmental (land cover) and technical factors (minimum power density for technically utilisation). These factors determine the power density on the ground and in turn the areas suitable for harnessing these resources (Hoogwijk, 2004).

Numerous studies assessed the global *technical potential*, exploring the suitability and availability of areas for RE generation (Campbell et al., 2008; Cho, 2010; Field et al., 2008; Goldemberg et al., 2000; Haberl et al., 2011; Lightfoot and Green, 2002; Moriarty and Honnery, 2012; Sims et al., 2007; Smeets et al., 2007; Tomabechi, 2010; WEC, 2010; Wolf et al., 2003). This assessment depends on a complex interaction of environmental, technical, institutional and social factors including: accessibility (Smeets et al., 2007); existing infrastructure (Moriarty and Honnery, 2012); energy transmission/transportation/storage (Sims et al., 2007); current land use (Smeets et al., 2007); and acceptance and willingness of individual land owners to produce RE (Hoogwijk, 2004). RET-specific environmental and social constraints have been summarized by Moriarty and Honnery (2012) and include: resettlement and adverse effects on biodiversity due to inundation (hydropower); noise, vibration pollution, visual appearance and bird death (wind energy); competition for resources (e.g. fertile land and water) and between biomass uses (food, feed, fibre, fuel) (bioenergy). Additionally, the conversion efficiency as well as operation and maintenance (O&M) requirements are considered (Hoogwijk, 2004).

Three studies explored the *economic potential* (De Vries et al., 2007; Gross et al., 2003; Hoogwijk, 2004), considering factors such as specific investment costs (De Vries et al., 2007), energy generation costs (Gross et al., 2003) and interest rates (Hoogwijk, 2004).

The reviewed REP studies apply large spatial resolutions (e.g. grid cell size of 0.5° latitude x 0.5° longitude; Hoogwijk, 2004; De Vries et al., 2007). Suitable and available land areas are assessed based on assumptions, average values and trends (De Vries et al., 2007; Hoogwijk, 2004; Lightfood and Green, 2002; Moriarty and Honnery, 2012). According to the *World Energy Council* (WEC, 2010) these averages and trends are often based on studies conducted at a specific area and at some point in the distant past. Hoogwijk (2004) and De Vries et al. (2007) found in sensitivity analyses of their REPA studies, that personal and social values have a profound influence on the availability of suitable areas. Hence, it is likely that extrapolation of such data to country, regional and global level yields inaccurate results.

Only one study assessed the *implementation (realizable) potential* for the year 2020. Social and institutional factors have been revealed as major barriers to RE implementation and the authors concluded that effective policies are needed (e.g. REI4P in South Africa) to overcome these barriers (Resch et al., 2008).

Amigun et al. (2011) obtained insights into the perspectives of rural communities in the Eastern Cape Province on a planned, large-scale bioenergy project. The authors concluded that conflicts between national and local interests may arise when RE development decisions are made without consulting local communities. The landscape in the former homelands of South Africa is dominated by smallholder subsistence farming. Complex historical processes have resulted in multiple land administration schemes controlled by traditional leaders, government institutions and farmer associations, with varying power division, impacting on land tenure and access to natural resources (Hamann and Tuinder, 2012). Hence, perspectives of multiple individuals need to be considered.

To achieve socio-economic development in rural areas, the REI4P established stringent guidelines on RE project ownership, fostering the inclusion of previously disadvantaged groups: 40% South African entity participation, 12–20% black ownership (Black Economic Empowerment, BEE) and at least 2.5% local community shareholding (Baker, 2015). However, the competitive bidding process is centralized and tailored to large-scale projects to cover the increasing energy demand with RR (Pollet et al., 2015). Consequently, RE generation is concentrated among a small number of companies, as in the South

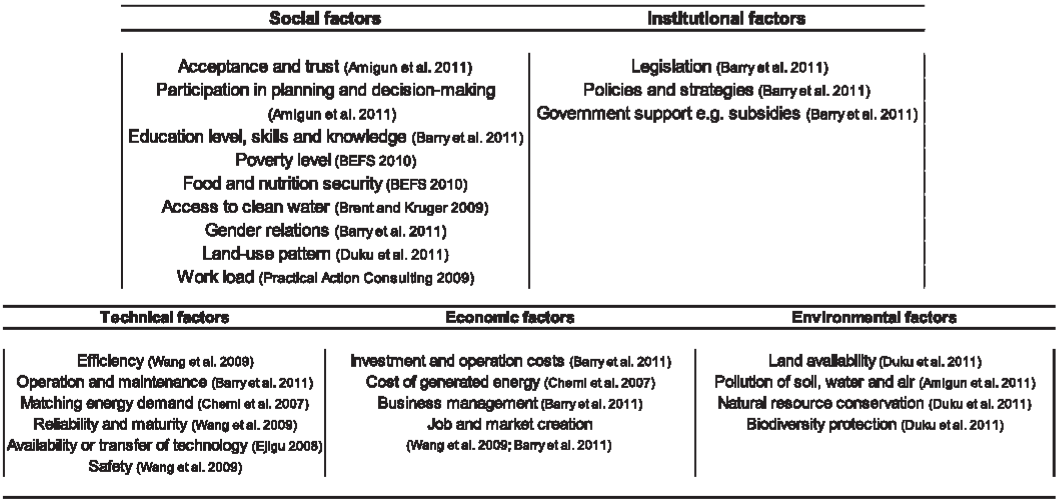

Fig. 3. Important factors for the selection of appropriate renewable energy technologies for implementation in rural areas in countries of the South.

African coal mining sector (Baker, 2015). The bidding consortiums are formally led by national companies and supported (financially) by international partners (Walwyn and Brent, 2015). Compliance with BEE and the focus on socio-economic community development is sometimes problematic to communicate to foreign companies and investors (Baker, 2015).

Thus it is questionable whether this top-down, centralized policy, favouring the lowest RE generation costs, is capable of including local stakeholders' interests to achieve the associated development aims.

All reviewed REPA methods apply a top-down approach, not or only partly considering local stakeholders' perspectives. Several authors have argued that RE-project planning and implementation requires a holistic approach to planning and action through interactive and effective communication, public participation from the beginning and pooled learning among the relevant stakeholders to directly benefit rural communities (Amigun et al., 2011; Brent and Kruger, 2009; Ejigu, 2008).

In IREPA, the structure of defined potential categories was adopted to assess the REIP. IREPA shifts from centralized, top-down planning and the extrapolation of average values and trends to a bottom-up assessment of the social, institutional, environmental, technical and economic factors at local level to account for local diversity.

3.2. Selection factors for appropriate renewable energy technologies and role of energy in people's lives

The local appropriateness of a RET depends on a variety of factors (Barry et al., 2011). Fig. 3 summarizes RET selection factors based on the literature. In REPA studies *key* or *major* RET of high importance on RE market and with electricity as energy output (Gross et al., 2003; Hoogwijk, 2004; Resch et al., 2008) are most frequently used as reference technologies (e.g. a 1 MW wind turbine with 69 m hub height; De Vries et al., 2007). Suitable areas are assessed based on the specific requirements of the reference turbine on the wind power density. For example only areas with at least 400 W m^{-2} at 30 m height are considered suitable (De Vries et al., 2007).

Technical, economic and environmental factors include technological efficiency, investment and operation costs as well as the kind and degree of environmental pollution, and are mainly quantitative. Institutional factors include general regulations for RET implementation (e.g. legislation, policies, strategies, agencies), public awareness raising, market promotion, technical capacity building, health and safety measures, enforcement of environmental protection laws and funds or subsidies including tax reduction/exemption and partnerships with donor agencies (Barry et al., 2011).

Whether a new technology is implemented and operated successfully in the long term depends on its acceptance (Amigun et al., 2011; Hailu, 2012). Acceptance is based on considerations such as information distribution, particular benefits, individual capacity of households and ability to meet their energy needs (Barry et al., 2011; Ejigu, 2008) and further on socio-cultural aspects such as current land-use patterns (Duku et al., 2011); gender relations, e.g. work distribution; food security (BEFS, 2010) and access to clean water (Brent and Kruger, 2009). In the *Survey of energy related behaviour and perception in South Africa* (DoE SA, 2012), the Eastern Cape citizens designated *keep electricity prices low* (76%), *reduced load shedding and power cuts* (60%), and *free electricity and help for poor households* (55%) as top priorities for government action.

Technology is a social construct and inextricably linked with individual behaviour, the latter often being the reason for technical failures e.g. repeated failure of electric connections or poor location of PV panels (García and Bartolomé, 2010; Schäfer et al., 2011). Additionally, people are not rational decision makers. There is a discrepancy between the material needs that people state and their actual behaviour (Frederiks et al., 2015). Knowledge and skills transfer, adapted to the local context is deemed important for technology acceptance (Barry et al., 2011). For example, replacing traditional indoor fireplaces with electric stoves significantly reduces indoor air pollution, related impacts on users' health and the risk of compartment fires (WHO, 2008). However, during case-study research it was found that smoke helps to keep mosquitoes

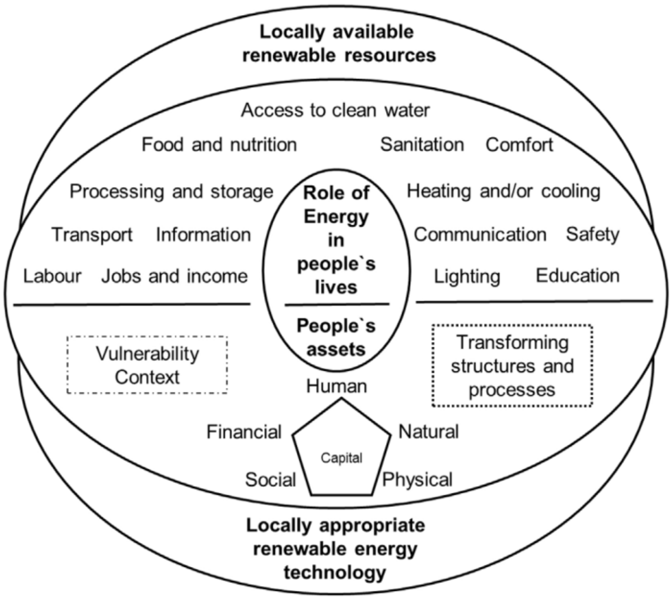

Fig. 4. A bottom-up approach for the selection of locally appropriate RETs based on locally available resources, the role of energy in people's lives and people's assets (Role of energy based on: Amigun et al., 2011; Barry et al., 2011; BEFS, 2010; Brent and Kruger, 2009; Cherni et al., 2007; Duku et al., 2011; Ejigu, 2008; Janssen and Rutz, 2011; Practical Action Consulting, 2009; Wang et al., 2009; People's assets, vulnerability context and transforming structures and processes adopted from the Sustainable Livelihoods Framework: Scoones, 1998).

and rodents out of the houses, thus protecting against insect-borne diseases and aiding food storage. Soot particles help seal thatched roofs.

Emphasising the role of energy in people's lives requires an exploration of local socio-cultural aspects (García and Bartolomé, 2010) and livelihood assets including available construction materials and technology parts (Fig. 4).

The SLF was adopted for IREPA to understand and holistically characterise the livelihoods of smallholder farming households (Table 4) (DFID, 1999). For example, the SLF was applied for planning small-scale bioenergy projects (Vargas, 2010), for impact analysis of foreign technologies on local livelihoods (Henao et al., 2012) and for selecting appropriate energy systems in rural areas (Cherni et al., 2007). In IREPA the SLF allows for consideration of the wider impacts coming along with the substitution of energy sources and for identification of local RET sustainability criteria.

3.3. Participatory impact assessment methods

Participatory impact assessment methods were reviewed and integrated for IREPA to consider the impacts a RET may has on local livelihoods (Table 4).

Participatory Learning and Action Research Methods are useful for community characterisation (see Section 2.2.1).

IREPA was informed by *Life-Cycle Assessment (LCA)* for the planning of RETs as it considers the resource and environmental aspects of the production, use and disposal of commodities based on the "cradle-to-grave" perspective (Finnveden et al., 2003; Keam and McCormick, 2008).

IREPA further retains the interdisciplinary assessment structure of the FAO's *Bioenergy and Food Security (BEFS) analytical framework*, consisting of a natural resource assessment paired with an analysis of the techno-economic, environmental and socio-economic background at country level to support policymakers in formulating bioenergy policies (BEFS, 2010).

IREPA further draws on elements of *Environmental Impact Assessment (EIA)* and *Strategic Environmental Assessment (SEA)* for exploring the impact of RETs on local livelihoods, with a focus on socio-economic and socio-cultural factors. This includes, among others, land use; resource management; community structure; employment; distribution of income; goods and services; local customs and attitudes (Alshuwaikhat, 2005; Finnveden et al., 2003; UNEP, 2008).

Lastly, IREPA integrates selected aspects of *Social Impact Assessment (SIA)*. For exploration of household and community characteristics, socio-political variables are adopted, including: population characteristics; community and institutional structures; political and social resources; individual and family changes; and community resources (Amezaga et al., 2010). In SIA stakeholder participation in the project implementation process aids decision-makers to understand the consequences of their decisions before actions are taken (Dutta and Bandyopadhyay, 2010).

3.4. Participatory selection of appropriate renewable energy technologies

Nowadays single criteria approaches that focus on the identification of the most efficient technology with the lowest costs are being replaced by Multi-Criteria-Decision Analysis (MCDA) methods (Wang et al., 2009). MCDA considers a wide

Table 4
Summary of reviewed methods and tools for data acquisition, analysis and impact assessment including their use in IREPA based on the scale of application, stakeholder participation and sustainability dimensions covered.

Method/Tool	Scale of application	Stakeholder participation	Sustainability dimensions	Use for IREPA	Source
Participatory Learning and Action Research Methods (PLA)	Small to large scale	Yes	Human, social, institutional, environmental, physical, economic	Participatory data and information acqusition methods	Chambers, 1994; Hart, 2008
Sustainable Livelihoods Framework (SLF)	Small to large scale	Yes	Human, social, institutional, environmental, physical, economic	Holistic characterisation and understanding of local livelihoods based on assets; data structuring	DFID, 1999; Scoones, 1998
Life-Cycle Assessment (LCA)	(Small) to large scale	No	Environmental (economic)	Cradle-to-grave perspective for planning RET options	Finnveden et al., 2003; Keam and McCormick, 2008
Bioenergy and Food Security (BEFS)	(Small) to large scale	No	Techno-economic, environmental, socio-economic	Modular assessment structure	BEFS, 2010
Environmental Impact Assessment (EIA)	Large scale	(Yes)	Environmental socio-economic socio-cultural	Socio-economic/-cultural factors for planning RET options	Finnveden et al., 2003; UNEP, 2008
Strategic Environmental Assessment (SEA)	Large scale	Yes	Environmental (socio-economic)	Strategy of defining goal and evalute options by using criteria	Alshuwaikhat, 2005; Finnveden et al., 2003
Social Impact Assessment (SIA)	Small to large scale	Yes	Socio-political	Bottom-up approach; social factors; stakeholder consultation,	Amezaga et al., 2010; Dutta and Bandyopadhyay, 2010

range of quantitative and qualitative factors and individuals' perspectives. Technology options and selection criteria are identified and subsequently ranked by participants to reach a decision. The most frequently used MCDA method in sustainable energy decision-making is the *Analytical Hierarchy Process* (AHP) (Taha and Daim, 2013; Wang et al., 2009). This descriptive method allows stakeholders (e.g. smallholder farmers) to compare and rank a set of selection criteria and technology options (arranged in pairs) to identify the most appropriate technology (Saaty, 1990). For example, an adapted AHP was applied to determine suitable RETs in Istanbul (Kaya and Kahraman, 2010) and to select the most appropriate "solar-PV home system" in rural Bangladesh (Ahammed and Azeem, 2013). The AHP was adopted for IREPA with the aim of allowing the local population to select appropriate RET.

3.5. IREPA – Application in a rural community in the Eastern Cape province of South Africa

Access to the community (IREPA-step 1) was established through the existing link to the NGO from previous research carried out by an author of this paper (S.L.). This allowed two authors of this paper (B.W., J.R.) to live in Mgwenyana for one month. Research was facilitated through the close relationship between the NGO and the local chief, who had approached the NGO to assist with finding sustainable solutions for the integrated use of energy that would also enhance food security.

The ThREP (IREPA-step 2), expressed as local power densities of the respective RR, indicates potential for solar, wind, hydropower and bioenergy at the study area (Table 5), while no geothermal energy potential exists (Banks and Schäffler, 2006).

Table 5
Power densities of locally available renewable resources in [W m^{-2}].

	Solar [W m^{-2}]	Wind [W m^{-2}]	Hydro [W]	Geothermal [W]	Biomass [W m^{-2}]
Average	186	14[a]	16721[c]	0	1.1
Seasonality	110–256	14–33[b]	2785–45972	0	1.06–1.17
Source	Helio-Clim 3	WASA	DWEA	Banks and Schäffler, 2006	NEO

[a] Roughness class 2; 10 m hub height (mainly found).
[b] Roughness class 2; 10 m hub height to r class 1; 25 m hub height.
[c] Mngazi River, 1.5 m head.

PLA methods (IREPA-step 3) revealed that the majority of households in Mgwenyana (86%) practice low-input, subsistence farming, while 94% rely on social grants for their income. It was therefore concluded that RE implementation should foster job and income creation.

All households visited experience a lack of food and dietary diversity, especially at the end of the month, and contaminated water supplies. Thus the authors suggest that RE production should support local food production, processing and storage e.g. by providing energy for pumping water for irrigation, running agricultural machinery, using a fridge or introducing the concept of nutrient recycling from organic residues and wastes along with the implementation of biodigesters.

While all households are connected to the grid (average household electricity demand: 0.96 kWh d^{-1}), firewood is the main energy source. Sufficient electricity is unaffordable for most households. Hence, RETs with low energy generation costs or with higher resource-use efficiency are favourable in this case.

Daily activities are strictly divided by gender: women do all household chores, including fetching wood and water, while men make decisions regarding household resources and generate income. However, 55% of households are de facto female-headed, with male partners having migrated for work, and with only 20% of them supporting the household financially. This results in women being responsible for the livelihoods of their family, often struggling in a male-dominated society. Women will be operators and maintainers of a RET. Thus it is beneficial if information dissemination, RE planning and technical training is addressed at women.

An important social aspect to consider in RET selection is *mona* (*Xhosa* - "jealousy"), imposing that every community member should have the same level of wealth, which is similar to the more popular *Xhosa* term *Ubuntu* ("I am because we are"). While this moral obligation supports social networks and caring for each other, on the other hand it poses barriers to pursue individual initiatives. *Mona* implies that a collective RE project, e.g. a mini hydropower station at the *Mngazi River* operated and maintained by a small group of engaged community members, is likely to be suppressed. The remaining community members may not buy the hydroelectricity in order to not enrich the members of the collective. Therefore, and due to the low power density of the river during dry season (Table 5), hydropower was excluded from further assessment. *Mona* further implies that all households should benefit equally, e.g. by RET implementation at each household or by receiving the same amount of funding for RET.

All households fall under the traditional leadership of the chief family. Individual or communal actions, entrepreneurial plans, land and resource use, relations to other communities and (personal) conflicts are discussed at regular community meetings and decisions, e.g. about RET implementation, are taken collectively. Subsequent RET implementation needs guidance by the chief family to avoid tensions within the community (*mona*).

Research further revealed that community members observe changes in weather and seasonal patterns. They are aware about environmental changes, manifested as direct impact on agricultural activities e.g. irrigation needs because of lower precipitation. This may serve as motivation for transforming towards environmentally sound energy sources.

The above community characteristics were analysed with regard to their social, institutional, economic, environmental and technical relevance for RET selection and were then transcribed into local RET sustainability criteria (Table 6).

The suitability of local RR was evaluated based on threshold values (IREPA-step 4a). The annual average solar irradiance (186 W m^{-2}; Helio-Clim-3, 2012) is very suitable for energy generation, with a local power density far above the threshold value of 120 W m^{-2} (Hoogwijk, 2004). The biomass inventory analysis identified grass from field clearance (currently burned before planting crops), organic kitchen waste as well as cow, goat, chicken and human excreta as suitable resources for biogas production. The aggregation of these resources results in an average biogas potential of 5.5 kW per household and day. Wind energy was excluded from the assessment. The annual average wind speed at Mgwenyana was found to be 1.19 m s^{-1} at 10 m height (WASA, 2012) (Table 5). This is far below the threshold value of 4 m s^{-1} at 10 m height, necessary for wind power generation (Kumar et al., 2010).

For the TREP the suitability and availability of areas in the community was explored (IREPA-step 4b). For solar panels, north-, east- and west-facing roof areas (63.6 m^2 per household) are considered suitable and are currently un-used. Installing PV-panels on the roofs requires no occupation of land areas potentially useable for food production. Combining the roof areas of all 736 households, the annual average of 2343 sunshine hours (Durban Climatetemps, 2012) and the conversion efficiency

Table 6
Ranked sustainability criteria based on the application of the Analytical Hierarchy Process (1st step) with local key-informants (n = 4; consistency ratio < 0.1) (Saaty, 1990).

	Ranked sustainability criteria	Averaged eigenvector
1.	Access to clean water	0.2234
2.	Protection of soil, water, air and biodiversity	0.1961
3.	Food and nutrition security	0.1782
4.	Gender aspects	0.0991
5.	Social cohesion and stability	0.0746
6.	Social benefits and increased well-being	0.0652
7.	Operation and maintenance (local resources)	0.0603
8.	Investment costs	0.0366
9.	Creation of "green jobs", new products/markets	0.0349
10.	Energy security/reliability	0.0315

Table 7
Renewable Energy Technologies considered appropriate for Mgwenyana based on the application of the Analytical Hierarchy Process (2nd step) with local key informants (n = 4, constistency ratio < 0.1) (Saaty, 1990).

Averaged Eigenvector	Ranked RE systems (according to eigenvector)	Normalized costs [ZAR per homestead]	Benefit: Cost ratio
0.2115	Integrated Terrace System	0.0341	6.1928
0.1167	Rocket stove	0.0100	11.6237
0.1154	Solar water heater coil	0.0075	15.3266
0.1098	Biodigester	0.3515	0.3123
0.0966	Solar geyser	0.5355	0.1805
0.0775	Photovoltaic light system	0.0613	1.2649

of locally available amorphous solar panels (10.1%; Green et al., 2010) indicates a technical solar electricity potential of 2805 kWh per household and year.

The GREP of biomass multiplied by the average efficiency of biogas stoves (63.5%; Rajendran et al., 2012) provides a technical biogas potential of 1279 kWh per household and year for cooking.

In IREPA-step 5 suitable RET options were pre-selected by the authors (B.W., J.R.) and the key-informants considering local RR, RET sustainability criteria and available construction materials and technical devices (Table 7). Small PV light systems (10W panel, 7.2 Ah battery, 4 LEDs) have low investment costs (610 ZAR), reduce the electricity expenses and are simple to install and use. Another solar option are water heaters. Solar geysers are implemented in social housing projects in South Africa. Because of the high investment costs (about 9600 ZAR), self-made water heaters from standard black pipe rolled to a coil and attached to a black wooden frame are a cheaper, yet effective option for heating water for cooking, washing and bathing.

Household-based plug-flow biodigesters with a fermenter volume of about $2m^3$ are deemed suitable to utilize currently unused organic household wastes, animal manures and grass. Up to $0{,}85m^3$ biogas per day can be produced, enough for cooking the staple meal *Umngqusho* (maize and beans). Field clearing with fire and, more important, firewood as main cooking fuel could be replaced, thereby reducing indoor-air pollution and deforestation. Additionally organic fertilizer is produced that can stimulate agricultural productivity and potentially increase food security. Another bioenergy option are *rocket stoves with sustainable forest management practices*. This implies a substitution of three-stone fires with a more efficient stove, while the biomass resource and collection is not changed. These stoves can be easily built from empty LPG cylinders. Sustainable management may aid conservation of natural forests and increase consciousness about the use of wood. Higher stove efficiency may decrease the time-consuming burden of firewood collection for women.

Additionally an Integrated Terrace System[2] suggested by the partner-NGO, complemented the list of proposed RET options.

The evaluation of these RETs with community members was not possible (IREPA-step 6 and consequently IREPA-step 7) due to their general lack of knowledge and understanding of RE. Hence, the AHP was performed by local key-informants (L. Boshier and D. Philips) and two authors of this paper (B.W., J.R.). Results of the AHP show that local social and environmental RET sustainability criteria such as access to clean water, soil, water and air protection, food security, gender-related aspects and social cohesion and stability were rated as more important than techno-economic criteria such as O&M and investment costs (Table 6).

The second AHP step revealed that an Integrated Terrace System, rocket stoves, solar water heaters or biodigesters, would be the most appropriate technologies for implementation (Table 7). All RET options are simple, cheap and made from locally available resources. All RETs are suitable for installation at household level and tensions within the community and especially *mona* can be avoided when everyone is generally able to use the same RET. The rocket stove and the simple solar water heater have the highest benefit:cost ratio (Table 7) and are therefore deemed to be most beneficial for the households by the local key-informants (L. Boshier and D. Philips) and two authors of this paper (B.W., J.R.). However, these are not only economic benefits. Although the substitution of often unaffordable grid electricity may saves financial resources, e.g. to be used to purchase food to enhance food and nutrition security, the benefits additionally imply social and environmental factors. Implementation of these RETs would enable:

i) to follow the intention of traditional leaders on showing innovative ways of using locally available materials and natural resources,
ii) to educate and develop skills among community members in manufacturing, operation and maintenance, because a general lack of knowledge of RE among the community members was found to be the largest barrier to RET implementation,
iii) to allow every community member to try and evaluate RET on an individual basis by keeping the risk associated with the introduction of new technologies low (Rogers, 1983).

[2] Aquaponic system for the organic production of tilapia (incl. feed), rice and vegetables with the aim of increasing food security and access to water for irrigation. Water is supplied by a ram-pump; fish faeces supplies plant nutrients.

4. Discussion

4.1. Centralized, top-down RE-policy in South Africa

To date RE policy instruments are the main driver of development in the RE sector (Negro et al., 2012; REN21, 2016; Resch et al., 2008). RE supporting policies frequently focus on and are often limited to the provision of fiscal incentives such as investment subsidies, provision of venture capital to support market introduction of RET, tax exemptions, emission regulations and feed-in tariffs (Gross et al., 2003; Negro et al., 2012). However, the lack of stable and properly aligned regional and local institutions is a key systemic problem in particular in countries of the South (Negro et al., 2012). Instability with regard to policy support, e.g. insecurity about energy tariffs, delayed issuing of power purchase agreements and conflicting messages from different government entities, is a major barrier for RE in South Africa (Pegels, 2011). Throughout Sub-Saharan Africa energy development projects show disillusioning success rates. Only 36% of the World Bank financed electric power projects were successful (Dunmade, 2002). In South Africa improvement of the coordination among policies and institutions is highlighted as prerequisite for effective RE implementation (Msimanga and Sebitosi, 2014).

Access to modern energy is perceived as important catalyst for economic growth and social equality (Pollet et al., 2015). Proposed bids for the REI4P are evaluated based on the requirements for ***local content*** (Msimanga and Sebitosi, 2014), the socio-economic development aims to be met (30%) and the energy generation price (70%) (Walwyn and Brent, 2015). So far South African companies have taken the lead in bidding consortiums, but considerable financial and technical back-up from international companies is involved (Msimanga and Sebitosi, 2014). ***Local content*** was claimed to be high in the bids, but actually technical equipment was not purchased from local manufacturers, although South African companies have implemented new construction facilities (Walwyn and Brent, 2015). Additionally, international energy experts and consultants are mostly not familiar with the historical context and show little interest in present-day challenges in South Africa (Msimanga and Sebitosi, 2014; Sihlongonyane, 2015). Consequently, the policy impacts of the REI4P on national economic growth and the inclusion of society are lagging behind expectations.

4.2. Transition towards participatory, bottom-up RE-technology selection

The limited focus of the REI4P on large-scale RE-supply at the lowest costs is a major barrier to national socio-economic development. Msimanga and Sebitosi (2014) call for a reform of the REI4P to include small and community-level projects (<1 MW), which are currently excluded due to high up-front planning costs. The reform requires the inclusion of socio-cultural factors in the REI4P (Amigun et al., 2011; this study). The planning of small and communal RE-project needs to be based on the exploration and acknowledgement of diverse local land and natural resource management schemes, traditional community hierarchies (Hamann and Tuinder, 2012; this study) and the role of energy in people's lives (Kaygusuz, 2011; this study).

Small and community level RE-projects may stimulate the energy-transition from bottom-up, in addition to the political commitment for the societal transformation towards a green economy in South Africa (DEA, 2011). RET-niches and a dedicated policy framework can reinforce each other to accelerate system innovation towards RE (Geels, 2005).

However, as revealed by this study and supported by Amigun et al. (2011), it is the lack of knowledge and understanding of RE that poses a major barrier to RET implementation in the rural Eastern Cape. This needs to be addressed by adequate communication strategies that disseminate information about climate change and the consequent energy-transition towards a low-carbon energy system (DEA, 2011; Pegels, 2011). Small and communal projects, initiated through a reformed REI4P and implemented at communal level, for example as public-private partnerships (Sovacool, 2013), provide suitable spaces for learning processes about RET characteristics, integrated food and RE agricultural systems, the role of energy in people's lives and household energy demand (quantity and quality) (Geels, 2005).

For project planning and implementation, it is suggested to include IREPA into the REI4P. IREPA provides a common methodology for RET assessment and appropriate technology selection at local level that aids comparability and systematic knowledge accumulation to accelerate decentralised RE production in South Africa (Smith et al., 2010).

4.3. Evaluation of IREPA based on case study research

The case-study research evaluated whether the IREPA methodology is suitable for the exploration of locally relevant factors for appropriate RET selection in rural smallholder farming systems. Access to and trust within the local community is regarded as a crucial prerequisite for a participatory bottom-up approach (IREPA step 1) (Wüstenhagen et al., 2007). This was ensured in our research through the existing relationship between the partner NGO and the local chief, who had approached the NGO to assist them in utilizing existing natural resources efficiently and sustainably. This provided a favourable setting for our research. PLA methods actively engaged the local population in the research process. Relevant factors characterising local livelihoods, in particular with respect to the role of energy in people's lives were identified (IREPA step 3). These factors, transcribed into local RET sustainability criteria, were used to assess the ThREP, the GREP and the TREP (IREPA step 2 and 4a/b). Data on RR, which were sufficiently available from statistical databases, were paired with household and community data, enabling the pre-selection and planning of RET options (IREPA step 5).

However, the community members were not able to participate in the AHP. The rating of criteria and RET options based on pair-wise comparisons was found to be too abstract, as this requires a sufficient knowledge level about RET (IREPA step 6 and 7). Consequently, key-informants took part in the ranking exercise. To account for such situations, Barry et al. (2011) suggest workshops with practical RET show cases for RE knowledge dissemination. Incorporating a practical workshop in IREPA after step 5 could provide community members with sufficient information on RET to participate in the decision-making process. Further, to enable participation of community members in decision-making, the AHP could be adapted by categorising the RET sustainability criteria into thematic clusters. This would reduce the number of pairwise comparisons, decrease complexity when participants only compare criteria of similar topics and thus increase accuracy of results (Brugha, 1998). Another option for enhanced participation is the straight-forward MCDA method Simple Multi-Attribute Rating Technique (SMART) (Chen et al., 2010). However, it has to be considered that not all community members might be able to participate, for example women, due to a male-dominated society; younger men and women due to social hierarchies and poorer community members due to lower social status (Lemke and Bellows, 2016).

For practical and sustainable RET implementation after IREPA, "early adopters" should be identified in the community. Due to their higher socio-economic status they are better able to take the risk associated with new technologies (Rogers, 1983). For the identification of early adopters, IREPA should include questions in the household survey to explore socio-demographic and economic characteristics, allowing for household stratification.

5. Conclusions

IREPA was developed as a participatory, bottom-up approach for appropriate RET selection and REIP assessment for RE project planning in smallholder farming systems to facilitate RE implementation in rural areas.

Current REPA methodologies lack a connection to the role of energy in people's lives. RE implementation is so far mainly driven by top-down policy instruments that are often limited to the provision of financial incentives (Negro et al., 2012). To encourage the implementation of RET a shift from top-down initiatives to bottom-up approaches is required. In case of South Africa the participatory, bottom-up perspective could enrich the REI4P to strengthen rural development. Prior to any rural RET implementation a participatory REPA, including educational aspects, such as IREPA should be performed. As the application of IREPA requires time and greatly benefits from transdisciplinary research, it is recommended that government institutions and development agencies collaborate with interdisciplinary research centres and dedicate sufficient financial resources to project planning.

IREPA ideally involves the local population in a mutual knowledge exchange and educational process for REIP assessment as part of RE project planning. In this way, IREPA explores locally relevant social, institutional, environmental and techno-economic factors which are subsequently employed in a participatory decision-making process for the selection of locally appropriate RET. The adaptions recommended by this research would render IREPA a suitable bottom-up approach for the assessment and effective implementation of RET, stimulating socio-economic development in rural areas.

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2.2 Transition towards renewable energy production? Potential in smallholder agricultural systems in West Bengal, India

This chapter is about the second IREPA application in two rural villages in India, evaluating the applicability of the IREPA approach in a different socio-cultural context. The RE potential for the two villages was assessed, selection factors were explored though participatory research and subsequently employed by the farmers to select locally appropriate renewable energy technologies.
Finally, the drivers and barriers for the smallholder farmers for leap frogging to RE production are discussed, revealing the perspectives of farmers and local officials.

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Article

Transition towards Renewable Energy Production? Potential in Smallholder Agricultural Systems in West Bengal, India

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Abstract: Renewable energy (RE) production promotes the efficient and sustainable utilization of natural resources at the local level. This study assessed smallholder farmers' perceptions of RE production in two villages in West Bengal, India. The availability and potential of renewable resources and livelihood characteristics of smallholders were explored. Relevant factors for the selection of appropriate RE technologies were identified, based on the participatory, bottom-up Integrated Renewable Energy Potential Assessment. The research area has abundant solar resources and substantial amounts of organic residues and waste suitable for biodigestion. Important factors for RE technology selection, as stated by farmers, are: ease of daily activities, government support, and limited land requirements. Solar-photovoltaic (PV) systems providing sufficient electricity for household use and irrigation are considered the most appropriate. Key informants focus on initial investment costs, government support, and reduced energy expenditure. They favor solar-PV systems for household electrification. Second choice was an integrated food and energy system that combines solar-PV for irrigation and vermicomposting of organic residues/wastes for fertilizer production. Smallholder famers' motivation to produce and use RE is high. Their perspective should be integrated in the design of RE-supporting policies and related programs to utilize local natural resources effectively and promote the transition towards renewable energy.

Keywords: sustainable livelihoods; renewable resources; energy transition; appropriate technology

1. Introduction

Affordable renewable energy (RE) and higher energy efficiency are the key drivers for a global transition towards sustainable, low-carbon energy systems, as postulated at the 21st Conference of the Parties of the United Nations Framework Convention on Climate Change (UNFCCC) [1].

The highest renewable energy potentials (REP) exist in rural areas of Latin America, Asia, and Africa [2]. In these areas, smallholder farmers typically manage 80% of the land area and natural resources [3], while access to modern and clean energy is often limited [4]. Smallholder farmers could produce sustainable energy that is economic efficient and environmentally sound by utilizing these REP.

India has been described as the "*home of small and marginal farms*" [5] (p. 1), with about half the population being directly engaged in agriculture [6]. Indian agriculture is currently facing multiple energy-related challenges in the areas of fertilizer production, mechanization, transport, and irrigation [6]. The energy demand in the world's third largest economy is increasing rapidly and, by 2032, will be four times higher than today [6,7].

The rural electrification program Rajiv Gandhi Grameen Vidyutikaran Yojana (RGGVY), launched in 2005, has significantly improved grid connection of rural villages [6], to electrification rates of 47% in Bihar, 61% in Jharkhand, and 92% in West Bengal. However, these figures do not reflect actual access to energy of rural households. According to [8], up to 50% of households in these states have either poor or no access to electricity, with voltage fluctuations, load shedding, and regular power cuts negatively affecting quality, reliability, and duration of electricity supply. To address these shortcomings, the RGGVY was modified in 2015 to form the Deen Dayal Upadhyaya Gram Jyoti Yojana (DDUGJY) program. This aims at strengthening rural supply through separation into an agricultural and non-agricultural distribution network and implementation of locally appropriate renewable energy technologies (RET) [6].

India has excellent solar, wind, small hydro, and biomass energy resources [7], which account for 5.5% of the global, realizable REP estimated for 2020 [9]. The Intended Nationally Determined Contribution (INDC) submitted to the UNFCCC in late 2015 set the goal of expanding RE production capacity from currently 36 GW to 175 GW by 2022 [10]. Furthermore, the Indian government highlights renewable energy as the key driver for the social inclusion of the poor [7], often small and marginal farmers [5].

Typically, RETs are selected and planned by external experts, based on techno-economic considerations, often failing to provide sustainable energy in the long term [11,12]. The reasons for this failure are manifold, but are associated with the adaptation of a RET to the local context: for example, specific weather conditions or RE system damage by animals; spare parts and technical service being unavailable or unaffordable; and RET-users being inadequately informed about energy production patterns, energy utilization, and system operation [13]. To encourage the use of RETs, multiple interrelated social, institutional, environmental, technical, and economic factors have to be considered [12,14–17]. This requires an exploration of local socio-cultural habits, attitudes, and relationships [18], as household energy consumption is not primarily based on rational decisions with regard to financial or other material interests [19].

This study explores locally relevant social, institutional, environmental, technical, and economic factors for the selection and design of appropriate RETs for smallholder farming households in two rural villages in West Bengal, applying the participatory, bottom-up Integrated Renewable Energy Potential Assessment (IREPA) [20]. Further, the prospect of smallholder RE production was assessed based on this in-depth analysis of the local context, considering renewable resource (RR) availability and perceptions of smallholder farmers and local key informants engaged in agricultural extension and rural development.

2. Materials and Methods

2.1. Case Study Area: Geographic, Agro-Ecological, and Socio-Demographic Characteristics

The state of West Bengal was selected as case study area because it is one of India's major food baskets, with 70% of the population directly engaged in agriculture [21]. Of these, 90% are smallholder farmers [22]. A quarter of the population has no access to electricity, while 40% partly has access, with supplies however being limited and unreliable [8]. Agro-ecological conditions are favorable: the area is endowed with strong irradiance, fertile alluvial soils, and plentiful water resources [23]. Average precipitation is 1435 mm a^{-1} [24]. In the dry season, channels from the Hooghly River and groundwater are used for irrigation. Abundant labor resources and access to agricultural inputs (fertilizers, pesticides, high-yielding varieties) result in high crop productivity. Land availability is the major constraint for agriculture [23]. Today, virtually all of the land is utilized and there are very few natural forests [25,26]. West Bengal is a traditional rice-growing area, but since 1997 there has been a shift towards the cultivation of fruit, vegetables, and flowers, as these provide higher revenues [23]. Based on these local characteristics, the area provides a suitable setting to assess the potential of smallholder RE production. Research was conducted from January to March 2015 in the two rural villages, Ghoragachha and Baikunthapur, in collaboration with the Department of Agricultural Extension of the State Agricultural University Bidhan Chandra Krishi Vishwavidyalaya (BCKV, Mohanpur, WB, India) under the Indian Council of Agricultural Research.

2.1.1. Ghoragachha

Location: Chakdaha Block of the Nadia District (88.31° E; 22.58° N).

Population: 1830 inhabitants in 134 households. The population (100% Muslim) is defined as "minority" in the official classification of the Indian population. The vast majority are smallholder farmers. Only 44 inhabitants are engaged in other jobs (e.g., embroidery, government sector). All households are connected to the grid [25].

Area size: 2825 acres (11.43 km^2), about 2000 acres agricultural land, 20 acres water bodies used for fish farming, the remaining area is residential [25].

Access to the village was facilitated through the Department of Agricultural Extension (BCKV, Mohanpur, WB, India), frequently organizing workshops about the introduction of new farming practices and technologies (fertilizers, pesticides, machinery). Thus, farmers were familiar with household interviews and technology evaluation. They willingly shared information about their livelihoods and perceptions regarding RET often engaging in open and critical discussions.

2.1.2. Baikunthapur

Location: Amdanga Block of the North Twenty Four Parganas District (88.32° E; 22.55° N), about 25 km south of Ghoragachha.

Population: 2940 inhabitants in 263 households, mainly belonging to the Hindu caste of Vaishyas. Most farmers have additional sources of income besides agriculture. Along the main road, there are 31 handicraft workshops, mainly carpentry and metal-work, and also a few agro-processing and Sheetal Pati (cool mat) weaving enterprises [26]. The village is connected to the grid [26], except for the poorest farming households on the outskirts of the village, where research was conducted.

Area size: approx. 700 acres (2.83 km^2), 550 acres farmland, 6 acres lakes, and residential area on the remaining land [26].

The additional interviews at Baikunthapur showed that the activities of the Department of Agricultural Extension from BCKV have not influenced the perceptions of the smallholders in Ghoragachha towards RE production. The Baikunthapur farmers willingly shared information about their livelihoods. The farmer livelihoods in both villages are very similar.

2.2. Integrated Renewable Energy Potential Assessment (IREPA)

IREPA is a participatory, bottom-up approach to REP assessment and appropriate RET selection in smallholder farming systems of developing and emerging economies. It integrates the biophysical perspective of natural science (RR assessment), the socio-cultural perspective of social science (smallholders' livelihoods), and the techno-economic perspective of energy engineering (RET planning) in an inter- and transdisciplinary approach. IREPA was previously tested in a rural area of South Africa [20] and adapted to this specific context, applying the following steps:

- Step 1: Contact with Research Area and Preliminary Data Assessment

Access to the two villages was facilitated by the Department of Agricultural Extension of the BCKV. Further, it was possible to draw on geographic, agro-ecological, and socio-demographic profiles and statistics from the Directorate of Micro, Small, and Medium Enterprises of the Government of West Bengal [25,26].

- Step 2: Theoretical Renewable Energy Potential (ThREP) Assessment

The bio-physical RR availability of solar, wind, hydro, geothermal, and bioenergy was assessed according to the REP categories defined by [9,27]. The RR data were obtained from international and national databases and scientific literature (Table 1).

Table 1. Data sources for renewable resource assessment at Ghoragachha and Baikunthapur.

Renewable Resource	Data Sources
Solar	[28]
Wind	[28,29]
Hydro	[30]
Biomass	[31], Own analysis, see Section 3.2.5
Geothermal	[32]

- Step 3: Household and Community Assessment

Multiple participatory research methods [33] were applied to explore the household characteristics and the structure of the two villages (Table 2). Details of local livelihoods were obtained from semi-structured, open-ended household interviews (n = 29) with the following question categories, drawing on the structure of the Sustainable Livelihoods Framework (SLF) [34]:

- Human Capital: education level, jobs and sources of income, other skills, work distribution, openness to innovation;
- Social Capital: household members, age, decision making, water/sanitation, health, food sources and preparation, gender roles;
- Institutional: social assistance, agriculture, and energy subsidies;
- Natural Capital: environmental concerns, access to natural resources, details of the agricultural system including crops, animals, and inputs;
- Physical Capital: land ownership, waste disposal, energy supply and use patterns, knowledge of RE.

Table 2. Overview of participatory research methods applied in Integrated Renewable Energy Potential Assessment (IREPA) step 3.

PLA Method	Number of Respondents	Description
Transect walk at Ghoragachha and Baikunthapur		Exploration of village structure; drawing of village map; informal interviews
Participant observation		Sowing, harvest, irrigation, fertilizer and pesticide application, rice processing, cooking (with traditional biofuels, LPG, biogas), dung-cake making
Open-ended, semi-structured household interviews	n = 29	Ghoragachha n = 21 (18 male, 3 female); Baikunthapur n = 8 (all male)
Visits of households using solar-PV and/or biodigesters	n = 10	Ghoragachha and Baikunthapur
Key-informant interviews	n = 8	Head of the Dept. Agricultural Extension, BCKV Professor at the Dept. Agricultural Extension, BCKV Director of Lake Hall Campus, BCKV Block Development Officer (BDO), Chakdaha Block Agricultural Development Officer (ADO), Chakadaha Block Two Ph.D. students, Dept. Agricultural Extension, BCKV M.Sc. Student, Dept. Agricultural Extension, BCKV
Participatory construction of an *Integrated Food and Energy System* for demonstration		At a smallholder farming household, Ghoragachha (See Section 3.3.3)
Focus-group	n = 8	Introduction of RET selection factors and pre-selected RETApplication of AHP and SMART with seven previously interviewed farmers from Ghoragachhafive key informants (BDO, ADO, two Ph.D. students, M.Sc. student)
Review of secondary sources		[8,17–22,32–34]

RET, Renewable Energy Technologies, AHP, Analytical Hierarchy Process; SMART, Simple Multi-Attribute Rating Technique.

Interviews, transect walks, and participant observations were always accompanied by one of the three students from BCKV, who translated from Bengali into English and vice versa. The information obtained was transcribed and coded to allow categorization, generalization, and interpretation [35] (p. 184ff). Subsequently, the information was cross-checked and triangulated with data from secondary sources listed in Table 2 and the key informants from BCKV. Quantitative data were processed using MSO Excel 2007, performing descriptive statistics to calculate percentages, averages, quantiles and ranges (min–max) [35].

The results were structured using the SLF, characterizing people's livelihoods based on five categories of Livelihood Assets (human, social, physical, natural, and financial). These are influenced by the external environment, which in turn affects the wider availability of assets, and circumstances people have to cope with, such as natural disasters, financial crises, seasonality, and others (Vulnerability Context); institutions, organizations, policies, and legislation (Transforming Structures and Processes); and the strategies adopted to achieve certain Livelihood Outcomes (Livelihood Strategies) [34].

These results were then categorized according to relevant social, institutional, environmental, technical, and economic factors, regarded as local RET sustainability criteria. Eight criteria were derived that determine the requirements for an RET to be appropriate in this specific local context. Not more than nine criteria should be employed in the Analytical Hierarchy Process (AHP) (Step 6) to keep execution manageable and increase consistency of results [32].

Biomass resources available for energy production (and cultivation areas) were explored at individual farm level. Local yield levels were obtained through household interviews supplemented by FAOSTAT data [36].

- Step 4a: Geographical Renewable Energy Potential (GREP)

The GREP determines the suitability of land areas for RE generation based on bio-physical RR data including temporal patterns [9,27]. Local RR power densities were evaluated based on threshold values for technical utilization. Average solar irradiance at ground level should be at least 120 W m^{-2} [27]. For wind energy, the average wind speed needs to exceed 4 m s^{-1} at 10 m hub height [7]. Power densities below these threshold values were excluded from the assessment. For hydro energy, the proximity of a river and its accessibility for smallholders was evaluated. For geothermal energy, the availability of easily accessible geothermal sources (e.g., hot springs) was assessed. The type, amount, and availability of the biomass resources obtained in IREPA Step 3 were analyzed. Only biomass residues or wastes without alternative uses, such as animal feed, were considered for energy production. The potential bioenergy output was estimated based on average values of residue-to-product ratios, energy content and biogas yields obtained from the literature (see Section 3.2.5).

- Step 4b: Technical Renewable Energy Potential (TREP)

The availability of suitable areas (and biomass residues and wastes) for RET installation was evaluated based on the local RET sustainability criteria (IREPA Step 3). Then, the conversion efficiencies of locally available RET were factored in [9,27].

- Step 5: RET Pre-selection and Energy System Design

Locally appropriate RET were pre-selected based on the TREP and the local RET sustainability criteria (IREPA Step 3), applying a cradle-to-grave value chain perspective for RE generation.

Four RETs were proposed and planned by the researcher, taking available materials and technology devices into account, including their costs and operation and maintenance (O&M) requirements.

- Step 6: Energy system impact assessment

Local appropriateness of the proposed RETs was assessed by applying two multi-criteria decision analysis (MCDA) methods with local participants: an adapted Analytical Hierarchy Process (aAHP) [37] and the Simple Multi-Attribute Rating Technique (SMART) [38]. The local RET sustainability criteria served as selection criteria in both MCDA methods.

The AHP is the most frequently used MCDA method in sustainable energy decision-making [12]. This descriptive method allows stakeholders (e.g., smallholder farmers) to compare and rank a set of selection criteria and RET options, arranged in pairs, to identify the most appropriate technology. However, the application of the AHP was found to be time-consuming and in some cases too abstract for the smallholders interviewed in the South African IREPA case study [20]. Therefore, the standard AHP [12] was adapted by clustering the RET sustainability criteria based on qualitative similarities [39] into: *(i) Overall benefits associated with RET implementation; (ii) Benefits associated with RET; (iii) Energy-use benefits;* and *(iv) Requirements for RET implementation.* Criteria clustering reduces the number of pairwise comparisons and helps participants clarify their thoughts, while increasing feasibility of application and accuracy of results [39]. Seven of the farmers previously interviewed participated in the aAHP questionnaire. First, the local RET sustainability criteria were arranged in pairs. The farmers rated the importance of the two criteria against each other on a scale of 1 to 9 (1 = equal importance; 9 = absolute importance over the other). Second, each participant compared the proposed RETs, arranged in pairs, with each other, and with respect to each sustainability criterion. The pairwise comparisons allow the computation of a decision matrix. Based on these ratings, the eigenvector of (i) each sustainability criterion and (ii) each RET are calculated using common matrix algebra. This expresses the priority of each participant [37]. However, the farmers found the abstract nature of pairwise comparisons difficult and complained about the time-consuming procedure.

For this reason, SMART was applied with five previously interviewed key informants instead of aAHP. SMART is based on a straightforward ranking of criteria and RET. First, the RET sustainability criteria were rated on a scale of 1–100, assigning the most important criterion the highest score, the second-most important criterion the second-highest score, and so on. Then, the four RETs were evaluated based on their performance/compliance with each RET sustainability criterion, assigning the highest score (1–100) to the best-performing/complying RET, the second highest score to the second best-performing/complying RET, and so on. Thus SMART is easier and less time-consuming to apply, as scores are directly assigned to each criterion and to each RET option [38]. Finally, the rankings obtained from aAHP and SMART revealed the most appropriate RET, at village level (taking the average results of all rankings) or at household level (taking the ranking of an individual farmer).

Differentiation between farmers' and key informants' rankings allowed a comparison of viewpoints based on personal situation between insiders (farmers) and outsiders (key informants).

- Step 7: Participatory decision-making process

Once IREPA has been applied, all stakeholders concerned (local smallholders, government bodies, companies and non-governmental organizations) should have comprehensive information at hand. If an RE project is to be realized, these stakeholders should be able to select locally appropriate RET with a high chance of successful implementation.

3. Results

3.1. Locally Relevant Factors for RET Selection

Interviews revealed that smallholder livelihood assets comprise: favorable agro-ecological conditions (natural capital); agricultural skills, knowledge, and openness to innovation (human capital); availability of agricultural extension services and governmental support through the block development offices (social capital); and access to productive resources and agricultural inputs (physical capital) (Figure 1). These assets result in high crop productivity (livelihood outcome). For example, the average paddy rice yield of 4.66 tons per hectare was found to be above the Indian average of 4.03 tons per hectare [36].

Farmers reported various unfavorable conditions (vulnerability context). Changes in weather patterns (temperature increase and rainfall decrease) experienced in recent years during the period January to April negatively affect winter crop (*Rabi*) productivity, increase irrigation demand (including energy expenditure) and cause temporal water insecurity. Older farmers reported declining soil fertility attributed to high cropping intensity (up to three crops annually). Use of fertilizers and pesticides has increased (and are necessary) to maintain crop yields, posing a major threat to farms' financial viability, exacerbated by rising prices for these inputs, and to the environment. Alternatives to synthetic fertilizers and pesticides are not offered by agricultural extension services, which are largely dependent and influenced by agrochemical companies. They advertise their products as part of agricultural trainings. The low social status of farmers in the caste system, high levels of corruption, and bureaucratic hurdles (e.g., time-consuming application for agricultural credits) hamper farm development, e.g., the shift from paddy rice towards less irrigation-intensive orchards. Market prices are dictated by middlemen (e.g., retailers), who also intervene in agricultural credit and subsidy applications.

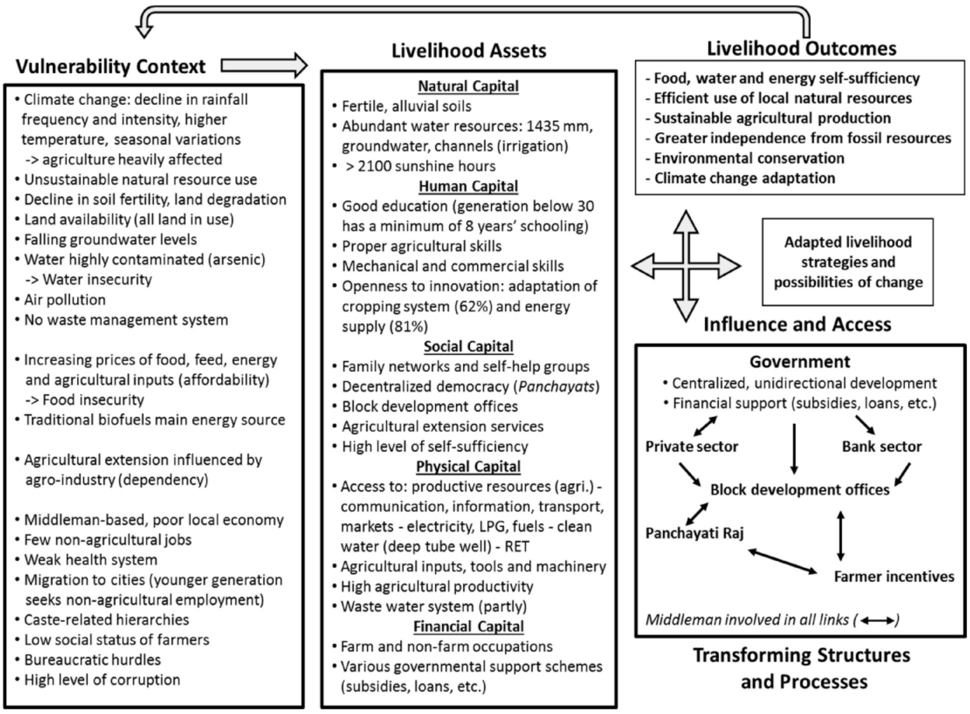

Figure 1. Results from the Household and Community Assessment structured according to the Sustainable Livelihoods Framework (adapted from [34]).

Smallholder farming is gridlocked in a situation of socio-economic dependence and negatively affected by agro-ecological and agro-economic circumstances. Two Baikunthapur farmers interviewed were considering quitting farming and migrating to Kolkata due to their inability to sustain their households from farming and the lack of alternative employment in the weak local economy.

Farm development and support is instigated by centralized government incentives and implemented by local Block Development Offices, private companies, and state banks. Individual incentives and bottom-up development are limited to the communication of suggestions for improvement to the Block Development Offices or the local government (Panchayati Ray).

Farmers' assets, their vulnerability conditions, and the transforming structures and processes determine the livelihood strategies they adopt. The implementation of RET can have beneficial livelihood outcomes for the concerned farmers.

Eight locally relevant factors for RET selection, derived from interviews, are summarized below.

3.1.1. Environmental Conservation

Concerns about the environment were expressed by about half the farmers interviewed. These include changes in local climate, declining soil fertility, waste disposal, and air pollution (Figure 2). *"When I was a child, nature was pollution free. Now it is polluted. Winter became less and lesser and has higher temperatures"* (male farmer, 38 years.). Ninety percent of the farmers expressed concerns about changes in local climate. A statistically significant increase in minimum and maximum temperatures has been reported throughout India, as well as a non-significant trend of decreasing precipitation in winter and the pre-monsoon season [40]. Decreasing water availability has been detrimental to smallholders' winter crop yield in recent years. Some farmers (28%) attribute negative impacts on the environment to the use of energy sources, for example soot and dust from firewood and CO_2 emissions from fossil fuels. These findings resulted in the local RET sustainability criterion: *Conservation of the natural environment (biodiversity), natural resources (soil, water, air), and ecosystem services.*

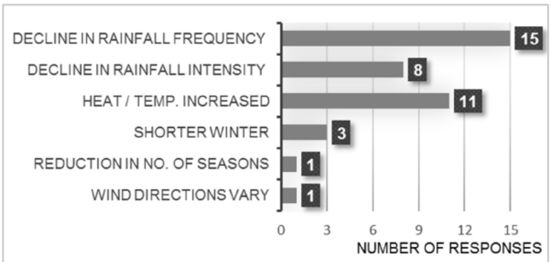

Figure 2. Farmers' observations about changes in weather and local climate by farmers ($n = 29$).

3.1.2. Land Requirement for RET Installation

Virtually all land in both villages is utilized. Land possession is not equally distributed among the farms. On average, a farmer in Ghoragachha owns 0.76 ha (range: 0.13 to 1.3 ha), in Baikunthapur 0.85 ha (range: 0.4 to 2.43 ha). Figure 3 classifies farms according to land size, willingness to use farmland for RET installation, and farms already using RET (solar-photovoltaic (PV), biodigester, or both). The installation of RET is more likely on larger farms—only a few already use RETs. Early adopters of new technologies typically have a higher socio-economic status and own more resources (land, financial capital), enabling them to take the risks associated with new technologies [41].

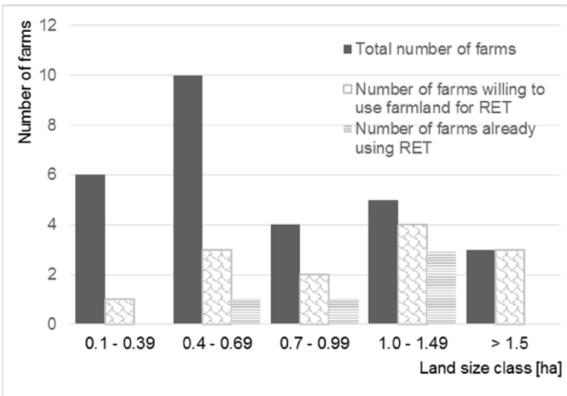

Figure 3. Classification of farms according to land size including number of farms willing to use farmland for RET and number of farms using RET already ($n = 28$).

The majority of farmers (82%) prefer growing food and feed crops on their land. The remaining farmers are only interested in combined food, feed, and fuel production if it increases revenues.

Most farmers (93%) are willing to use roof areas for solar-PV and yard areas for small biogas systems. The resulting sustainability criterion is: *Land requirements for RET installation including feedstock (production) for bioenergy.*

3.1.3. Energy Security and Reliability

All farming households in both villages are grid-connected, except for the poorest households on the outskirts of Baikunthapur. Frequent power cuts in the pre-monsoon and monsoon period lead to an insecure electricity supply. This had already motivated six farmers to install solar-PV systems. For cooking, however, the majority of households (89%) rely on traditional biofuels (agricultural residues, cattle manure) (Table 3), mainly because these are freely available on-farm. During the monsoon season, when biofuels become wet, LPG (and kerosene) is preferred for cooking. The households currently use diverse energy sources, adapted to seasonal availability, affordability, and reliability of supply. This resulted in the RET sustainability criterion: *Secure and reliable energy supply that matches energy demand at times when energy is needed.*

Table 3. Energy sources used for cooking in the farming households (n = 29).

Energy Source Used for Cooking	Percentrage of Farming Households
Traditional biomass and LPG	52
Traditional biomass and kerosene	10
Traditional biomass only	24
LPG only	3
Biogas and traditional biomass	3
Biogas and LPG	7

3.1.4. Reduced Expenditure on Energy Sources

All households in Ghoragachha consider themselves energy-secure. In Baikunthapur, 43% of households report an electricity deficiency, 29% lack energy for irrigation, transport, and processing. On average, a household consumes 101 kWh electricity, 10.6 kg LPG, and 366 kg traditional biofuels per month (Table 4), accounting for 22% of monthly household expenditure. The farmers adapt their electricity and LPG consumption to affordability. For example most households (62%) use LPG for preparation of small morning and evening meals, while preparing the main meal on cheap traditional biofuels. However, no relationship was found between household income level and energy sources used. This choice is largely influenced by non-financial factors: on-farm availability of agricultural residues/cattle manure, seasonality and reliability of electricity supply, taste of food, and cooking time requirements.

Table 4. Monthly household energy demand and expenditure for electricity, LPG, and traditional biofuels.

	Household Demand	Household Expenditures		
	Ø	**Ø**	***min***	***max***
Electricity	[kWh month^{-1}]	[INR month^{-1}]		
	101	495	83	2500
LPG	[kg month^{-1}]	[INR month^{-1}]		
	10.6	314 *	83 *	420 *
Traditional biofuels	366	1281 **	*140* **	*3202* **

Ø-household size: 5.0 members (both villages); Ø-household income: 9589 INR month^{-1} (min: 4000–max: 36,000);
* 1 LPG cylinder (14.2 kg): 420 INR incl. delivery; ** If purchased: 2–5 INR kg^{-1} (1 € = 70.66 INR; February 2015).

Most farmers associate the implementation of RETs with a reduction in energy expenditure (Figure 4). This can be attributed to price increases for electricity (+22.2%), diesel (+9.7%), and LPG (+6%) from 2012/13 to 2013/14 [42]. The resulting RET sustainability criterion is: *Reduction in energy expenditures considering the projected increase in fossil-resource prices.*

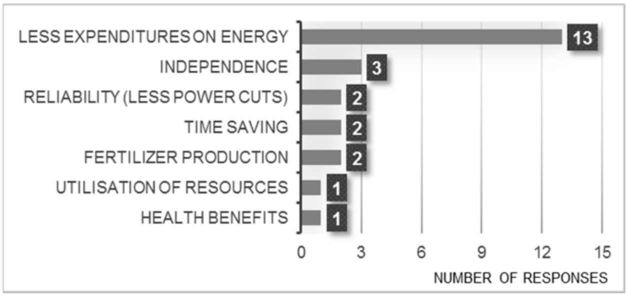

Figure 4. Farmers' responses on potential livelihood benefits from RET (n = 27).

3.1.5. Government Support of RET

Several RE support programmes exist in India, e.g., the *National Biogas and Manure Management Programme* (NBMMP; launched in 1981) [43] and the *Jawaharlal Nehru National Solar Mission Programme* (JNNSMP; launched in 2012) [44]. The *West Bengal Renewable Energy Development Agency* (WBREDA, Kolkata, WB, India) coordinates these programmes at state level, while local Block Development Offices are responsible for RE implementation. The government provides financial support for initial investment through credits from state banks. Contracted private RE companies provide technical support in construction and O&M of RETs. Only 36% of interviewed farmers are aware of these RE support programmes, although the farmers regard partnerships (PTP) between government bodies, the private sector, and farmers the most viable strategy for RE introduction (Figure 5). Several RETs have been installed through such programmes: in Baikunthapur, two biodigesters; in Ghoragachha, five biodigesters and six solar-PV systems. However, RE has since been withdrawn from the local development agenda. The Block Development Officer and the Agricultural Development Officer of Chakdaha stated: *"(Currently) Trainings for farmers don't have RE aspects"*, (we) *"now subsidize diesel for pumping* (water)*, LPG for cooking and access to grid electricity"* (personal communication, 27 February 2015). Hence, current RE implementation is self-driven, based on individual applications for RE support programmes. Nevertheless, five farmers are planning to install a biodigester or solar-PV system. These findings lead to the RET sustainability criterion: *Availability of and access to government support for installation as well as for operation and maintenance of RET*.

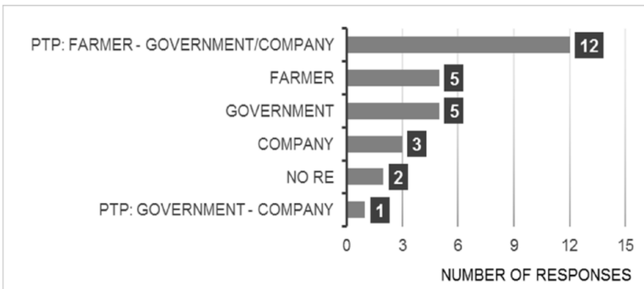

Figure 5. Farmers' opinion on how and by whom RE should be produced.

3.1.6. Investment Costs of RET

Six farmers have installed mini solar-PV systems consisting of one 75 Wp panel, an 80 Ah battery, a small table fan, and four compact fluorescent lamps (CFL), financed by a loan from JNNSMP, with a five-year pay-off period at an interest rate of about four percent. The partner company, KIRTI Solar, provides free maintenance support throughout the pay-off period. Farmers appreciate the reduction in energy expenses and the reliable light provision. *"Before solar, my electricity bill was 3000 INR (€ 42) for 3 months. Now it is 1800–2000 INR (€ 25–28) for 3 months. It makes life easier"* (male farmer, 33 years). However, the investment costs of 26,000 INR *(€ 370)* are considered too high for such a small solar system. Other disadvantages reported include: lights become dim after three days without sun; other electrical appliances such as TV or mobile phone charger cannot be connected; and minor benefits that materialize in the distant future.

In the two villages, seven fixed-dome biodigesters (*Deenabandhu-Type*, fermenter volume 3 m^3) have been installed since the year 2000. The NBMMP granted a subsidy of 5000 INR towards the total investment costs of about 9000 INR (€ 130) [45]. The biogas yield of about 400 to 700 litres per day [46] is sufficient for the preparation of one meal for up to five people [47].

The willingness to install RET is directly related to the initial investment and future (economic) benefits. These findings result in the RET sustainability criterion: *Initial investment costs (affordability) and willingness to make a long-term investment with benefits materializing in future years.*

3.1.7. Education and Development of New Skills

Technology-specific skills are required for O&M of RET. About half of the farmers are keen to learn new skills, agricultural and non-agricultural, in order to increase and diversify their income, while 41% are skilled in mechanics, carpentry, or construction. Extension services exist, in particular in Ghoragachha, providing information and training on new technologies and farming practices. The younger generation (<30 years) has a minimum of 8 years' schooling and increasing numbers of farmers' children attend university. The educational and skills background of the farmers is deemed suitable for RET O&M, while a technical-support infrastructure already exists for solar-PV and biodigesters. Further implementation of RETs will foster skills development among farmers and may in turn provide new employment and income opportunities in RET installation and O&M for those already skilled. This was taken up as an RET selection criterion: *Education on RET installation, operation and maintenance to create new job and income opportunities.*

3.1.8. Ease of Daily Activities

Currently, the farming households are striving after a modern lifestyle, altering energy use patterns. Televisions, smartphones, laptops, and internet access are part of daily life, requiring electricity. Thus, the majority of households (79%) are shifting towards electricity (including solar-PV) and LPG (including biogas) for cooking (Figure 6). The use of LPG is motivated by: negative health impacts of traditional biofuels induced by indoor air pollution; blackening of interior walls and furniture; high workload of biofuel collection and processing; and time-consuming cooking procedures. Typical statements recorded are: *"Women don't like using wood because of lifestyle"* (male farmer, 32 years); and *"I prefer LPG, it's quicker to cook"* (woman, 22 years).

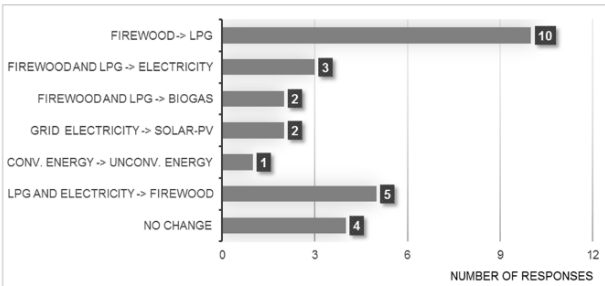

Figure 6. Ongoing substitution of energy sources in farming households (n = 27).

By contrast, five households are not satisfied with modern energy sources: LPG smells and causes irritation of the eyes; kerosene reduces the lifespan of machinery (e.g., irrigation pumps); and electricity has frequent power cuts. Instead, firewood is preferred because it is freely available on-farm and "*the taste of food cooked on chulhas is much better*" (male farmer, 36 years.).

Five households are considering switching to RE as a more reliable source of electricity (solar-PV), or as a cheaper energy source for cooking (biogas). The ongoing transition and the arguments brought up by the farmers are summarized in the RET selection criterion: *Ease of daily activities related to energy, in particular a reduction in time and labour burden for collection, processing, and utilization of traditional biomass sources, and reduction in adverse effects of energy carriers on user's health.*

3.2. Renewable Energy Potential: Solar, Wind, Hydro, Geothermal, Biomass

3.2.1. Solar Energy

The average annual irradiance of about 200 W m^{-2} [28] in the two villages is excellent for solar energy production. The total land area and 2108 annual sunshine hours [48] give a theoretical solar energy potential of 17.32 PJ a^{-1} and 4.29 PJ a^{-1} for Ghoragachha and Baikunthapur, respectively (Table 5).

Table 5. Renewable resource availability (as average power density) and theoretical (ThREP), geographical (GREP), and technical (TREP) renewable energy potential for Ghoragachha and Baikunthapur.

	Solar		**Wind**		**Hydro**		**Geothermal**		**Biomass**	
⌀ power density	(W m^{-2}) 199.70		(W m^{-2}) 4.98		(MW) 391.70		(W m^{-2}) 0.20		(W m^{-2} a^{-1}) 0.43	
Min/Max	170–257		1.3–11.7		n.a.		n.a.		0.41–0.45	
	(PJ a^{-1})		(PJ a^{-1})		(PJ a^{-1})		(PJ a^{-1})		(PJ a^{-1})	
	Gh.	Ba.	Gh.	Ba.	Gh.	Ba.	Gh.	Ba.	Gh.	Ba.
ThREP	17.315	4.299	0.011 *		12.353		0.778 **		0.156 #	0.039 #
GREP	17.162	4.280	<threshold		not accessible		not accessible		0.004 ##	0.008 ##
TREP	0.015	0.003	<threshold		not accessible		not accessible		0.003 ##	0.005 ##
Source	[28]		[28,29]		[30]		[32]		# [31]; ## This study	

Total village area: Ghoragachha: 11.42 km^2/Baikunthapur: 2.83 km^2; * Swept area = 1 m^2; ** Hot springs at Bakreshwar (about 200 km north-west of research area). # data based on [31]; ## data based on this study (see Table 6).

Excluding areas unsuitable for solar energy (lakes, forest-covered land, roads, and pathways) reduces the geographical solar potential slightly to 17.16 PJ a^{-1} and 4.28 PJ a^{-1}, respectively (Table 5). The selection of areas available for TREP assessment was based on farmers' opinions: 45% of farmers in Ghoragachha and 43% in Baikunthapur would be willing to use agricultural land for solar energy production. The majority of farmers would be willing to use the land area around their houses and the roof (Ghoragachha: 93%; Baikunthapur 83%). Taking an average efficiency of 12.2% for locally available polycrystalline solar panels [49], the technically useable solar potential in Ghoragachha is 0.015 PJ a^{-1} and 0.003 PJ a^{-1} in Baikunthapur.

3.2.2. Wind Energy

Mean annual wind speed in the research area (1.93 m s^{-1}) is below the threshold value of 4 m s^{-1} at 10m hub height and thus not technically useable for energy production [7].

3.2.3. Hydroenergy

The research area is in close proximity to Hooghly River, a tributary of the Ganga. The Hooghly has an average discharge of about 40,000 m^3 s^{-1} [30] and embodies a theoretical hydroenergy potential of 12.3 PJ a^{-1}, but is inaccessible for smallholder farmers.

3.2.4. Geothermal Energy

West Bengal has considerable potential for geothermal energy with thermal springs at Bakreswar, located over the Sonata lineament. However, there are no thermal springs within the research area, situated about 200 km southeast of Bakreswar [32].

3.2.5. Energy from Biomass

The net primary productivity (NPP) in the research area serves as an initial indicator of natural biomass growth and seasonal patterns. The NPP is highest (average 1.5 g C m^{-2} day^{-1}) from September to February, after the monsoon. From March to August the average NPP is considerably lower (0.6 g C m^{-2} day^{-1}), revealing a distinct seasonality in biomass growth [31]. The annual NPP results in a theoretical bioenergy potential at Ghoragachha of 0.16 PJ a^{-1} and at Baikunthapur of 0.04 PJ a^{-1} (Table 5).

The majority of farmers (86% in both villages) prefer food crop production for subsistence and marketing. Dedicated energy crops, and therefore biofuels, are not considered a viable option. The local cropping system has three seasons: *Kharif* is the paddy rice season (monsoon crop); *Rabi* is the winter crop season for brinjal, chili, potato, onion, and cauliflower; and *Zaid* is the season for cucumber, bottle gourd, and ridge gourd. The majority of farms also have orchards with a variety of fruit trees such as *ber* (local apple), orange, and mango. The residues of these crops, as well as organic wastes and animal manure are suitable resources for biogas production. The amounts available were recorded in household interviews and used for assessing the geographical and technical bioenergy potential (Table 6).

Table 6. Overview of suitable biomass resources available for biogas production, total biogas volume, and corresponding geographical and technical bioenergy potential at Ghoragachha and Baikunthapur.

Feedstock	Average Crop Yield	RPR *	Biogas Yield **	
			Ghoragachha	**Baikunthapur**
	(t ha^{-1})	**(x: 1)**	**(m^3 $farm^{-1}$ a^{-1})**	**(m^3 $farm^{-1}$ a^{-1})**
Rice straw *(Kharif)*	4.7	1.5	595	428
Vegetable residues *(Rabi)*	26.5	0.5	591	662
Vegetable residues *(Zaid)*	7.2	0.5	138	154
	Amount available			
	Ghoragachha	*Baikunthapur*		
	kg $farm^{-1}$ a^{-1}	kg $farm^{-1}$ a^{-1}	(m^3 $farm^{-1}$ a^{-1})	(m^3 $farm^{-1}$ a^{-1})
Organic waste ^	449	70	29	5
Human excreta #	456	531	30	35
Animal manure ##	2034	9636	48	226
Total biogas volume (m^3 $farm^{-1}$ a^{-1})			1431	1510
Geographic bioenergy potential$_{LHV}$ (PJ $village^{-1}$ a^{-1})			0.004	0.008
Technical bioenergy potential$_{Th.\ Eff.}$ (PJ $village^{-1}$ a^{-1})			0.003	0.005

* RPR = Residue–Product Ratio (x: 1) based on [50] (for vegetables) and [51] (for rice); ** based on averaged biogas yields for vegetable mixtures from [52–55]; ^ Excluding organic wastes used as animal feed; # Amount of human excreta and biogas yield estimated based on [56]; ## Refers to farms with animals (Ghoragachha: 71%; Baikunthapur 88%), biogas yield based on [56]; LHV = Lower heating value of biogas: 21 MJ m^{-3} [57]; Th. Eff. = Thermal efficiency of biogas stoves 63.5% [47].

Availability of these biomass resources depends on their current utilisation (Figure 7). The majority of households (89%) use dried crop residues, in particular fruit tree branches and lignified stems of brinjal, pepper, and chili plants, for cooking. Residues with lower lignin content are composted or fed to animals, for example rice husks (mixed with water) and rice straw.

As 71% of farms in Ghoragachha and 12% of farms in Baikunthapur do not keep cattle, the rice straw from these farms would be available for biogas production. Cattle manure is collected, one part is dried and burnt for cooking, and the rest is composted and used as organic fertilizer.

Organic household wastes are fed to goats and chicken, however, in Ghoragachha 62% and in Baikunthapur 25% of farmers do not use organic waste as feed, making the remaining potentially available for biodigestion. As goats and chicken roam around the houses freely, manure collection would be too time-consuming. Therefore, only cattle manure is considered in the estimation of potential biogas yield (Table 6).

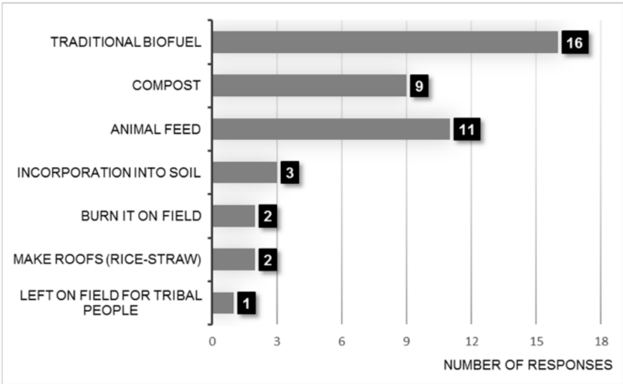

Figure 7. Current utilization of agricultural residues and wastes (*n* = 29).

Farmers with a biodigester were advised to use cattle manure only as feedstock. However, in the past decade the number of cattle in the villages has decreased considerably because: (i) agriculture is being increasing mechanised; (ii) grazing patches have been converted to crops; (iii) the price of cattle feed has increased; and (iv) cattle smuggling to Bangladesh has increased domestic cattle prices [58]. As a result, three out of six biodigesters have been abandoned due to the lack of feedstock. Agricultural residues and organic wastes are suitable for biogas production and all farmers would be willing to use them as additional feedstock. For example, after our interview, one farmer re-started his recently abandoned biodigester with vegetable residues.

Biogas can replace traditional biofuels for cooking, and the digestate can substitute compost as organic fertilizer. Thus, organic residues and wastes used for cooking and composting are potentially available for biodigestion. In addition, the farmers signalled their willingness to use human excreta as biogas feedstock. One toilet-connected biodigester was already under construction.

This results in a potential biogas yield of 1431 m^3 per farm and year at Ghoragachha and 1510 m^3 at Baikunthapur, and an annual geographical biogas potential of 0.004 PJ for Ghoragachha (134 households) and 0.008 PJ (263 households) at Baikunthapur. Considering the average thermal efficiency of biogas stoves (63.5%; [47]), the annual technical potentials are 0.003 PJ (1118 MWh) at Ghoragachha and 0.005 PJ (2316 MWh) at Baikunthapur.

3.3. Renewable Energy Technology Pre-Selection and Planning

Considerable solar and biomass resources were identified in both villages. The technical solar potential (Ghoragachha: 4150 MWh a^{-1}; Baikunthapur: 880 MWh a^{-1}) and bioenergy potential (Ghoragachha: 1118 MWh per year; Baikunthapur: 2316 MWh per year) could cover the total energy demand to 215% at Ghoragachha (2454 MWh a^{-1}) and to 66% at Baikunthapur (4817 MWh per year).

For this reason, solar and bioenergy technologies were planned in accordance with the eight *local RET sustainability criteria*, the households' energy demand and locally available technology parts.

3.3.1. Solar-PV Systems

Three solar-PV systems were planned (Table 7): one 500 Wp system sufficient for low household electricity demand; one 1000 Wp system covering average household demand; and one 1500 Wp system additionally enabling solar irrigation. The households remain grid-connected, but the PV systems provide a battery back-up of about 3 h per 500 Wp, increasing the reliability of electricity supply, e.g., during the monsoon period when power cuts are frequent, at reasonable costs. The farmers can transport the batteries in addition to the pump-set (at Baikunthapur already electric) to their field by freight bike. The PV panels cover a maximum roof area of 12 m^2, available at all households visited.

Table 7. Proposed solar-PV systems with technology parts and investment costs adapted to household and agricultural electricity demand: low: 1.8 kWh day^{-1}; average: 3.5 kWh day^{-1}; high: 5.1 kWh day^{-1}.

Electricity Demand	low	Ø	high
PV system capacity	500 Wp	1000 Wp	1500 Wp
Panel area [m^2]	4	8	12
Solar PV system parts	Costs [INR]	Costs [INR]	Costs [INR]
Panels	28,494	57,000	85,500
Battery	20,700	37,862	52,818
Inverter	4395	5637	6667
Charge Controller	2500	2500	2500
Roof installation structure, cables, etc.	7000	9000	10,000
Installation	8000	8000	8000
Total investment costs [INR]	71,089	119,999	165,485
JNNSMP subsidy: 30% of total costs [INR]	21,327	36,000	49,646
Tax savings—accelerated depreciation [INR]	13,933	23,520	32,435
Net investment costs [INR]	35,829 *507 €*	60,479 *856 €*	83,404 *1180 €*
Monthly savings [INR]	250	500	750
Financial amortisation [years]	11.9	10.1	9.3

Sources of technology parts and costs: Solar panels: https://www.bijlibachao.com/solar/solar-panel-cell-cost-price-list-in-india.html; Battery: http://www.snapdeal.com/product/exide-inverter-plus-100ah-battery/954943293; Inverter: http://www.snapdeal.com/product/microtek-upseb-1500-va-inverter/669312; Charge controller: http://www.snapdeal.com/product/inductionpowers-ipscc12v40a-solar;panels/799104181; Roof installation structure: http://www.solarmango.com/in/faq/2; Cables: Electronic shop at Kalyani (nearest bigger city); (Exchange rate €—INR, February 2015: 1 € = 70.66 INR).

Total investment costs of the 1000 Wp system are as high as an average annual household income (INR 115,071 = € 1630). A substantial reduction is achievable through the JNNSMP. This subsidy covers 30% of total investment costs and allows accelerated tax depreciation [44].

Compared to the investment costs (INR 26,000) of the 75 Wp solar systems already installed in a few households, the proposed systems would cover the entire household electricity demand, considerably reducing electricity expenditure and allowing amortisation within 9 to 12 years.

3.3.2. Household Biodigesters

"Deenabandhu" biodigesters, developed in India [59], were suggested here as the most appropriate bioenergy technology. Construction materials and technology parts, as well as O&M skills, are locally available. Biodigester costs (about 9000 INR for 3 m^3 fermenter volume [45]) can be substantially reduced to about 4000 INR through the NBMMP subsidy [43].

Considerable amounts of agricultural residues, organic wastes, cattle manure, and human excreta are available, resulting in a potential biogas yield of 4 m^3 per day and household. This volume could replace LPG and firewood for cooking up to four times [47]. Replacing LPG would save on average 314 INR per month, eliminate the burden of traditional biofuel collection and processing, and substantially reduce indoor air pollution. The digestate could provide valuable organic fertilizer, reducing requirements and expenditure for synthetic fertilizers by up to 30% [59]. As farmers currently transport compost from their households to the fields, using digestate instead would not require any change in application.

3.3.3. Integrated Food and Energy Systems

The innovative *terrabioponic* system was constructed in collaboration with two farmers as a showcase for the focus group (see Section 3.4) to demonstrate water-efficient solar irrigation, direct nutrient recovery, and space-efficient organic crop production (Figure 8). In this system, plant nutrients are recovered from organic wastes in a vermicompost (*bio*). Leachate from the vermicompost is collected and mixed with irrigation water. Planting pods made of bamboo, sealed with plastic foil and filled with soil (*terra*), are connected in series with hosepipes and arranged in descending order on a staircase-like structure made of re-used wood. The organic nutrient solution is pumped to the highest point from where it flows under gravity through all planting pods (*ponic*), the vermicompost, and back into the water tank. Additionally, solid vermicompost is regularly applied to the pods.

(**a**) (**b**)

Figure 8. (**a**) Terrabioponic food and solar-energy demonstration system at a farmer's household in Ghoragachha immediately after construction and (**b**) seven weeks after planting cucumber, tomato, brinjal, and beetlewine (right) (further information www.geco-gardens.de).

Investment costs for the solar parts, piping, and plastic foil were about 11,000 INR (€ 160). Other construction materials were sourced in the village free of charge. The *terrabioponic* food and energy system is scalable in size, independent of agricultural land and can be installed on flat roofs.

3.4. Impact Assessment and Technology Selection

The proposed RETs and the *RET sustainability criteria* were presented to eight farmers in a focus group at Ghoragachha and subsequently ranked by the farmers, employing the aAHP. The aAHP questionnaire was perceived as too abstract and time-consuming, despite clustered criteria. Only seven farmers completed the criteria rating, and six completed the RET ranking.

Subsequently, the aAHP questionnaire was replaced with the SMART method to increase response rate. Three (out of six) key informants from BCKV, the Block Development Officer (BDO) and the Agricultural Development Officer (ADO) of the Chakdaha Block participated in appropriate RET selection.

The farmers ranked the social RET sustainability criterion *Ease of daily activities* highest, followed by *Governmental support* and *Land requirements* (Table 8). The impact of RET on *Environmental conservation* was more important to the farmers than the techno-economic factors such as *Investment costs*. Solar-PV for household electrification and irrigation was considered the most appropriate RET (Table 9). However, the standard deviation is very high in both the criteria and RET ranking, revealing a strong heterogeneity with different criteria and impacts important for individual farmers. There is no single

RET option that fits each farming livelihood. Thus, the aAHP ranking of each farmer should be considered on an individual basis to determine the most appropriate RET at household level.

Table 8. RET selection criteria ranked by farmers (n = 7) based on the Analytical Hierarchy Process with criteria clusters (adapted from [37]) (STD = standard deviation).

Rank	Selection Criteria	Averaged Rating	STD
1	Ease of daily activities	0.1669	0.1817
2	Government support	0.1531	0.0944
3	Land/area requirements	0.1504	0.1282
4	Environmental conservation	0.1358	0.1052
5	Investment costs	0.1250	0.2217
6	Reduced expenditures on energy	0.1107	0.0856
7	Energy security and realibility	0.0959	0.1200
8	Education and development of new skills	0.0563	0.0532

Table 9. RE systems ranked by farmers (n = 6) based on the Analytical Hierarchy Process with criteria clusters (adapted from [37]) (STD = standard deviation).

Rank	RE Systems	Averaged Rating	STD
1	Solar-PV home system	0.2934	0.0726
2	Solar-PV irrigation system	0.2926	0.1266
3	Integrated food and energy system	0.2404	0.0887
4	Biodigester	0.1953	0.1422

By contrast, key informants rated techno-economic and institutional selection criteria as more important than social and environmental criteria (Table 10). Their criteria ranking is more homogenous than the farmers' ranking. The solar-PV system and the integrated food and energy system were ranked highest (Table 11). However, the high standard deviation of the RE systems ranking again reveals individual preferences of the key informants for a particular RE.

Table 10. RET selection criteria ranked by key informants (n = 5) based on the Simple Multi-Attribute Rating Technique (adapted from [38]) (STD = standard deviation).

Rank	Selection Criteria	Averaged Rating	STD
1	Investment costs	0.1649	0.0343
2	Government support	0.1586	0.0262
3	Reduced expenditures on energy	0.1242	0.0234
4	Land/area requirements	0.1225	0.0343
5	Energy security and realibility	0.1132	0.0186
6	Ease of daily activities	0.1124	0.0130
7	Education and development of new skills	0.1048	0.0207
8	Environmental conservation	0.0994	0.0156

Table 11. RE systems ranked by key informants (n = 5) based on the Simple Multi-Attribute Rating Technique (adapted from [38]) (STD = standard deviation).

Rank	RE Systems	Averaged Rating	STD
1	Solar-PV home system	0.7890	0.1014
2	Integrated food and energy system	0.7807	0.0611
3	Biodigester	0.7712	0.0780
4	Solar-PV irrigation system	0.7133	0.1518

4. Discussion

4.1. Selection Factors—Whose Perspective Counts

There were distinct differences between smallholder farmers and key informants in the factors considered important for locally appropriate RET. Farmers evaluated new technologies and practices based on (holistic) daily-life experience, and beneficial impacts on local climatic conditions, soil fertility, fluctuations in market prices for agricultural in- and outputs, and fossil fuel prices. Their interest in RET was aroused when strategies on 'how to best cope with current agricultural issues' became apparent. For example, once they became aware of the benefits associated with a biodigester (replacement of LPG and traditional biofuels, use of organic fertilizer to increase soil fertility) and the possibility of using agricultural residues and organic waste as feedstock in addition to manure, farmers asked for technical details and related costs.

In contrast, key informants primarily emphasised technical, financial, and institutional factors for RET selection. Similar results were recently published by [60], who evaluated 28 barriers to RET adoption in India. Eight experts from academia and industry ranked institutional support and local resource availability highest, followed by technical complexity and financial factors. Socio-cultural and personal behavioural factors were found in the lower half of the ranking.

With decentralized RE in particular, where energy consumers become energy producers, the social and behavioural dimension is crucial for energy choices. As [19] (p. 1391) points out, "*Consumers are far from the purely rational decision-makers assumed by traditional economic models, and there is often a wide gap between peoples' values and material interests, and their actual behaviour*". This study provides in depth insights into the livelihoods of smallholders in two rural villages. The selected RET are appropriate in this socio-cultural and institutional context as well as considering locally available natural resources. Although the two rural villages investigated here may not be representative, and implementation and operation of the RET in the long term was beyond the scope of this study, the results presented here emphasise the importance of a participatory, bottom-up approach in RET selection and planning that involves intended users from the beginning. Broadening the perspective of rural development experts, politicians, and private-sector partners is deemed essential. This enables them to understand the daily challenges of intended RE producers and users, evaluate the impacts of RETs and thus ensure local appropriateness. The example of the biodigesters abandoned due to the lack of cattle manure illustrates the importance of a participatory bottom-up assessment of the local context. This should be based on mutual learning between intended users and experts, prior to the implementation of RETs.

4.2. How can the Transition towards Modern and Clean Energy in Smallholder Farming Systems in West Bengal be Promoted?

To date, about 90% of households in West Bengal use traditional biofuels for cooking ([8], this study). Biofuel consumption of households researched in this study (366 kg per month) is 36% higher than the Indian average (234 kg per month) [61]. About one-third of the households interviewed refuse to change current energy sources, with some even shifting back from LPG and electricity to traditional biofuels. Reasons stated include: unreliability of electricity supply; better taste of food cooked on *chulhas*; and the expense of electricity and LPG compared to traditional biofuels freely available on-farm. Throughout India, availability, affordability, and reliability of modern energy sources determine the substitution of traditional biofuels [8].

The majority of households in the researched villages however are gradually shifting towards LPG and electricity, few are leapfrogging to solar-PV and biogas. The major driver for this energy transition is the pursuit of a modern lifestyle associated with ease of daily-life activities. Modern electronic devices have found their way into rural households. Smartphones and laptops have become crucial for higher education—more and more farmers' children attend universities—and predominate leisure activities of the younger generation. This highlights the importance of access to electricity in rural areas.

Traditional gender roles in the Muslim (Ghoragachha) and the Hindu (Baikunthapur) culture affect the shift in cooking energy. The oldest male household member is typically responsible for decision making. Cooking is the obligation of women. Those women interviewed (would) appreciate LPG, because it means no biofuel collection, processing, and storage, shorter cooking time, no indoor-air pollution, and no blackening of the household interior. However, it was not possible to obtain reliable information, as only three women were allowed by their husbands to participate in the interviews with the male researcher (although assisted by a female research assistant)—and only in presence of their husbands.

Rising fossil fuel prices [42] and increasing awareness of the need for environmental conservation are initiating the transition towards RE in the researched villages.

Of the RET proposed, farmers and key informants rated solar-PV systems as most appropriate. According to [62], solar-PV is regarded the most promising RET in India, as grid electrification of rural villages is often not techno-economically viable. It is predicted that the gap between electricity supply and demand will increase in the near future, accelerating the implementation of decentralized PV systems. Land scarcity restricts solar-PV to small units [62], thus favouring smallholder farming households. The authors of [8] reported considerably high acceptance rates for decentralized solar-PV in their representative study: 34% of the 8566 rural households surveyed prefer micro-grids to grid electricity, and 79% expressed great interest in solar lanterns for lighting. In our study, reliability and sufficiency of electricity supply were also found to be crucial drivers for solar-PV. Sufficient electricity supply requires larger systems than the 75 Wp systems already implemented in the researched villages. In this case, a grid-connected 1 kWp solar-PV system with a battery back-up is recommended for an average smallholder farmer to provide sufficient and reliable electricity. Larger PV systems, like the proposed 1.5 kWp, can provide additional power for irrigation pumps, enabling farmers to cope with changing climatic conditions.

Farmers using biodigesters considered the production of organic fertilizer an immense benefit. More efficient utilisation of organic residues and waste would provide a solution to the constraint of insufficient cattle manure for an adequate biogas supply, thereby increasing overall farm efficiency. Biodigestion is vital for biomass recycling (water, carbon, and nutrients) within an agricultural system and a crucial element in the integrated livestock–biogas–vegetable/fruit systems in neighbouring China [63].

This study introduced an innovative integrated food and energy system, in addition to "conventional" RET, combining solar energy with efficient, sub-surface irrigation and effective utilisation of organic residues and waste, in line with the current shift towards organic farming. Almost all farms in the researched villages have home gardens with organic vegetables and fruit for self-consumption. The BDO of Chakdaha, who has an organic garden himself, reported that farmers are aware of the negative effects of pesticides and chemical fertilizers on product quality and soil fertility (personal communication, 27 February 2015). Three farmers interviewed are planning to shift to organic farming with the aim of improving soil fertility, reducing chemical fertilizer and pesticide application (and associated expenditure), achieving higher market prices, and conserving agro-biodiversity. Given the growing demand for organic produce in India and internationally, organic farming provides a lucrative option for smallholder farmers [64]. Recent infrastructure development has increased the marketing radius of agricultural products for the farmers of the two villages. In addition to rural markets, paved roads now enable these farmers to sell their produce on the peri-urban and urban market of Kolkata [23]. The combination of solar-electricity generation and cultivation of organic produce based on local renewable resources represents a promising step towards environmentally sound smallholder food and RE production, independent of fossil fuels.

On the one hand, the Indian government encourages the transition towards sustainable and clean energy through various RE support schemes. On the other hand, it subsidises LPG and diesel and promotes investments in rural grid expansion [6]. Government support is available for RE implementation and financing. The JNNSMP covers about half the investment costs for solar-PV systems, and the NBMMP funds specific materials (pipes, valves, and biogas stoves) and the construction of biodigesters [43,44]. Both programmes are public–private partnerships. Installation is carried out by private, government-accredited RE companies. However, substantial investment from smallholders is still required, often restricting access to these programmes to financially better-off farmers [65]. The solar-PV systems (farmers' first choice) are much more expensive (€ 507–1180) than a biodigester (€ 127). Solar systems can reduce annual energy expenditure by 84 € (compared to grid electricity), and biodigesters reduce annual expenditure by 53 € (compared to LPG). This results in rapid amortisation of a biodigester (about 2.4 years), but a considerably longer pay-off period for solar-PV systems (9.3 to 11.9 years). Hence, biodigesters would be affordable for a larger numbers of farmers in the short term and could accelerate the transition from LPG to biogas. Those smallholders considering abolishing traditional biofuels may leapfrog directly to biogas. The transition from grid electricity to solar PV is likely to take time, despite the majority of farmers' interest in this RET and their eagerness to implement solar panels to increase household electricity reliability. The reduction in cost of solar panels predicted by [66] of up to 59% by 2025 would considerably increase their affordability for smallholder farming households and may greatly stimulate solar-PV implementation in the near future.

5. Conclusions

Villages in the research area are experiencing considerable changes with regard to weather conditions, declining soil fertility, and price increases for agricultural inputs and energy, forcing farmers to adapt their agricultural production systems. Additionally, farming households seek a modern lifestyle. The younger generation has access to higher education and utilises modern communication and information tools, while women long for clean cooking fuels. These trends have direct implications for RE, including climate change mitigation, digestate as organic fertilizer, adaptation of organic farming, reduced energy expenditure, and access to modern and clean energy, and thus motivate the farming households in a variety of ways to use and produce RE. Few interviewed farmers already implemented mini solar-PV systems, biodigesters, or both, supported by government initiatives. However, the technologies advocated are not satisfying the farmers' energy demand: 75 Wp solar-PV systems are small and comparably expensive and the biodigesters do not utilize their full potential, as the farmers were advised by the implementing agency to use cattle manure only.

Notwithstanding, government support is crucial for the implementation of RET in India, as highlighted by the interviewed smallholders and the key-informants in the ranking of RET selection factors. However, development initiatives and policies are centrally planned and trickle through from country to state to district to block level in top-down manner while not sufficiently taking local conditions (e.g., renewable resource availability) and farmers' perspective into account.

The bottom-up exploration of smallholder livelihoods and available renewable resources on local level could render the design of RE support policies by providing the missing link between: (i) the policy landscape conducive for RE development, recently underpinned by the *Intended Nationally Determined Contribution (INDC)* submitted to the UNFCCC; (ii) the motivation of smallholder farmers to use and produce RE; and (iii) the already existing decentralized, state-led development agencies (Block Development Offices) to substantially expand RE generation in India, while supporting millions of smallholder farmers in utilising local resources more effectively, protecting the environment and pursuing for a modern lifestyle.

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Abbreviations

aAHP	adapted Analytical Hierarchy Process;
BCKV	Bidhan Chandra Krishi Vishwavidyalaya;
CFL	compact fluorescent lamps;
GREP	Geographical renewable energy potential
GW	Giga Watt; INR - Indian Rupee
IREPA	Integrated Renewable Energy Potential Assessment
JNNSMP	Jawaharlal Nehru National Solar Mission Programme
LPG	Liquefied Petroleum Gas
MCDA	Multi-criteria decision analysis
MWh	Mega Watt hours
NBMMP	National Biogas and Manure Management Programme
NPP	Net primary productivity
O&M	Operation & maintenance
PJ	Peta Joule
PV	Photovoltaic
PTP	Partnership
RE	Renewable energy
REP	Renewable energy potential
RET	Renewable energy technology
RR	Renewable resource
SMART	Simple Multi-Attribute Rating Technique
ThREP	Theoretical renewable energy potential
TREP	Technical renewable energy potential
RPR	Residue: Product Ratio
WBREDA	West Bengal Renewable Energy Development Agency
Wp	Watt peak

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3. Urban Gardening in Germany: Cultivating a Sustainable Lifestyle for the Societal Transition to a Bioeconomy

This chapter explores the impacts of urban agriculture for raising awareness among the growing urban population about sustainable agricultural production and sustainable consumer behaviour.
Therefore, the characteristics and motivations, cultivation methods and technologies, and the perceived change in consumer behaviour of urban gardeners in Germany was analysed. The web-based search and analysis of 657 urban community gardens, accompanied by an online survey with 380 respondents, provides comprehensive insights into the growing urban gardening community, the multifunctional roles urban gardening and its societal impacts through a bioeconomic lens.

Further, the concept of circular terrabioponic smart-garden systems to facilitate and promote sustainable urban food production is introduced, with the aim of attracting further city inhabitants to urban agricultural activities for the societal transition towards a bioeconomy.

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Urban Gardening in Germany: Cultivating a Sustainable Lifestyle for the Societal Transition to a Bioeconomy

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Abstract: Urban gardening has the potential to turn the growing number of consumers into conscious producers by raising awareness of natural resource cycles, contributing to environmental conservation and climate change mitigation. This study investigated the motivations for urban gardening in Germany, based on an extensive review of 657 urban gardening project websites. The subsequent online survey of 380 project participants provides a characterization of the gardeners, giving insight into both cultivation methods and technologies used and the participants' consumer behavior. It was shown that urban gardening has an influence on consumer behavior and can induce a change towards a more sustainable lifestyle. The gardens provide a space for the exchange of social values, knowledge and ideas on different ways of life among the diverse participants. Hence, urban gardening creates far more than just food; it influences society on multiple levels. Urban gardening can support the bottom-up societal transition towards a bioeconomy as both have common attributes. Finally, the paper proposes an innovative, resource-efficient cultivation system that may attract further societal groups to the urban gardening lifestyle, with the aim of fostering the development of the bioeconomy.

Keywords: urban gardening; survey; motivations; characterization; cultivation methods; terrabioponics; transformative group; societal transition; bioeconomy

1. Introduction

Urban food production is currently experiencing a renaissance, with urban gardening becoming a global trend. On every continent, more and more people are starting to garden in cities [1–3]. The motivations for this development are manifold and differ from urban garden to urban garden and from region to region. In countries of the South, urban gardening is often driven by the basic human need of food consumption, as poorer people in particular garden in order to become food secure [3,4]. In the Global North, the reasons are quite different: urban gardening has become a lifestyle trend, with the gardens becoming meeting points that unite various interest groups. Some urban inhabitants want to participate in city development and the shaping of their own district or block [4,5]. In this way, urban gardening establishes new forms of public–private partnerships for the utilization, design and financing of particular (public and private) spaces in cities [6]. New green areas are created. Others want to reconnect with nature [7]. Through urban gardening, city dwellers can experience nature on their doorstep. During the process of preparing the soil, through to planting and finally harvesting a crop, they create, observe, alter and eventually come to understand the growth and decomposition cycle of natural resources. This influences their own nutrition habits and raises a consciousness for food production as well as natural resource use and labor input [4]. Another group of gardeners is more interested in greening the city. From an environmentalist perspective, these areas serve as habitats for various plants and animals that provide a range of ecosystem services to the city [5,8]. Transpiration of plants can have a cooling effect on city climates during the hotter seasons [9]. Plant surfaces can filter air pollutants (NO_2, SO_2, O_3 and particles with a size less than 10 μm), thus helping to clean city air [10]. Additionally, green areas like public parks, private home gardens and urban community gardens, where city dwellers garden together on public and private spaces, increase the retention of water through high soil infiltration rates at times of intense rainfall events [8]. The flowering of plants throughout the gardening season attracts a wide range of pollinators [11]. In addition to providing habitats for plants and animals, green areas in cities are also meeting points for the people themselves, across generations, cultural backgrounds, occupations and income levels [5].

Cities can benefit from urban gardening in many ways. In Germany, it is seen as an important component of city development plans, for example in the guidance and research recommendations of the 'National Platform for Future Cities' [12].

In future, the number of people living in cities and metropolitan areas will increase. On a global scale, the proportion of urban inhabitants is projected to grow from 48% in 2014 to up to 70% in the year 2050 [13,14]. In some regions, these figures have already been reached, such as 72% in Europe in 2014 [14] and 75.5% in Germany in 2016 [15].

Urban gardening can turn the growing number of consumers into producers. This has the addition effect of raising awareness of natural resource cycles and their currently unsustainable exploitation. The resulting change in consumer behavior can contribute to the conservation of the environment and mitigation of climate change.

These goals are also inherent in the development of a bioeconomy. The bioeconomy strives for a sustainable economy that is based on natural matter cycles to conciliate economic growth with environmental conservation and climate change mitigation [16,17]. To achieve this, more sustainable modes of production and consumption need to be created [18]. Thus far, the bioeconomy development is mainly driven by a top–down approach of technical innovations and novel processes to substitute fossil resources with biomass as well as the creation of green business models [18,19]. However, the transition towards a bioeconomy can only be achieved when it is understood and endorsed by the society and promoted by the people themselves [16]. *"The development of the bioeconomy is part of a societal transition that units multiple trends and initiatives from 'green economy' and 'sharing economy' to 'citizen science' and 'urban farming'" [17].* Recently, [20] described urban gardening as local (block or quarter level) participatory approaches of transformative economic activities with the urban gardens being the nuclei of crystallization of this movement.

This study investigated the ways in which urban gardening can influence consumer behavior and act as a potential starting point for a more sustainable lifestyle. For this purpose, it explored the motivations for the establishment of urban gardening projects in Germany, based on an exhaustive review of their project websites. In addition, an online questionnaire was used to survey urban gardeners from these projects. The results were analyzed to give an overview of the demographic factors of urban gardeners, together with production methods and technologies used. The survey also explored the impacts of urban gardening on the consumer behavior of people who had begun the practice in recent years. Based on the results, an innovative, resource-efficient urban garden concept is introduced that can serve as a useful tool to further encourage the urban gardening trend. Finally, the implications of these findings for the societal transition towards a bioeconomy are discussed.

2. Materials and Methods

This study applied a two-pronged approach to explore, analyze and characterize urban gardening in Germany. The first step was the exploration of urban gardening projects based on an exhaustive web search that was carried out in August and September 2017 according the steps for conducting a literature review [21] (p. 29f): (i) The following urban gardening network websites (databases) were screened to identify urban gardening projects: *foundation anstiftung* (map of projects all over Germany) [22], *gruenanteil* (map of projects all over Germany) [23]; *Urbane Oasen* (map listing urban gardening projects in North Rhine-Westphalia) [24]; bonnimwandel (map of urban gardening projects in the city of Bonn) [25]. The project name, location and website link were collected in a MSO Excel 2016 file; (ii) based on a preliminary reading of the project websites, the following key words were derived and subsequently employed in the search engine google (Google LLC, Menlo Park, CA, USA) to identify further projects not part of the networks: *urban gardening/farming, city gardening/farming, urbane(r) Garten/farm, Gemeinschaftsgarten, Nachbarschaftsgarten, Interkultureller Garten, Integration + Garten*, *Stadt + Garten/gärtnern* and *guerrilla gardening*; (iii) in this study, projects were defined as 'urban gardening projects' when several people (at least two) actively engage in the cultivation of vegetables, fruit (trees), herbs or ornamental plants on private (but accessible for group members and/or public) or public areas in urban or peri-urban areas. In most cases, these groups used the term 'urban gardening' or 'urban farming' on their website or called themselves a 'community garden', 'neighborhood garden', 'intercultural garden' or similar. Private (home) gardens, (organized) allotments and urban gardens managed by municipalities were excluded from the investigation; (iv) a list of 657 projects was compiled and the motivational aspects of the foundation of the urban gardening projects were collected by collating information on the aim(s), mission and/or vision from the websites and copying them into the excel file. Next, the aim, mission and/or vision statements of the projects were grouped into categories and labeled with a term (code), developed from the emerging information [21] (p. 186f); (v) the aim, mission and/or vision statements were broken down into buzzwords to derive a final set of distinct categories and sub-categories [21] (p. 189) (Table 1); (vi) finally, the frequency with which a sub-category was mentioned on a website was recorded, with multiple aim, missions and/or vision statements being counted separately.

Following the website review, the second step comprised an online survey using the software package *SoSci Survey* [26]. The link to the online questionnaire was sent via e-mail to all contact persons of the urban gardening projects identified in the first research step. The contact persons were asked to forward the e-mail with the survey link to all members of their urban gardening project (snowball sampling) [21]. The online questionnaire provided a resource-efficient way of contacting a large number of people in a short period of time during the non-gardening season. A total of 380 urban gardeners answered the questionnaire between 15th December 2017 and 15th January 2018.

The online questionnaire consisted of 16 questions. Eleven were standardized single- or multiple-choice questions. The other five asked the participants to enter their year of birth, postcode, number of members in the garden project, founding year of the garden project, and number of years they had been gardening. In addition to demographic factors (age, gender, origin, education level, occupation, family status, private garden area), the participants were asked about their experience with methods and technologies used for urban gardening and whether or not they liked them. Those gardeners with no experience of a particular method or technology were asked to rate their degree of interest based on a Likert scale of 1 to 5. Further questions solicited information on their consumer behavior before and after their participation in an urban gardening project began. These questions enabled the analysis of whether their gardening activities had altered their consumer behavior.

Answers to the questionnaire were analyzed performing descriptive statistics in MSO Excel 2013. Averages, ranges and trends were calculated [21]. Finally, to further investigate the urban gardening phenomenon, a cluster analysis was employed to identify mutually exclusive segments of urban gardeners with a comparable attitude towards modern production technologies using IBM SPSS Statistics 25 (Armonk, NY, USA). All variables included in the cluster analysis are shown in Section 3.4. A two-step procedure was used as clustering method: sub-clusters were initially defined and subsequently merged until an optimal number of clusters was reached. This method was chosen, since in the second step, a standard agglomerative clustering algorithm estimates myriad solutions and reduces them to an optimal number of clusters. To do this, we applied Schwarz's Bayesian Inference Criterion that features less subjectivity than other clustering methods [27].

Table 1. Motivation categories for urban gardening based on information given on German urban gardening project websites.

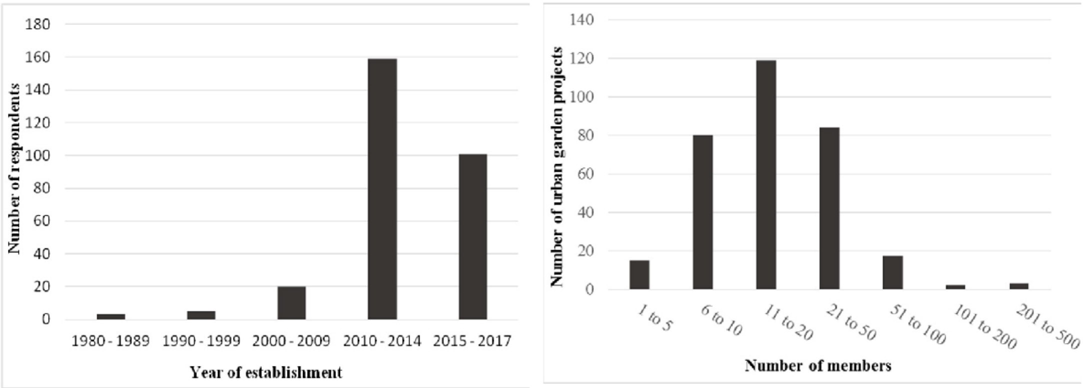
Category	Sub-Category
Social community	
	Social gathering and learning Social meeting, networking/exchange/community Neigbourhood vitalisation, solidarity Local identity (*'Heimat'*)
Gardening, experience nature	
	Learn gardening, joy of gardening, fun Experience nature, work in/with nature
Intercultural communities	
	Cultural/social diversity Intercultural meeting, exchange and community Integration
Environment and ecology	
	Sustainability, sustainable lifestyle Future development Biodiversity Organic production, old varieties and diversity Soil fertility, permaculture Beekeeping
Public involvement	
	Public engagement/involvement/design Use of public spaces for communities Encourage (political) discussions Grassroots democracy, self-determination
Education	
	Education, environmental education Awareness of organic, regional and healthy nutrition Experimental garden, educational garden
Recreation	
	Relaxation, leisure time Cultural activities
(Self-)Sufficiency	
	Urban self-sufficiency, local food
Urban image	
	City greening/beautification, nature in the city Living space, local recreation areas
Health and nutrition	
	Healthy food, health, nutrition Organic food
Therapeutic approach	
	Trauma therapy, coping strategies
Commercial project	
	Urban gardening as a business model Production for sale (seeds, plants, foods, drinks)

3. Results

Urban gardening projects and the participants are characterized in the following, emphasizing on the motivations for urban food production, the cultivation methods and technologies used as well as attitudes of the project participants towards modern production technologies. Finally, a modern and resource-efficient urban gardening technology is introduced.

3.1. Urban Gardening Projects in Germany

A total of 657 urban gardening projects were identified in Germany (November 2017), the vast majority of which had been founded since 2010 (Figure 1a). Most projects have 11–20 participants (Figure 1b).



(a) (b)

Figure 1. (**a**) Year of establishment of urban gardening projects in Germany 2017 ($n = 657$); (**b**) Number of members per urban gardening project ($n = 365$).

The reasons for the establishment of urban gardening projects in Germany are manifold (Figure 2). The most important motivations are: social interaction, intercultural exchange, working and learning with nature, and gardening ecologically to live sustainably.

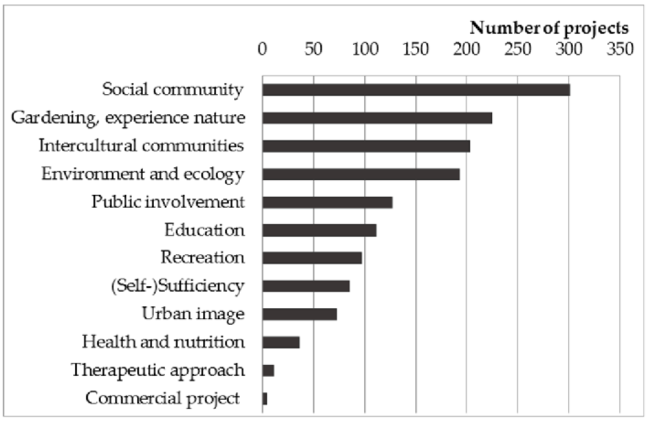


Figure 2. Motivations for the establishment of urban gardening projects ($n = 657$) in Germany up to November 2017.

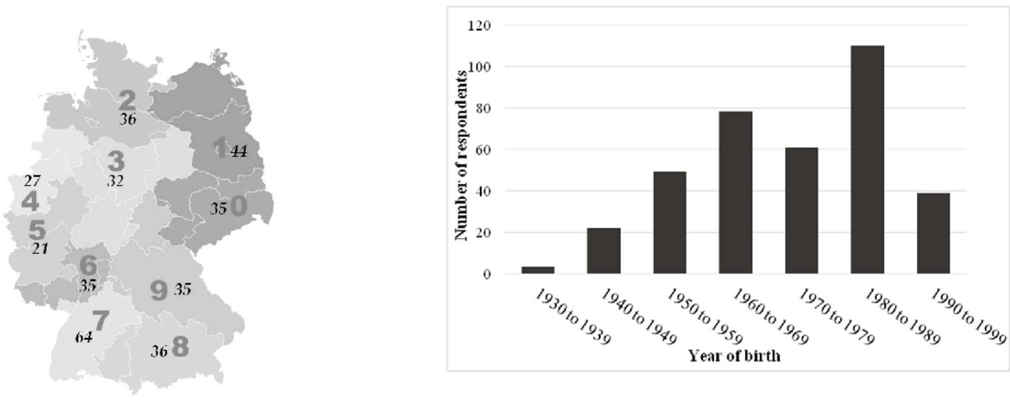
Values such as community spirit, neighborhood and solidarity are central to 301 of the projects (*social community*). *Gardening* as *experience of nature* (225 projects), where people learn about and to work with nature, is the second most important reason for urban gardening. This is followed by the category intercultural exchange and integration (*intercultural communities*, 203 projects) and sustainable lifestyles and ecologically sound gardening practices (organic production, soil fertility, biodiversity) (*environment and ecology*, 193 projects), which have almost equal importance. The initiation of and participation in social discourse are encouraged by 127 projects (*public involvement*), calling for grassroots democracy for decisions on the utilization of public spaces. *Education* about the environment is the focus of another 111 projects. The aspects *(Self-)sufficiency* (85) as well as *health and nutrition* (36) were found to be of less importance. A similarly low ranking was obtained for improvement of the *urban image (73)* in terms of beautification of a city through greening. Only four projects are driven by *commercial* interests, and eleven pursue a *therapeutic approach* (Figure 5).

Thus social and ecological (sustainability) aspects were found to be the main drivers of the establishment of urban gardening projects in Germany. These social and ecological values are in common with the principles and values associated with the societal transition towards a bioeconomy (Section 1).

3.2. Characterisation of Urban Gardeners in Germany

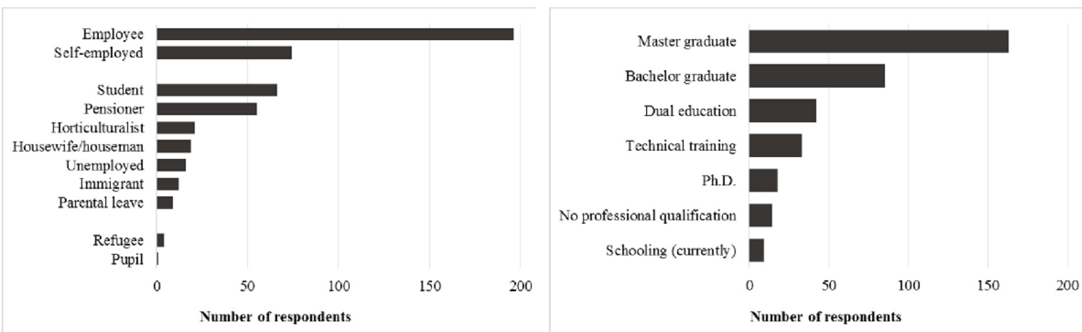
The geographical distribution, according to postcode zones, of urban gardeners who responded to the survey reveals that urban gardening is currently performed in cities throughout Germany (all federal states, Figure 3a). The participants in urban gardening projects are a very heterogeneous group. Two thirds (66%) of the survey respondents were female, suggesting that more females than males garden in cities. Further, urban gardening is performed by city inhabitants of all age groups, with most gardeners being born between 1980 and 1989 (Figure 3b). Whether the gardeners originate from rural (<5000 inhabitants—31% of respondents) or urban (>100,000 inhabitants—30% of respondents) areas does not influence their urban gardening activities.

On average, the respondents have been active in an urban gardening project for 3.3 years and already have 12.8 years' gardening experience. The majority of respondents are employees, self-employed or students (71%), followed by pensioners (Figure 4a). Consequently, urban gardening is, to a large extent, a leisure activity.



(a) (b)

Figure 3. (**a**) Geographical distribution of urban gardeners in Germany (n = 365) according to postcode zones (Map adapted from [28]); (**b**) year of birth of the surveyed urban gardeners in Germany (n = 362).



(a) (b)

Figure 4. (**a**) Occupation/legal status of urban gardeners in Germany (n = 473, multiple responses allowed); (**b**) Highest educational qualification of urban gardeners in Germany (n = 364).

The highest proportion of urban gardeners (54%) is in a partnership, 40% of respondents are single without children, and 33% of the respondents have children.

Furthermore, urban gardening tends to be performed by people with a higher education (73%, Bachelor's degree from a university, incl. university of applied sciences, or higher) (Figure 4b).

Urban gardening projects offer the only possibility of gardening, apart from on windowsills, for 27% of the respondents (Figure 5). One third of the respondents have at least a balcony or terrace that could be used for urban gardening, while 29% have a home garden or garden property.

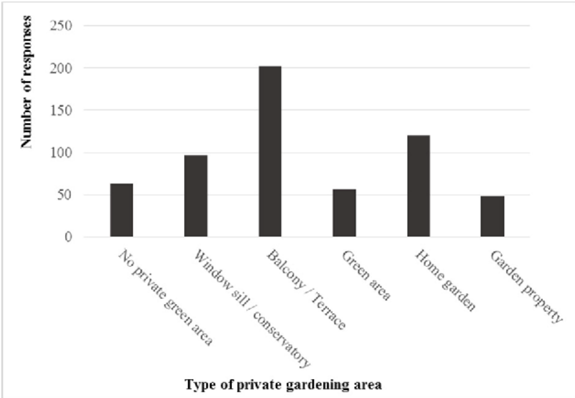


Figure 5. Private area available for cultivation to urban gardeners in Germany (n = 365; multiple responses allowed).

The major reason for joining an urban gardening project is that the project represents 'something bigger' that the participants want to support or join, such as the integration of refugees, societal transformation and environmental protection. Many of the respondents are either the founder or a member of the founding group of the project. Many people were attracted by gardening projects in their neighborhood or were personally invited by project members. Another group of respondents had actively searched for a project in their city (Figure 6).

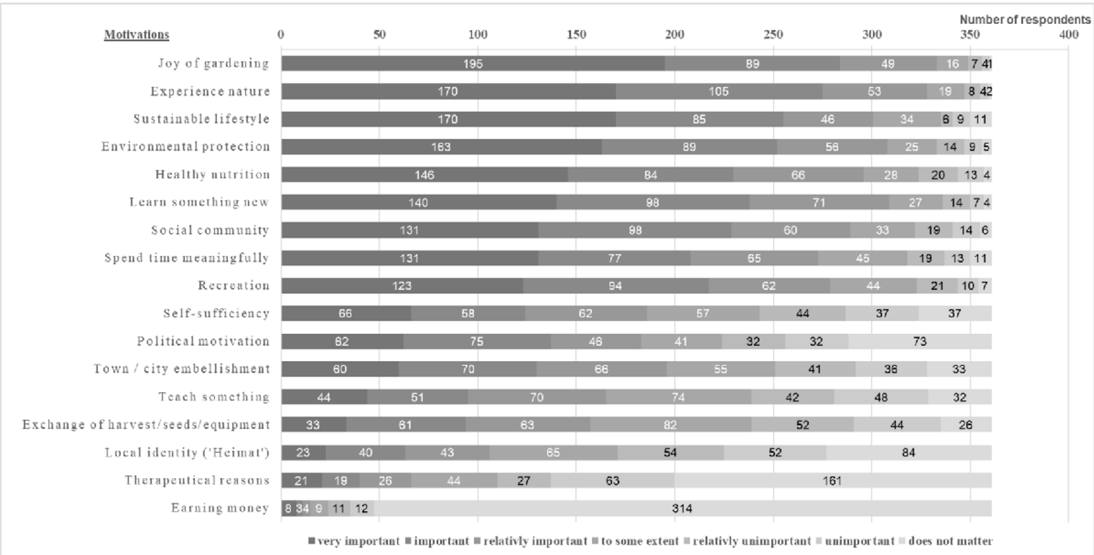


Figure 6. Reasons for joining an urban gardening project (n = 359).

The personal motivation for urban gardening is strongly related to the experience of nature, for example through the joy of gardening activities, pursuit of a sustainable lifestyle, and protection of the environment (Figure 7). The personal aspect of healthy nutrition and the social aspect of being part of a community are also very important. The gardeners want to spend their (free) time meaningfully for example by learning something new, but also enjoy spending time in the gardens for recreation purposes. Some urban gardeners seek to achieve food self-sufficiency, aim to embellish their town/city through the gardens or are politically motivated. Other motivations include teaching others and exchanging harvest/seeds/equipment. Earning money through urban gardening is not a motivation for the vast majority of gardeners.

Furthermore, the answers given by the respondents to the question 'How important are the following criteria when buying gardening equipment?' underline the importance of sustainability in their consumer behavior (Figure 8). Functionality, durability and regionally sourced products made from sustainable resources are important buying criteria for garden tools and materials. Cheap prices are only important to some extent or relatively unimportant, while the design does not matter for the majority.

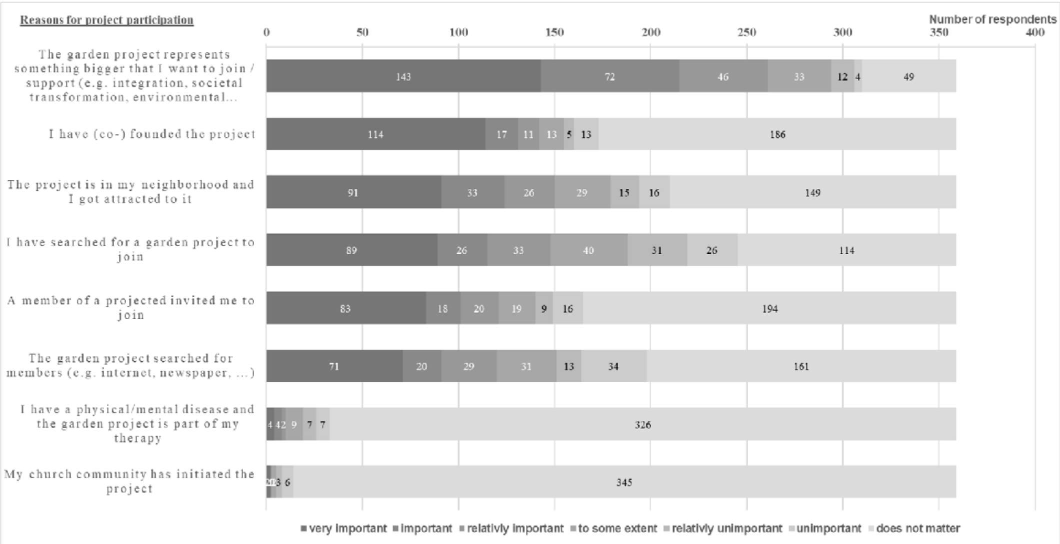


Figure 7. Motivations for urban gardening ($n = 361$).

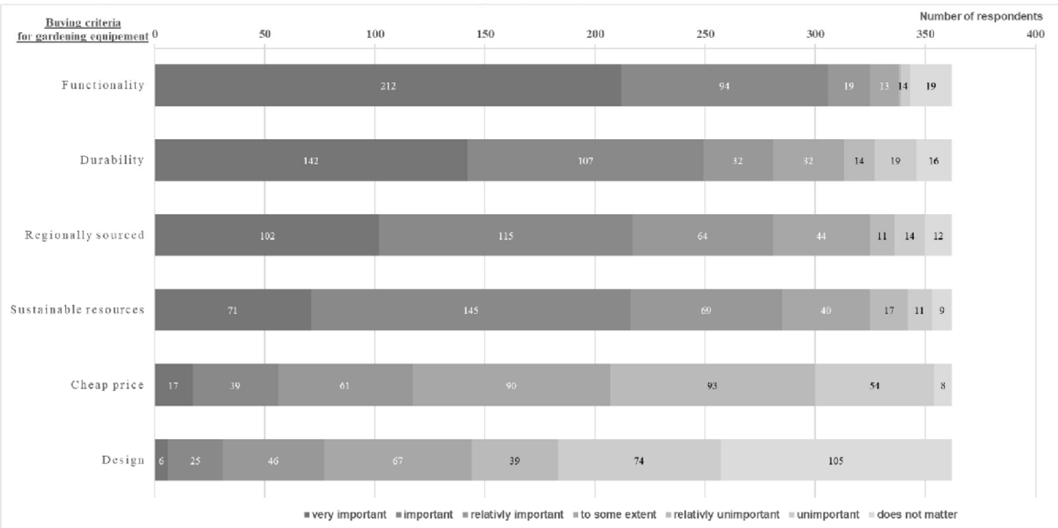


Figure 8. Relevant criteria for urban gardeners when buying gardening equipment ($n = 362$).

3.3. Urban Gardening in Germany: Production, Cultivation Methods and Related Technologies

Almost all urban gardeners in Germany cultivate food crops. Ornamental plants constitute the second most frequent produce (Figure 9). Livestock, predatory insects, animals (non-food use) and energy currently only play a minor role. However, livestock production, the keeping of pets and the promotion of predators are likely to increase in the coming years at the urban gardening projects. Over a third (36%) of respondents is also considering energy production (electricity, gas, heat) in their garden.

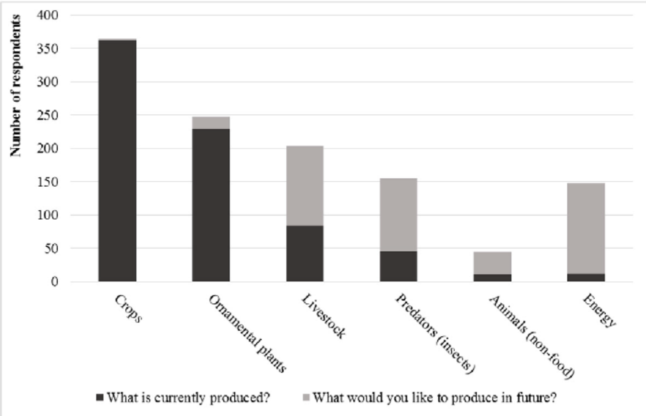
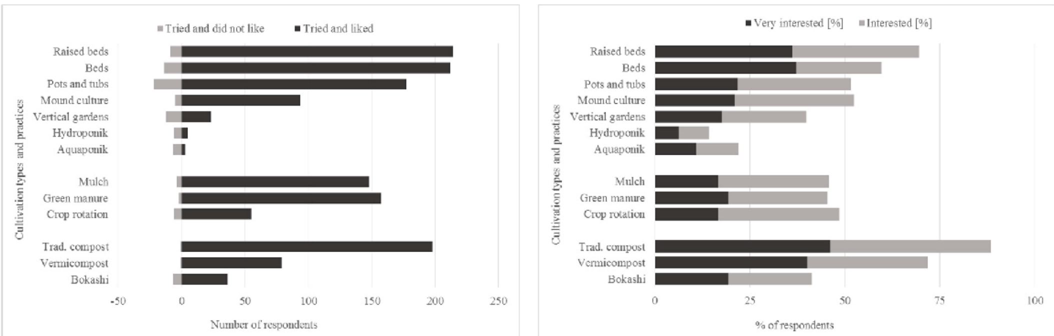


Figure 9. What is currently produced in urban gardening projects in Germany and what gardeners would like to produce in future (*n* = 380).

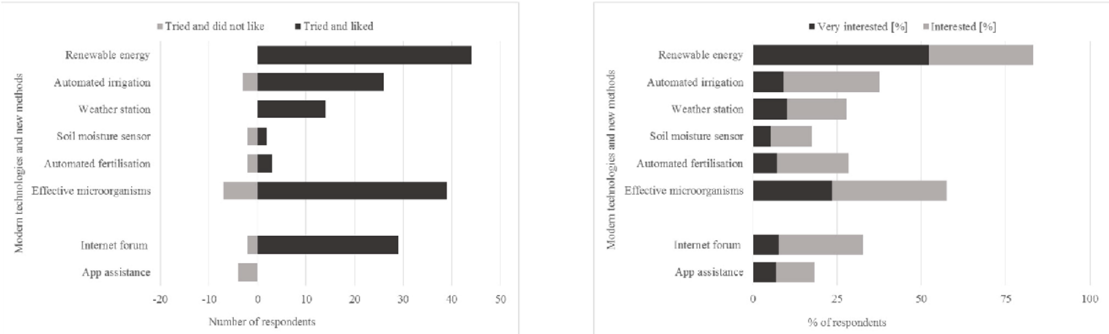
Common plant cultivation methods include traditional garden beds and raised beds (Figure 10a). Cultivation in pots and tubs is also popular, but 12% did not like this method. Mound cultures (similar to raised beds, but without a surrounding support structure) are also built and used. The interest in these cultivation methods expressed by gardeners who have no experience of them shows the same pattern (Figure 10b). Vertical garden structures (e.g., attached to walls) are not very common. However, those who have tried (and possibly needed) these structures rated this gardening form positively (Figure 10a). The interest in vertical gardening is also quite high (Figure 10b). To date, the modern hydroponic and aquaponic systems are not very well known. The few gardeners who have tried these systems seem disappointed and consequently rated these cultivation methods negatively (Figure 10a). However, a few gardeners who have no experience of aquaponic (22%) or hydroponic (14%) systems are interested in trying them (Figure 10b).



(**a**) (**b**)

Figure 10. (**a**) Cultivation areas and gardening practices tried and assessed (liked/not liked) by urban gardeners (*n* = 10–226); (**b**) interest in cultivation areas and gardening practices of those urban gardeners who have no experience of the respective area or practice (*n* = 134–353).

Half of the gardeners apply mulch (42%) to their cultivation patch and/or plant green manure (44%). Both methods are rated positively. Only 17% of the gardeners plan and keep to crop rotations on their cultivation patches, and of these 11% are not satisfied with them (Figure 11a). Almost half of the gardeners are interested in using these three cultivation methods (Figure 10b).



(**a**) (**b**)

Figure 11. (**a**) Modern technologies and new methods tried and assessed (liked/not liked) by urban gardeners (n = 4–46); (**b**) interest in modern technologies and new methods of those urban gardeners who have no experience of the respective technology or practice (n = 316–358).

About half (55%) of the urban gardeners produce their own fertilizer from traditional composting and are satisfied with it. One in five gardeners (22%) uses and likes the special form of vermicomposting, while 12% use the Bokashi method (Figure 10a). Of those who do not compost, 88% are interested in starting it. Vermicomposting has very much caught the attention of urban gardeners, with 72% of the respondents expressing their interest in it (Figure 10b). Organic production methods including composting, green manure and mulching are quite common among the urban gardeners.

Finally, the gardeners were asked about both their interest in as well as their experience of modern technologies and practices that can aid gardening, for example by decreasing effort, increasing yields, making it easier to obtain detailed information, and producing renewable energy (Figure 10a,b).

The latter received the most attention. Those gardeners (12%) who already use a renewable energy technology in the garden project are satisfied with it (Figure 11a). Another 83% would like to produce renewable energy in their garden (Figure 11b). Effective microorganisms are used by 12% of the respondents to improve composting, soil fertility and plant health. About 15% are not satisfied with this method, while 57% of the urban gardeners show great interest in it (Figure 11a,b). Approximately one third of urban gardeners either use or are interested in Internet forums for information exchange (33%) and automated irrigation (37%). Other modern technologies and methods included in the survey are not in use to date. A few urban gardeners expressed their interest in weather stations and automated fertilization (both 28%), while only 18% would welcome a gardening information app and only 17% are interested in using soil moisture sensors.

3.4. *Urban Gardeners' Attitudes towards Modern Production Technologies*

A two-step cluster analysis was performed to analyze urban gardeners' interest in the modern production technologies *vertical production, aquaponics and hydroponics* in greater detail. Two different segments of urban gardeners (clusters) were identified (Table 2). The box plots of the cluster analysis reveal intra-group differences (Figure 12).

Respondents belonging to cluster 1 are highly interested in the production technologies mentioned above. About 40% of respondents belong to this group, mainly younger male gardeners. The other approximately 60% of the gardeners belong to cluster 2; these respondents tend to be older and female. Whether the urban gardeners grew up in rural areas or cities does not influence their interest in modern technologies.

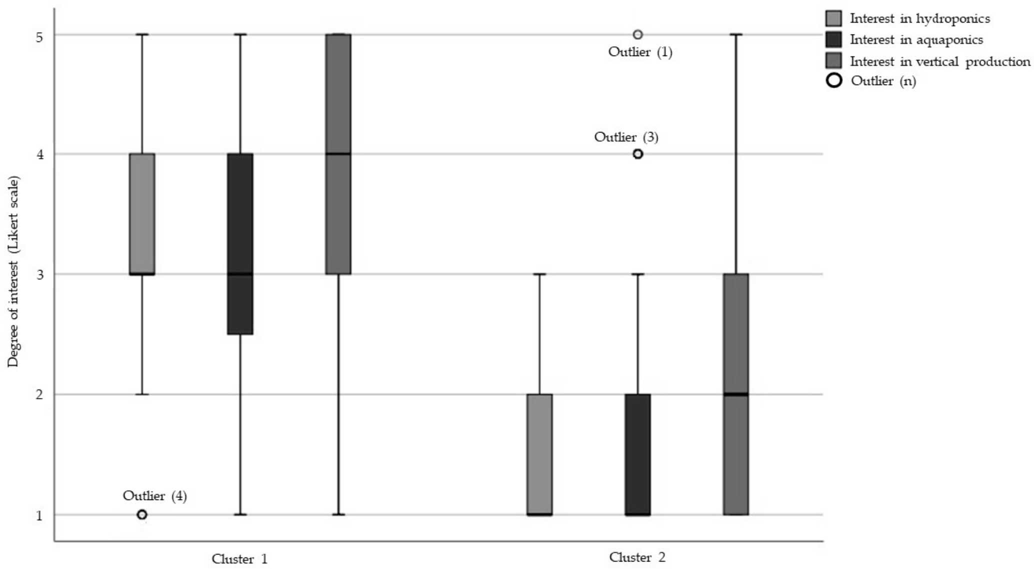


Figure 12. Box plots of the two-step cluster analysis. Degree of interest based on Likert scale: 1 = no interest, 5 very high interest (circles indicate outliers in the clusters).

Table 2. Interest of urban gardeners in modern production technologies based on a two-step cluster analysis (*n* = 303).

	Cluster 1	**Cluster 2**	**Total**
Number of respondents	119	**184**	303
Interest in 'new' production methods [1 = not interested; 5 = very high interest]			
vertical production	**3.93**	2.38	2.99
aquaponics	**3.31**	1.51	2.21
hydroponics	**3.27**	1.38	2.12
Gender [1 = male; 0 = female]	**0.41**	0.28	0.33
Gardening experience [in years]	11.07	**13.53**	12.56
Age [in years]	**43.13**	46.70	45.30
Residence during childhood [1 = town < 5.000 inhabitants; 4 = City > 100,000 inhabitants]	2.50	2.43	2.46
Motivation for urban gardening [1 = not applicable; 7= fully applicable]			
Earn money	1.22	**1.23**	1.23
Therapeutic aspects	2.66	2.56	2.60
Self-sufficiency	**4.61**	4.20	4.36
Political motivations	4.24	4.20	4.21
City/town beautification	4.60	4.43	4.50
Local identity	3.58	3.26	3.39
Learn something new	6.03	5.67	5.82
Healthy nutrition	**5.97**	5.45	5.66
Environmental protection	5.93	5.78	5.84
Sustainability	5.95	5.73	5.82
Exchange of harvest/seeds/tools	**4.51**	3.95	4.17
Solidarity within the gardening group	5.76	5.55	5.63
Recreation	5.63	**5.66**	5.65
Meaningful utilization of leisure time	5.72	5.45	5.56
Experience nature	6.11	**6.14**	6.13
Gardening pleasure	6.29	6.18	6.22
Dissemination of knowledge	4.29	4.03	4.13

The general motivation for urban gardening differs only slightly between the two groups. Gardeners interested in modern production technologies perform urban gardening because a self-sufficient, healthy nutrition is important to them. This group is interested in exchanging harvest, seeds and tools, learning something new and using free time for meaningful activities. Environmental protection and sustainability aspects associated with urban gardening (Section 1) tend to be more important to them than to cluster 2. The cluster 2 respondents tend to consider urban gardening as a form of recreation in which they can experience nature. They favor conventional garden beds or raised beds for gardening.

3.5. Urban Gardening Impacts Consumer Behavior

Urban gardening reconnects urban inhabitants with nature [7]. The gardeners learn about natural resource use as well as the time and labor inputs required to produce food. To analyze the effect of this on consumer behavior, the survey asked urban gardeners whether they actively changed their food-buying habits since they started gardening. Indeed, the results show distinct changes in consumer behavior (Table 3).

Urban inhabitants increased their food self-sufficiency in summer by 471% and in winter by 79% compared with the year before they started gardening. As their produce is self-consumed, with a proportion being preserved for the winter, the percentage of fresh cooking ingredients also increased (+18%). With the freedom of choice of what to plant in their gardens, the consumption of traditional fruit and vegetable varieties also rose by 25%. As the vast majority of urban gardeners produce vegetables (Figure 9) and only a few raise livestock, participation in a gardening project also leads to a decrease in consumption of meat and sausage (−10%) and other animal products, such as dairy products (−4%).

Table 3. Changes in consumer behavior of urban gardeners since their active participation in an urban gardening project ($n = 310$).

Investigated Aspects of Consumer Behavior	Change [%]
Food self-sufficiency during summer	+471
Food self-sufficiency during winter	+79
Consumption of meat and sausage	−10
Consumption of other animal products	−4
Cooking with fresh ingredients	+18
Consumption of traditional fruit and vegetable varities	+25
Organically produced food	+26
Regionally produced food	+35
Seasonally produced food	+42
Engagement in other projects supporting a sustainable future	+5

In addition, the method of production and origin of the food purchased became increasingly important to the urban gardeners. The respondents purchase 26% more organic food, 35% more regionally produced food and 42% more seasonally produced food. These figures show that urban gardening alters the consumer behavior of the gardeners beyond the borders of the gardening project. The consumer behavior becomes more organic, regional and seasonal, coupled with a healthier diet (less animal products, more fresh ingredients). Consequently, urban gardening alters urban food systems, rendering them more sustainable.

4. Discussion

4.1. Urban Gardeners—Characteristics of a Transformative Group

Urban gardening projects have grown up in cities in all German federal states, mainly within the past decade.

4.1.1. Characterization of Urban Gardeners in Germany

Urban gardeners in Germany are a heterogeneous group in terms of demographic factors—age, gender, occupation, educational background and origin. The majority of gardeners are between 29 and 59 years old, have a relatively high education level and are in employment. This is in line with the findings of [5], who sampled 38 urban gardens in Germany in 2013 with 60% of the interviewees being female and 47% having an academic background. Similar educational background, income level and gender (more females than males) characteristics were also identified for participants in self-harvest gardens in Germany [29].

Due to the diversity of the participants, urban gardens can be characterized as spaces with a high potential for the exchange of social values, knowledge, (gardening) practices and ways of life. In addition to creating diverse forms of gardening, the project activities can lead to lasting relationships between people in groups with significant power and social status differentials. This in turn provides the basis for a strong collective capacity, which can benefit society through the active shaping of city development [30].

In collective action theory, however very heterogeneous groups are deemed as negative for social interaction and consensus building [31]. Rogge et al. [2] recently analyzed the heterogeneity of urban gardening groups in Germany with respect to social sustainability and the social capital created. Their results indicate that a too high heterogeneity within gardening groups has a negative impact on the social sustainability of the projects. However, [2] state that the heterogeneity measured is neither too high nor too low, leading to the assumption that the participant diversity is positive for the creation of social capital. The interaction of diverse cultural identities, viewpoints, backgrounds and lifestyles can promote mutual learning. Urban gardeners are and need to be creative with respect to both gardening practices (e.g., space-efficient vertical gardens, pots and container gardens, renewable energy production), their organizational structure and their collaboration with municipalities [32], as the urban environment are primarily not predestined for gardening. The heterogeneity is also reflected in the multiple motivations for urban gardening.

4.1.2. Motivations for Urban Gardening

The motivations for urban gardening are manifold. This is expressed by the project founders as well as by the gardeners themselves. The founders see the creation of a social community as their main motivation. This is grounded in the collective desire of the majority of participants to live an ecologically sound lifestyle that connects them with nature and, at the same time, helps protect the environment. This phenomenon of reconnection with nature [33] is described by [34] as 're-grounding'. Various studies in Germany [2,7,20], Switzerland [35], Austria [36], Italy [37], the US [30,33,38], and Canada [38] confirm the importance of community building and social exchange through gardening. The members participate in the projects because they enjoy gardening activities, being close to nature, working with living plants and animals, and 'getting their hands dirty' to create tangible (e.g., garden beds, food, flowers) and non-tangible outputs (e.g., meeting points, local recreation areas, knowledge sharing, participation in city development).

However, the respective importance of the various motivational aspects for urban gardening vary from case to case. Studies in the US and in Switzerland confirm the 'joy of gardening' as the top-motivation for urban gardening activities [33,35]. A case study in Milan (Italy) ranked the aspect of healthy food most important, followed by gardening as exercise and for relaxation [37]. Food self-sufficiency is a benefit for the gardeners to some extent, but is not a major motivation for gardening activities. The same result was also reached by case studies from Ljubljana, Milan and London that analyzed the economic performance of urban gardens in these cities [39]. The amount of food produced and/or revenues created are often too low to be of significance in economic terms [20]. However, [40] point out that urban food production can yield sufficient vegetables to meet the recommended personal dietary intake, using less than 10% of urban areas. Hence, urban gardening can decrease the pressure on rural farmland in particular through the production of crops consumed fresh, such as vegetables, fruit and herbs.

The socio-ecological motivations to live a sustainable lifestyle based on a sustainable and healthy nutrition form the backbone of urban gardening, also in the US where the movement began [38]. The urban gardening movement has since spread around the globe, with these motivations being the main driver of urban gardening in the Countries of the North [4]. International institutions, including the Food and Agricultural Organization of the United Nations (FAO), the World Health Organization (WHO), Resource Centers on Urban Agriculture and Food Security (RUAF Foundation) conceptualize urban gardening based on these main motivations [41].

4.1.3. Urban Cultivation Methods and Technologies

First and foremost, food and ornamental plants are cultivated and animals are raised in cities in a variety of ways. Fresh food is self-produced locally and seasonally, using mainly organic cultivation methods [5]. Being a producer means satisfying the basic human need for food in a self-controlled, self-dependent and thus responsible way [20].

In this sense, urban gardening encompasses a strong social innovation dimension [41,42], even though the frequently applied cultivation methods—beds, raised beds, mound culture and composting—are not innovative themselves [5]. The survey and subsequent cluster analysis revealed that modern cultivation systems such as hydroponics, aquaponics and certain production technologies (e.g., automated fertilization, soil moisture sensors, weather stations and app support) are only being adopted slowly. Modern technologies, such as hydroponic and aquaponics systems as well as roof-top farms, have higher resource use efficiency and productivity [42–44], but require substantial amounts of construction material and energy input. Hence these technologies diffuse more slowly than low-tech applications like rainwater harvesting and irrigation systems, which are easier and cheaper to install and maintain [42].

The urban gardeners surveyed in this study are more interested in organic cultivation systems that reconnect with nature, such as traditional composting, vermicomposting, effective microorganisms, mulching and crop rotations. Renewable energy technologies are also being increasingly implemented to provide electricity in the gardens, for example for automated irrigation.

4.1.4. Influence of Urban Gardening on Consumer Behavior

The values associated with urban food production are based on knowledge of production and processing, control over and trust in these methods, with respect to freshness, flavor and organic production [45]. This study shows that self-production of food in urban gardens has a large influence on consumer behavior. Since taking up gardening, the participants of urban gardening projects in Germany purchase more seasonally, regionally and organically produced food. This indicates that there is interest and willingness to learn where the food comes from and how it is produced.

The interest in and demand for traditional fruit and vegetable varieties has also increased. The gardeners are attracted by the broad spectrum of fruit and vegetable varieties. One main reason for this may be the widespread public belief that the contents of mineral macronutrients, trace elements and vitamins are much higher in traditional/old varieties than in modern high-yielding varieties [46]. Although this is only partly true and very much depends on the specific varieties and their growing conditions [46], the trend contributes to healthy nutrition and agricultural diversity.

The change in consumer behavior is a strong political statement that calls for sustainable food production methods and supply chains.

4.1.5. Multifunctional Roles and Societal Impacts of Urban Gardening

Urban gardening is currently triggering societal discourse on the sustainability and future viability of agricultural production, food value chains and consumer behavior. Food and nutrition has become a democratic instrument for sensitizing society to food systems, markets and demands nutrition habits and wasteful consumer behavior, while encouraging alternative food networks [42,45]. Cities form the starting point of this debate—in the past because of the lack of trust in production and processing methods, today additionally because the neoliberal food value chains are threatening human livelihoods (especially in countries of the South), biodiversity, natural ecosystems and climate for the sake of economic growth [20].

One aspect that is particular to urban gardening is the fact that the participants act on several levels at the same time [20]. Most of the gardening projects see themselves as open learning and sharing platforms [5,20], which can foster social values like the common sharing of goods and the empowerment of people [42]. The projects often focus on knowledge dissemination to stimulate open learning processes [42], for example by offering workshops on and trainings in topics such as organic growing, alternative cultivation methods (e.g., raised beds, container/pot and mobile gardens), food processing and conservation. In addition, new forms of collaboration with local stakeholders are initiated, for example canteen/restaurant-supported gardening, pop-up gardening on abandoned areas, communal kitchens and school gardens [5,32]. A strong network of support and exchange is vital to gardening projects from the very beginning. The initiation of a gardening project first requires the ownership of the cultivation space to be clarified, followed by implementation of supportive structures for the creation of basic infrastructure and knowledge exchange. Close collaboration between the garden projects and municipalities can often help develop the full potential of urban gardening with its associated benefits for cities (see Section 1) [5]. For example, the project 'Himmelbeet' in Berlin gave rise to strategies for tackling exclusion, disinvestment and depoliticization of public spaces [6].

Urban gardening provides a strong social bridge with the capability to increase civic engagement and social empowerment [42]. This is based on sharing and exchanging diverse knowledge, cultural values and practical skills. All three arise from food production and are transferred into various levels of society and governance, actively shaping city development [5,20,40].

The societal transition potential of urban gardening reaches far beyond just growing food in cities. By digging the soil and planting vegetables, urban inhabitants actively engage in the discourse on global sustainability [38] and contribute to overcoming key challenges posed by urbanization: climate change, food security, biodiversity and ecosystem services, agricultural intensification, resource efficiency, urban renewal and regeneration, land management, public health, social cohesion, and economic growth [47]. Global agricultural and environmental threats are tackled bottom-up by becoming a producer at ground level. This characteristic is important in addressing the complex requirements for social change [20]. Urban gardeners are a growing group of people who denounce the imperial lifestyle with respect to food production, distribution and consumption and their fatal consequences on the environment, climate and livelihoods of people in Countries of the South [20].

Consequently, urban food production fosters environmental and social values [45]. This results in a strong political statement being sent out from the urban gardens to the adjacent neighborhood, local political institutions (e.g., city development departments) and international institutions with the aim of supporting the sustainable development goals [4,5,20,30,40,42,47].

4.2. Urban Gardens—Cultivation Areas for the Growth of the Bioeconomy?

Urban gardening actively transforms consumer behavior, shapes city development and brings the current agricultural production system into public discourse. Since urban inhabitants have started to garden, the ecological and socially sound production of food has increased in importance. The survey also showed that urban gardeners purchase gardening equipment based on the criteria *functionality*, *durability*, *regionally-sourced*, and *sustainable materials*. *Cheap prices* and the *design* are only of secondary importance. It is likely that urban gardeners also apply these criteria in their choice of other products and services consumed, such as new products made from biobased rather than fossil resources. The urban gardening trend helps make more people understand natural matter cycles. This awareness can be transferred to other areas in life, indicating the great potential for urban gardening to alter demand and consumer behavior in society towards sustainable products.

The supply of sustainable products made from biobased resources is the core of the growing bioeconomy. Urban gardening and the bioeconomy share common attributes: both are based on natural ecosystems, matter flows and natural cycles of growth and decomposition. Currently, scientific and technical innovations are among the major driving forces of the bio-based economy [19]. A holistic and system approach in the realization of technical innovations is crucial to the bioeconomic transformation process. The technical innovations require social acceptance, economic feasibility and the creation of ecologically sound value chains [17]. The success of the societal transition towards a bioeconomy ultimately depends on people's understanding of natural matter cycles, and their support of and commitment to the sustainable use of natural resources [16]. Technical innovations made for the development of the bioeconomy need to be matched to the interests of political, economic and civil society stakeholders. Hence, the adoption of innovative technologies and new products (e.g. made from biomass rather than fossil resources) is a social development process that requires the transformation of social values and consumer behavior [48]. Knowledge and understanding of sustainable natural resources utilization in society are vital for the transition towards a bioeconomy. In this respect, (urban) food self-production is a very promising activity for the stimulation of sustainable resource use.

4.3. Terrabioponic Gardening—Sowing the Seeds of Natural Resource Appreciation

In line with the motivations for urban gardening and technology preferences of the gardeners assessed in the survey, a resource-efficient urban gardening technology is proposed here to further encourage the urban gardening trend and the societal transition towards a bioeconomy: Terrabioponic smart-garden systems (Figure 13). These garden systems recycle plant nutrients from organic household waste by vermicomposting (*bio*). The resulting organic nutrient solution ('vermitea'), containing plant nutrients and beneficial microorganisms [49] is directed to the crops via an automated irrigation system in the bottom layer of the planting containers (*ponic*). Solid vermicompost added to organic planting substrate as nutritive organic fertilizer ensures natural growing conditions by supplying humus, macro- and micronutrients, beneficial soil microorganisms (including N-fixing and P-solubilizing bacteria) and growth hormones (*terra*) [49]. The integrated water and nutrient cycle is operated automatically by a 12V solar system with battery and timer. Additionally, the terrabioponic garden system is equipped with a smart control and management board with an interactive user interface (app). This allows the system to be controlled from anywhere and offers a smart planting calendar to guide the user through the gardening season. Water level and dissolved oxygen sensors indicate when irrigation/water change is necessary in the planting pots. Temperature and light sensors provide information on plant growth and calculating the harvest date of individual crops. Sensors measuring pH and EC (electric conductivity) indicate the decomposition rate of the organic waste (indicator of compost worm activity) and the resulting fertilization effect of the nutrient solution.

The proposed terrabioponic smart-garden system is based on the cultivation methods and technologies that were identified as most favored by the urban gardeners in the survey: raised beds, vermicomposting and automated irrigation based on renewable energy. Terrabioponic cultivation is derived from recirculating aquaponic systems [43]. The aquaculture part was replaced by a vermicompost and the fish feed with organic kitchen wastes as nutrient source. The Cuban cultivation approach *organoponico* also utilizes vermicompost in planting pots, but manual watering [50]. The terrabioponic garden system circulates vermitea through the planting containers via an underground irrigation layer. This enables automated, efficient irrigation and organic fertilization simultaneously.

The autonomous garden systems are designed for balconies, terraces, backyards and flat roofs. Food production is based entirely on available urban resources—organic waste, water and solar energy—for ecologically sound production on a seasonal and local basis. The fact that organic waste, fed into the vermicompost, can be used as a single nutrient source for vegetable production was demonstrated by [51]. Natural resource cycling provides the core of terrabioponic gardening. Natural growth and decomposition processes are directly observable and become tangible for the users. The users are (re-)connected with these processes, by directly working with them guided by the app. Knowledge is gained about how food is produced, what resources are needed, where these resources come from and how natural cycles influence production. The understanding of these basic natural principles and resource cycles is also vital for the societal transition to a bioeconomy [16].

Figure 13. (**a**) Overview of the terrabioponic garden system: functionality diagram; (**b**) test garden system on a private balcony with 3x planting containers, 1x vermicompost , 1x water tank and solar power supply in Freiburg i.Br., Germany; (**c**) vermicompost with *Eisenia foetida*; (**d**) aerated water tank for the production of the organic nutrient solution ('vermitea'); (**e**) irrigating gravel layer in a planting container with plant roots (bottom right). Further information: http://www.geco-gardens.de.

The terrabioponic smart-garden systems combine all three dimensions of the bioeconomy [52]: *Bio-resources* are used directly in a *bio-ecological* system. The terrabioponic smart-garden system thus represents an innovative biotechnological tool that enables the population to perform bioeconomic on a daily basis.

The terrabioponic smart-garden systems are therefore deemed a promising tool for the cultivation of bioeconomic thinking in further societal groups. The involvement of the younger generation in particular is necessary for the development of a future, knowledge-based bioeconomy. However, the survey revealed that the generation younger than 29 is not very active in urban gardening. This group, often referred to as 'digital natives', may be attracted through the app interface and the smart gardening guide. The terrabioponic garden allows food self-production in a digital and 'playful' way. Given that the well-known Facebook game 'FarmVille' has been installed by over 700 million people worldwide [53], there is a large potential for technophile people to start 'playing' FarmVille in real.

In addition, the cluster analysis revealed that more males than females are interested in modern cultivation methods and technologies including vertical gardens, hydroponics and aquaponics, which apply automated irrigation, sensor control and technological setups [1]. Therefore, the perspective of using modern technologies to build and control a biological (garden) system may encourage more males to take up urban gardening.

Automation also has the advantage of making gardening less time-demanding. The terrabioponic smart gardens require maintenance about once a week to feed the compost worms with a defined amount of organic waste (depending on the size of the growing area) and refill the water tank (if not attached to a tap or a drainpipe from the roof). This lowers the entry point for gardening by reducing time-consuming activities such as regular watering and fertilization.

The space-efficient, smart gardens with an attractive design are also deemed suitable for canteens and restaurants. Fresh food ingredients can be produced directly where these are prepared and consumed. Organic kitchen wastes can additionally be recycled into vegetables and herbs. This value proposition may also be attractive to companies and institutions as it emphasizes their sustainability thinking.

Utilizing modern technology to grow food in urban areas can therefore be an effective practical tool to make urban gardening attractive to societal groups other than those identified in the survey (Figure 14). Terrabioponic smart gardens make natural matter cycles visible and tangible. Urban citizens experience natural resource cycles through a circular garden system based on growth and decomposition. Guided by the smartphone app, the gardeners obtain new knowledge that can stimulate the understanding and appreciation of natural resource cycles (Figure 14). This production method promotes environmental (natural resource cycles), social (effort/labor of crop cultivation) and economic (value of the produce) values. These values create an awareness of agricultural food production and in turn alter consumer behavior towards more sustainable (regional, seasonal, organic, fresh) food purchasing decisions. Hence, urban gardening can alter the consumer behavior of various societal groups in an environmentally sound way, facilitating the societal transition towards a bioeconomy.

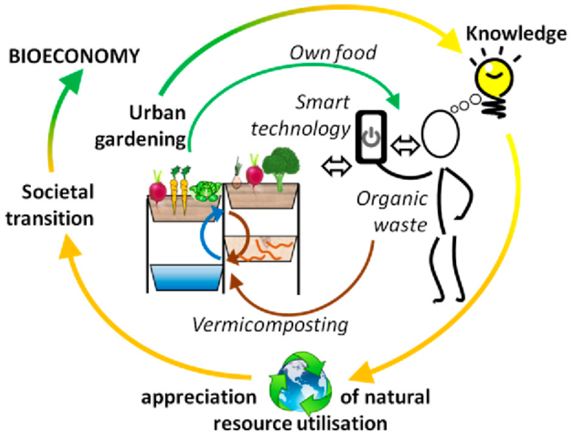


Figure 14. Resource cycles and socio-technical interactions of the terrabioponic smart-garden systems (vegetable and resource symbols from [54]).

5. Conclusions

This study explored the motivations for urban gardening in Germany, characterized the participants in terms of demographic factors, production methods and technologies used and analyzed the impacts of urban gardening on consumer behavior. First, the aims and mission/vision statements on the project websites were explored; subsequently an online survey was sent to the project participants. This approach was limited by the fact that not all urban gardeners could be reached, as the projects included in the study are only those with a website. Secondly, contact with the project participants could only be established via the project contact persons, who were asked to forward the link to the survey. Further research might benefit from face-to-face interviews at the project sites to reach all subgroups of gardeners, including those without email access and non-German speakers. In addition, the link between urban gardening and the development of the bioeconomy conceptualized here, needs be investigated in more detail, for example by exploring the interest and/or activities of urban gardeners in other initiatives such as the renewable energy transition, clean mobility, biobased (fossil-free) products, the sharing economy etc. Nevertheless, 657 project websites were screened and 380 urban gardeners surveyed in this study, such that the results can be considered reliable.

The socio-ecological motivations to live a sustainable lifestyle based on sustainable and healthy nutrition form the backbone of urban gardening in Germany. These motivations influence the consumer behavior of the participants: since taking part in gardening projects, they purchase more seasonally, regionally and organically produced food. The projects create social communities and promote mutual learning by connecting people with diverse cultural identities, viewpoints, backgrounds and lifestyles. This renders urban gardens transformative spaces that drive the public discourse on the sustainability and future viability of agricultural production, food value chains and consumer behavior, including their fatal impacts on biodiversity, natural ecosystems and the climate. This coincides with the main motivations for the development of a bioeconomy. Through its multiple functions and a strong collective capacity, urban gardening can trigger societal change towards a knowledge-based bioeconomy, which goes far beyond providing sustainably produced biomass, especially food [55]. Consequently, urban gardening activities offer great potential for the bottom-up fostering of the societal transition towards a bioeconomy and provide the social counterpart to the techno-economically driven bioeconomy policies advocated top-down by political and scientific institutions.

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4. Bridging the Gap between Biofuels and Biodiversity through Monetizing Environmental Services of Miscanthus Cultivation

This chapter explored, assessed and monetized environmental services in an agricultural production system in order to investigate the potential of this approach for increasing agricultural sustainability. Further, the conceptual case study about the sustainable supply of miscanthus biomass for a large-scale isobutanol biorefinery in Germany derives recommendations for the sustainable intensification of agricultural production.

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Bridging the Gap Between Biofuels and Biodiversity Through Monetizing Environmental Services of *Miscanthus* Cultivation

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Key Points:
- Environmental services of the perennial lignocellulosic crop *Miscanthus* were monetized for marginal agricultural land in Germany
- Monetary value of *Miscanthus* cultivation accounts for 1,200–4,183 € a^{-1}, three times higher than the value of the raw material for biofuel
- Monetizing environmental services bridges the gap between biofuels and biodiversity by promoting the use of second generation biofuels

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(continued)

Abstract Carbon neutrality in the transport sector is a key challenge for the growing bioeconomy as the share of biofuels has stagnated over the past decade. This can be attributed to basic economics and a lack of a robust market for these technologies. Consequently, more sustainable biomass supply concepts are required that reduce negative impacts on the environment and at the same time promote environmental services for sustainable agricultural cropping systems including erosion prevention, soil fertility improvement, greenhouse gas mitigation, and carbon sequestration. One promising concept is the cultivation of perennial biomass crops such as *Miscanthus* (*Miscanthus* Andersson) as biofuel feedstock. In this study, the multiple environmental services provided by *Miscanthus* are first explored and subsequently monetized. Then the integration of *Miscanthus* cultivation for biomass production into European agricultural systems is assessed. One hectare of *Miscanthus* provides society with environmental services to a value of 1,200 to 4,183 € a^{-1}. These services are even more pronounced when cultivation takes place on marginal agricultural land. The integration of *Miscanthus* into existing agricultural practices aids both conservation and further optimization of socio-economic welfare and landscape diversification. As these environmental services are more beneficial to the public than the *Miscanthus* farmers, subsidies are required to close the gap between biofuels and biodiversity that are calculated based on the provision of environmental services. Similar approaches to that developed in this study may be suitable for the implementation of other biomass cropping systems and therefore help foster the transition to a bioeconomy.

Plain Language Summary The transition to a nonfossil transport sector is one of the most difficult and at the same time crucial challenges of the growing bioeconomy. In order to provide enough sustainably sourced biomass for biofuel production, a vast range of requirements need to be fulfilled—first and foremost the use of marginal agricultural land under low-input conditions. Only in this way is it possible to avoid land use conflicts with food crop cultivation and biodiversity conservation. However, the utilization of marginal agricultural land often entails economic disadvantages for farmers. These financial losses should be compensated for by the public sector, as long as the cropping system provides environmental services such as groundwater protection, climate regulation, moderation of extreme weather events, and habitat functions. Monetizing the environmental services using concrete examples is still uncharted scientific territory; existing promotion concepts must be assessed as underdeveloped.

1. Introduction

Biofuel development is currently not on track (Le Feuvre, 2020). Production growth rates in the United States (1%) and Europe (0.5%) have fallen far behind the desired growth rates of 6% and 8%, respectively, set to reach the envisioned share of 10% biofuels in the transport sector by 2030 (International Energy Agency, 2019). The IPCC special report *Global warming of 1.5°C* (IPCC, 2018) points out that both electricity (e.g., solar-based) and biofuels (e.g., agriculture-based) are major drivers of the decarbonization of the transport sector.

Paulino et al. (2018) evaluated these two key technologies in a life-cycle assessment (LCA) against the two fossil-fuel-based alternatives compressed natural gas and diesel. Overall, electricity and biofuels lead to the highest reduction of climate change impacts at 43% and 46%, respectively. However, the LCA also

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revealed the disadvantages of biofuels and electricity. Electric vehicles lead to an increase in the impact categories human toxicity (about +75% cancer effects/about +200% noncancer effects), ionizing radiation human health (about +200%), freshwater eutrophication (about +400%), and water resource depletion (about +400%) (Paulino et al., 2018). Biofuels perform more favorably in all these categories but put pressure on ecosystems and associated functions in the following impact categories: acidification (about +90%), terrestrial and marine eutrophication (about +160% and +315%, respectively), and in particular land use (about +760%). Nevertheless, biofuels may still outperform fossil fuels in many impact categories other than climate change, provided that perennial C4 grasses are chosen to provide the biomass and are grown according to good agricultural practice (Kiesel, Wagner, & Lewandowski, 2017). Ultimately, biofuels perform least favorably compared to electric transportation in the impact categories related to the agricultural production of the biomass. Agriculture, forestry, and other types of land use create 23% of global human CO_2 emissions (IPCC, 2019). With more biomass being required for biofuels however, the food-agriculture-environment trilemma is likely to worsen (Araújo et al., 2017; Tilman et al., 2009). Agricultural land is limited and about 33% to 50% is already being degraded (Saturday, 2018; Wu et al., 2019). Agricultural production however is increasingly needed for food, feed, fiber, and fuel production for a developing bioeconomy, and also due to the growing world population and changing diets (Calicioglu et al., 2019; Tripathi et al., 2019). At the same time, the pressure of agricultural production is a major driver of the sixth global mass extinction (Barnosky et al., 2011; Ceballos et al., 2017; Ceballos & Ehrlich, 2018; Elshout et al., 2019; Isbell et al., 2017). Examining this trilemma (Tilman et al., 2009) from a value-chain perspective reveals options to turn it into multiple opportunities for the development of a sustainable bioeconomy (Lewandowski, 2016). One finding is that the production of biofuels should primarily rely on residues and organic wastes from agriculture and forestry, including the respective processing industries (Von Cossel, Wagner, et al., 2019). If dedicated biomass crops are utilized as feedstock for biofuel production, these need to provide a high yield potential and additional environmental benefits (Carlsson et al., 2017; Gelfand et al., 2013; Mishra et al., 2019; Valentine et al., 2012; Von Cossel, Lewandowski, et al., 2019; Von Cossel, Wagner, et al., 2019; Wagner et al., 2019). In addition, biomass crops should be grown on marginal agricultural land, where food production is compromised by adverse climatic, geographical, geological, or economic factors (Carlsson et al., 2017; Fernando et al., 2015, 2018; Galatsidas et al., 2018; Gelfand et al., 2013; Gopalakrishnan et al., 2011; Lask et al., 2019; Nabel et al., 2018; Von Cossel, Lewandowski, et al., 2019; Wagner et al., 2019; Xue et al., 2016). Perennial biomass crops have distinct advantages on above- and below-ground biodiversity (Bellamy et al., 2009; Williams & Feest, 2019), soil fertility, groundwater protection (Ferrarini et al., 2017; Mishra et al., 2019), climate change mitigation (Clifton-Brown et al., 2017; Emmerling & Pude, 2017; McCalmont et al., 2017), and carbon sequestration (Bui et al., 2018; Canadell & Schulze, 2014). Hence the production of perennial crops on marginal agricultural land carries the potential to restore degraded agricultural lands, which, at a later stage, can (again) become attractive for food production (Barbosa et al., 2015, 2018; Fiorentino et al., 2018; Pogrzeba et al., 2019). Finally, the fuel produced and the technology used need to be state of the art. Here one very promising solution is the production of isobutanol instead of ethanol (Boock et al., 2019).

Over the past decade, there has been increasing interest in the production of isobutanol (Boock et al., 2019; Brosse et al., 2012; Ezeji & Blaschek, 2010; Tollefson, 2008) because of its superior fuel properties compared to ethanol: (i) high energy density of 85% of standard petrol mix (ethanol 66%); (ii) blending with petrol is possible at any ratio; (iii) no corrosion of engines and pipelines due to its low absorption of water from air; and (iv) high octane levels, leading to less knocking in engines while increasing efficiency (Boock et al., 2019; Cai et al., 2018; Del Campo et al., 2017, 2018; Tollefson, 2008). Isobutanol is produced by pretreating herbaceous, cellulosic biomass with acids and enzymes. There are various pretreatment options available (Cai et al., 2018) that release monomeric sugars to be further utilized by microorganisms in biorefineries to produce isobutanol (Cai et al., 2018).

Currently, large-scale isobutanol production (Ezeji & Blaschek, 2010) is close to market entrance, because Gevo Inc. (USA) signed a construction license agreement with Praj Industries Ltd. (India) in 2019 to commercialize the production of renewable isobutanol. The transport fuel will be produced using various feedstocks from sugar production (sugarcane/sugar beet juice, syrup, molasses), annual crops like cassava, rice, wheat, sorghum, and agricultural residues including rice and wheat straw, corn stover, cotton stalks, and empty fruit bunches (BiofuelsDigest, 2019).

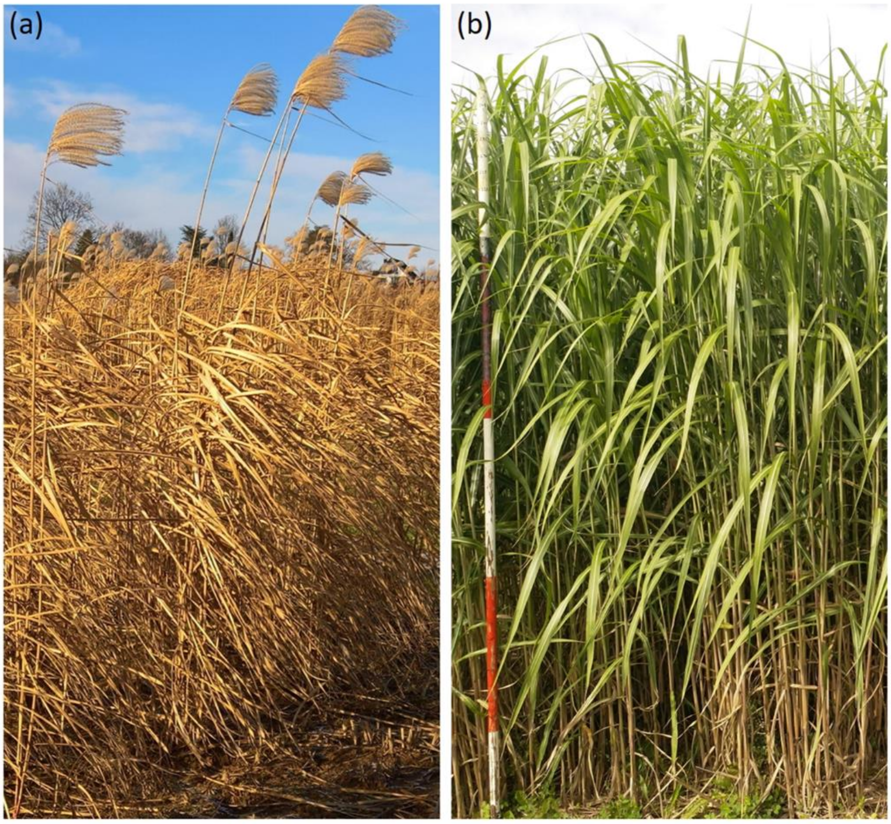

Figure 1. A 1.5-year-old (a) and a 5-year-old (b) field trial with *Miscanthus* × *giganteus* (Greef et Deuter) in southwest Germany. The pictures were taken in December 2017 (a) and August 2019, respectively.

This large feedstock base offers ample options for the production of isobutanol, but ensuring sustainable production requires multiple economic, environmental and social aspects to be considered (Von Cossel, Wagner, et al., 2019). Of particular importance is the avoidance of direct competition with food production. This renders cassava, rice, wheat, and sorghum somewhat unsuitable feedstocks (Tilman et al., 2009).

Today, *Miscanthus* (*Miscanthus* Andersson) is considered one of the most promising biomass crops for the development of a social-ecologically sound bioeconomy (European Commission, 2018c; FNR, 2018; Galatsidas et al., 2018; van der Weijde et al., 2017). *Miscanthus* originates from East Asia (Greef & Deuter, 1993) and grows under various environmental conditions in Europe and North America (Lewandowski et al., 2003). It is a perennial, rhizomatous C4 grass with a high biomass production potential of up to 40 Mg dry matter (DM) ha^{-1} a^{-1} in Europe (Anderson et al., 2011; Brosse et al., 2012), provided that adequate growth requirements (Ramirez-Almeyda et al., 2017) and cultivation techniques (Ramirez-Almeyda et al., 2017) are met. The perennial production cycle and crop management for *Miscanthus* were thoroughly described (Anderson et al., 2011; Brosse et al., 2012). *Miscanthus* biomass is suitable for a number of conversion and utilization routes: combustion (Iqbal & Lewandowski, 2016; Kiesel, Nunn, et al., 2017; Lewandowski et al., 2000; van der Weijde et al., 2017), bioethanol production (Cosentino et al., 2008; Koçar & Civaş, 2013; Scordia et al., 2013; Sørensen et al., 2008), and biorefining (GRACE, 2019), with combustion for energy and heat generation currently being the main utilization pathway (Iqbal et al., 2017). There are various genotypes of *Miscanthus* under investigation (Clifton-Brown & Lewandowski, 2002; Clifton-Brown et al., 2001, 2010; Greef & Deuter, 1993; Iqbal et al., 2017), with the hybrid *Miscanthus* × *giganteus* (Greef et Deuter) (Figure 1) being most commonly used (Anderson et al., 2011; Christian et al., 2008; Clifton-Brown et al., 2001, 2017; Iqbal & Lewandowski, 2016; Lewandowski et al., 2003).

The applications biogas production (Baute et al., 2018; Kiesel & Lewandowski, 2017; Mangold et al., 2019; Mangold et al., 2019; Ruf & Emmerling, 2017; Schmidt et al., 2018; Von Cossel et al., 2018; Wagner et al., 2019; Wahid et al., 2015) and animal bedding material (e.g., for chickens, horses, and cows) (Kasimati et al., 2015; Rauscher & Lewandowski, 2016; Renkema et al., 2016; Van Weyenberg et al., 2015) have also been recently put into practice (Van Weyenberg et al., 2015). However, the large potential of *Miscanthus* is not reflected in the small cultivation area of about 20,000 ha in Europe (Lewandowski, 2016). Reasons for this include a lack of knowledge of this new crop among farmers, accompanied by uncertainties about the financial returns of its cultivation due to the young, still evolving market and the currently higher revenues for other (annual) energy crops (Sherrington et al., 2008).

When considering the cultivation of *Miscanthus* on marginal agricultural land, its economic performance and the yield level are both crucial (Clifton-Brown et al., 2001; Gopalakrishnan et al., 2011; Ramirez-Almeyda et al., 2017). To be economically viable for biogas production, *Miscanthus* should yield at least 11 Mg DM ha^{-1} on marginal agricultural land (Wagner et al., 2019). Here it is particularly important to consider biophysical, climatic, geomorphologic, and economic marginality factors (Von Cossel, Lewandowski, et al., 2019). The later include, for instance, field-farm distances as well as the size and the shape of the cultivation areas (Winkler et al., 2020).

To encourage farmers to actually grow *Miscanthus* and improve economic performance, Sherrington et al. (2008) and Emmerling and Pude (2017) proposed subsidies as an appropriate measure to facilitate *Miscanthus* market development (Sherrington et al., 2008). A further option could be paying *Miscanthus* growers for the environmental services provided to society, as in particular the perennial nature of the grass provides various ecosystem services such as erosion mitigation (Cosentino et al., 2015), greenhouse gas mitigation (Clifton-Brown et al., 2007; Hastings et al., 2017; Kiesel, Wagner, et al. 2017; Wagner et al., 2019), soil fertility improvement (Bourgeois et al., 2015; Emmerling, 2014; Felten & Emmerling, 2011; Ruf et al., 2017), groundwater protection (Christian & Riche, 1998; Clifton-Brown & Lewandowski, 2000; Ferrarini et al., 2017; Lewandowski & Schmidt, 2006; McIsaac et al., 2010; Monti et al., 2019; VanLoocke et al., 2012), and carbon sequestration (Borzêcka-Walker et al., 2008; Dondini et al., 2009; Felten & Emmerling, 2012; Nakajima et al., 2018). For these reasons, *Miscanthus* was approved as a greening measure in Europe in January 2018 (European Commission, 2018b). This measure is a first step to lowering farmers' reluctance to cultivate *Miscanthus* on marginal agricultural land in face of the associated risks (lower yield, uncertain establishment success etc.). This is because farms are obliged by law to apply greening measures on at least 5% of their farmland and, as it produces a good biomass yield, *Miscanthus* (together with cup plant) is one of the few greening measures that can be beneficial for the farmer. As yet however, there is no remuneration model that takes into account the ecosystem services mentioned above, for example in the form of a "common goods bonus" (Grethe et al., 2018; Neumann et al., 2017). So far, no studies have analyzed how the monetary value (as the sum of direct market pricing, avoidance costs, factor valuation, contingent valuation, and benefit transfer) of the ecosystem services provided by *Miscanthus* cultivation can be assessed.

Thus, the aims of this study are (i) the exploration and monetization of environmental services (external benefits) of *Miscanthus* cultivation based on a literature review and (ii) an analysis of these services with respect to the benefits provided for specific types of marginal agricultural land in order to develop marginal agricultural land low-input systems (MALLIS) (Biala et al., 2007; Ramirez-Almeyda et al., 2017; Von Cossel, Lewandowski, et al., 2019) in Europe. This study provides a value-chain approach to the decarbonization of the transport sector in Europe by making *Miscanthus* cultivation more attractive for use as a biofuel feedstock and at the same time enhancing ecosystem functions.

2. Materials and Methods

First, the economic, ecologic, and social impacts of *Miscanthus* cultivation are explored and assessed employing "The Economics of Ecosystems and Biodiversity" (TEEB) approach, advocated by the United Nations Environmental Programme (UNEP) (TEEB, 2013). This approach allows an internalization of associated external costs, in particular adverse impacts on the environment, in agricultural biomass production as well as a quantification of benefits, primarily environmental services, in economic terms (TEEB, 2013). Following the TEEB approach, the ecosystem services provided by *Miscanthus* cultivation are valorized in monetary terms in order to highlight the value of ecosystem services with respect to agricultural policy development (TEEB, 2013).

The elicitation of services applicable to *Miscanthus* cultivation is based on the Common International Classification of Ecosystem Services (Haines-Young & Potschin-Young, 2018). When attempting to valorize ecosystem services in agricultural landscapes, it is important to distinguish between services provided by natural ecosystems and services provided by cultivated landscapes where humans use ecosystem services, for example, pollination and water for the production of resources, products, and services (De Groot et al., 2002). According to Matzdorf et al. (2010), landscape-level services provided by *Miscanthus* cultivation should be referred to as "environmental services," and this term is used in the following sections. These environmental services also include the conscious avoidance of permitted inputs and practices in order to reduce negative external effects, when the owner of the land area (in this case) is also the producer of the effects (Matzdorf et al., 2010). The cultivation of low-input perennial crops on agricultural lands has multiple environmental, social, and economic benefits, especially when compared to high-input annual crops (Kiesel, Wagner, et al., 2017; Wagner et al., 2019) such as maize (*Zea mays* L.), currently the main bioenergy crop in Germany (FNR, 2018).

The second step was the summarizing of recent developments in *Miscanthus* research and production in Europe using the literature database "Scopus" (Elsevier B.V., Amsterdam, Netherlands) and "Google Scholar" (Google Inc., CA, USA). From this, cultivation requirements, agricultural production steps and utilization options were derived.

Subsequently, suitable agricultural areas for *Miscanthus* production in Europe were identified, where it would not compete with food production due to biophysical constraints (Elbersen et al., 2018; Terres et al., 2014; Van Orshoven et al., 2012, 2014; Von Cossel, Lewandowski, et al., 2019). In this study, the major constraints were selected based on the findings of Von Cossel, Lewandowski, et al. (2019). The most suitable areas for *Miscanthus* cultivation on marginal areas were identified using the DSS tool of the EU-funded project MAGIC (MAGIC, 2019), providing a spatial distribution of the major types of marginal agricultural land in Europe (MAGIC DSS, 2019). For this conceptual study, the fictional case study area of Brandenburg (Germany) was chosen. The selection of this area was based on the following criteria: the large-scale aggregation of marginal areas (Figure 2) with sandy soil, low field capacity, and low precipitation (MAGIC DSS, 2019); its central geographic position in Europe; its favorable distribution infrastructure including railways as well as crude oil and product pipelines (Information Technology Associates, 2017); and because it is one of the major agricultural states in Germany (MLUL, 2018a). All these criteria qualify this area as a suitable location for the potential large-scale production of *Miscanthus* biomass and the economically feasible operation of an isobutanol biorefinery.

Finally, the environmental services of *Miscanthus* cultivation are discussed with respect to different design and implementation approaches of *Miscanthus*-based MALLIS for the feedstock production in the emerging isobutanol industry.

3. Valorization of Ecosystem Services Provided by *Miscanthus* Cultivation

The valorization of environmental and social services provided by the perennial crop *Miscanthus* based on the UNEP's TEEB approach (De Groot et al., 2012; De Groot et al., 2002) reveals an economic value of 1,200 to 4,183 € ha^{-1} a^{-1} for the case study area of Brandenburg (Figure 2). The range is due to both site-specific conditions and large variations in the selling price of *Miscanthus* biomass (65 to 95 € $Mg^{-1}DM^{-1}$) at assumed yield levels of 15 and 25 Mg DM ha^{-1} a^{-1}. Table 1 provides an overview of provisioning, regulating, maintaining and cultural services assessed in this study on an annual, per hectare basis. The following sections describe the valuation methods for the different services applicable to *Miscanthus*.

3.1. Provisioning Services

3.1.1. Provision of Raw Material

The currently most important ecosystem service provided by *Miscanthus* cultivation is the supply of biomass for multiple utilization options including isobutanol production, combustion, animal bedding, anaerobic digestion, and building materials (Anderson et al., 2011) as well as for ornamental use in floristry.

Miscanthus for isobutanol production is harvested using a maize chopper with subsequent baling in March at yield levels of 15 to 25 Mg dry matter (Winkler et al., 2020). The annual production costs for a 10-ha field

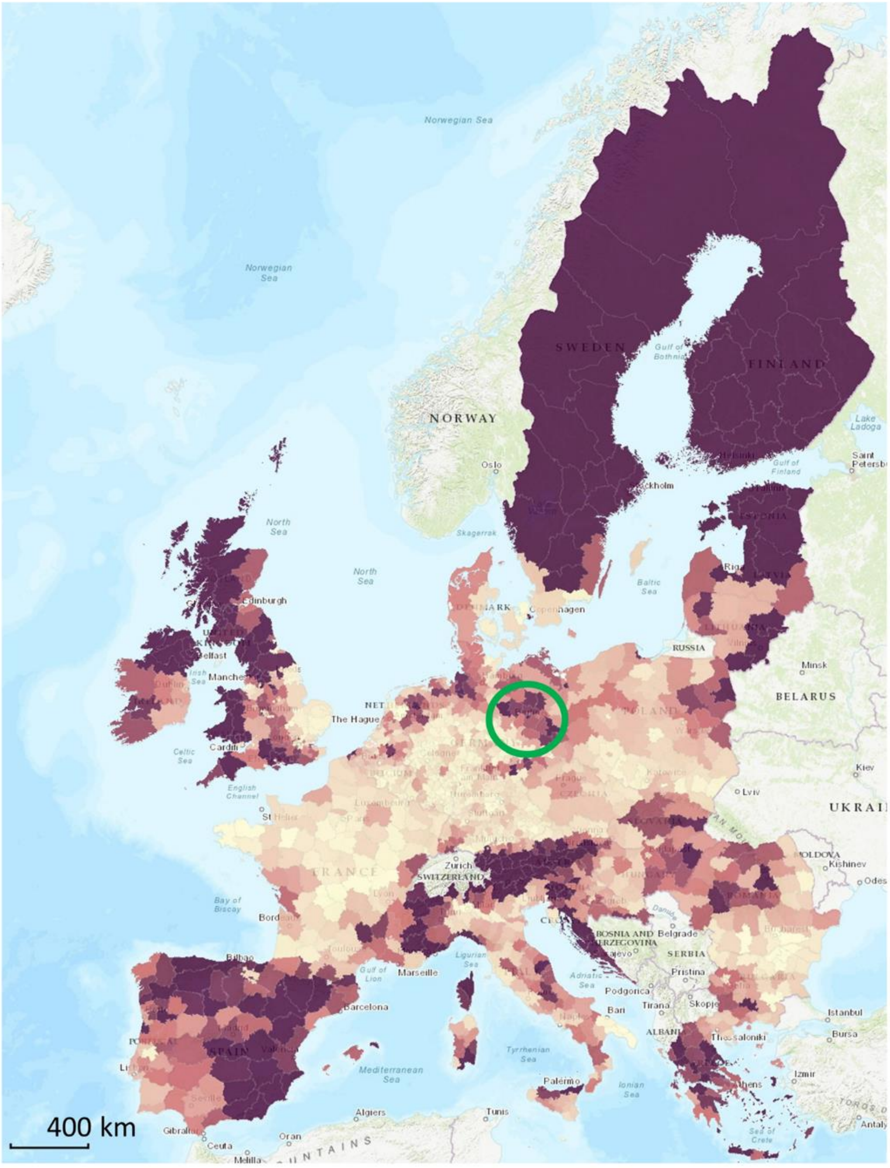

Figure 2. Spatial distribution of marginal agricultural land in Europe (EU-27) (adapted from DSS) 143. The darker the color, the higher the proportion of total agricultural land (not total land) of marginal agricultural land per region. The green circle shows the region of Brandenburg (Germany).

amount to 783 € (15 Mg yield level) and 1,080 € (25 Mg yield level). The selling price for the baled biomass is between 65 and 95 € Mg^{-1}. This results in attainable gross margins of between 192 € ha^{-1} a^{-1} (15 Mg DM ha^{-1} a^{-1}; selling price 65 € Mg^{-1} DM^{-1}) and 1,295 € ha^{-1} a^{-1} (25 Mg DM ha^{-1} a^{-1}; selling price 95 € Mg^{-1} DM^{-1}).

3.1.2. Provision of Genetic Resources

Miscanthus has a great genetic diversity, allowing the plant to be cultivated in a wide range of soils and climates. However, *Miscanthus* breeding is still in its infancy (Vermerris, 2008). The sterile hybrid *Miscanthus × giganteus* (Greef et Deuter) is currently the only genotype grown for commercial utilization. Consequently, there is untapped potential for further breeding of other genotypes of this high-yielding biomass crop with specific features adapted to local climatic and soil conditions.

At present however, there is very limited knowledge on the materials and products that biodiversity and the genetic resource base can provide to human society. As such, these services belong to the most difficult

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Table 1
Assessed Annual Monetary Value of Ecosystem Services Provided by 1 ha Miscanthus (Various Genotypes of Similar Morphology) on Marginal Agricultural Land Areas in the Federal State of Brandenburg, Germany

Ecosystem service categories	Description	Valuation method[a]	Value (€ ha^{-1} a^{-1})	References
Provisioning services				
Raw material	Feedstock for isobutanol production	1	192 to 1,295	(Winkler et al., 2020)
Genetic resources	Crop genetic resources	4	18	(Brenner et al., 2000; Costanza et al., 1997)
Fresh water/groundwater	Provision of drinking water through sediment passage	1	0 to 111	(Bannik et al., 2008; BDEW, 2017; BfG, 2019; LBGR, 2019; MLUL, 2018a; Schmidt et al., 2003)
N_2 fixation	Substitution of N fertilizer	1	0 to 65	(Beale & Long, 1997; Keymer & Kent, 2014; Liu & Ludewig, 2019)
Ornamental resources	Flowers and leaves for decoration[b]	1	0 to 33	(Ausbildung.de, 2019; Der-renner.com, 2019)
Regulating services				
Air quality regulation	CO_2 conversion to O_2; O_3, SO_x	5	64	(Tianhong et al., 2010; Van der Ploeg & de Groot, 2010)
Climate regulation	CO_2 sequestration	1	217	(EEX, 2019; McCalmont et al., 2017)
	CO_2 substitution	1	514	(Brosse et al., 2012; Cai et al., 2018; EEX, 2019)
Waste treatment	Reduction of N leaching into environment	2	30	(Christian & Riche, 1998; Matzdorf et al., 2010; McIsaac et al., 2010)
Improvement of soil fertility	Yield increase of crops following *Miscanthus*	1	23	(Clifton-Brown et al., 2017; LOGISTEC, 2015; Markets Insider, 2019; PGRO, 2019)
Nutrient cycling	N, P, K recirculation in plant-soil system	1	65	(Agrarheute.com, 2019; Masters et al., 2016; Ruf et al., 2017)
Erosion prevention	Erosion decrease	2	0 to 43	(Van der Ploeg & de Groot, 2010)
Moderation of extreme events	Flood plain management[c]	1	0 to 771	(Grossmann et al., 2010; McCalmont et al., 2017; Rosolova et al., 2010)
Habitat services				
Pollination and biocontrol	Pollination of crops Biocontrol agents for crop pests and diseases	5	50	(Brenner Guillermo, 2007; Fernando et al., 2015)
Cultural services				
Aesthetic information	Close-to-nature flood plain planting	4	0 to 857	(Grossmann et al., 2010)
Recreation and tourism	Local recreation value of agricultural landscape	4	27	(Alvarez-Farizo, 1999; Bergstrom et al., 1985; Brenner Guillermo, 2007)
Estimated annual monetary value of environmental services provided by 1 ha *Miscanthus*			1,200 to 4,183	

Note: Values with ranges are very site-specific.
[a]Valuation methods: 1—direct market pricing, 2—avoidance costs, 3—factor valuation, 4—contingent valuation, 5—benefit transfer. [b]It is assumed that only 1% of the area is used for this service. [c]This service only applies to flood-prone areas and has to be subtracted for areas without the risk of flooding.

category for valorization (Brenner Guillermo, 2007). This also applies to the perennial grass *Miscanthus* with its high, but untapped genetic potential. Due to the lack of specific data, the average value of 17.81 € ha^{-1} a^{-1} (20 $ ha^{-1} a^{-1}) for grasslands was assumed here, based on a contingent valuation (Costanza et al., 1997) used by Brenner-Guillermo (Brenner Guillermo, 2007) for grasslands in Spain.

3.1.3. Provision of Drinking Water

The soil below a low-input *Miscanthus* field has the ability to filter precipitation water, especially from the second year onwards when no pesticides are applied. Water filtration through soil removes substantial amounts of particles, pathogens, and organic and inorganic chemicals by sediment passage (Schmidt et al., 2003). This natural filtration has been utilized for drinking water for a long time in Germany, where 61.5% of drinking water is sourced from groundwater (BDEW, 2017). Sediment passage can substitute, simplify, or support other water treatment and purification steps and thus reduce drinking water filtration costs. For example, reduced dissolved organic carbon load rates increase the lifetime of carbon filters, thus saving replacement costs (Schmidt et al., 2003). Consequently, perennial, low-input crops such as *Miscanthus* appear a suitable soil cover to enhance water purification through sediment passage.

In the Brandenburg case study area, 86% of the soils have a high sand and loam content (MLUL, 2018a) and a high sorption capacity for heavy metals (LBGR, 2019). They are thus considered suitable soils for sediment passage.

The annual average precipitation in Brandenburg is about 560 mm (MLUL, 2018a) with the climatic water balance being only positive during winter, when 158 mm or 1,580 m^3 ha^{-1} infiltrate in the soil (BfG, 2019). About 40% of that water moves into surface water bodies and 60% into groundwater (Bannik et al., 2008). Consequently, 94 mm or 938.5 m^3 ha^{-1} flow into groundwater and are filtrated through the soil. Filtration accounts for 9.2% of the drinking water production costs (Bodensee-Wasserversorgung, 2019). As sediment passage is typically not the only type of filtration used for drinking water (Schmidt et al., 2003), a conservative assumption of a 10% reduction in filtration costs is taken for the valorization of this natural prefiltration. The end-consumer price of drinking water in Brandenburg of 1.43 € m^{-3} is used (Brawag.de, 2019). In this study, the provisioning service of drinking water filtration through *Miscanthus* cultivation is estimated as reducing water filtration costs by 0.118 € m^{-3} or 111.12 € ha^{-1} a^{-1}.

3.1.4. Provision of N_2 Fixation

In a study on N_2 fixation in the rhizosphere of *Miscanthus* roots, it was found that 16% of the N content in the whole plant of *Miscanthus* (1 year old plants) can be absorbed by N_2 fixation (Keymer & Kent, 2014). Even though this number probably depends strongly on site conditions and agricultural management (e.g., N fertilization) (Liu & Ludewig, 2019), it is assumed that 16% of *Miscanthus*' annual N demand can be covered by N_2 fixation, which would correspond to a partial substitution of synthetic N fertilizers. Since the N quantity within fully developed *Miscanthus* stands (with an average annual dry matter yield of 25 Mg ha^{-1}) is on average 31 g m^{-2} during the main vegetation phase (Beale & Long, 1997), this would result in an N fertilizer substitution of 50 kg ha^{-1} a^{-1}. And with a market price of urea of 341 € Mg^{-1} (46% N), 64.87 € ha^{-1} a^{-1} would be provided (Table 1). Due to the uncertainties of the location influences and the transferability of the value (16% N) to fully developed *Miscanthus*, a minimum value of zero is given here.

3.1.5. Provision of Ornamental Resources

A number of *Miscanthus* genotypes are popular ornamental plants for home gardens, landscaping and also in floristry, where the flowers and leaves are used in floral bouquets (Der-renner.com, 2019). For *Miscanthus* × *giganteus* (Greef et Deuter), this utilization option only applies to the use of leaves, because fully established *Miscanthus* × *giganteus* (Greef et Deuter) does not produce flowers under normal growth conditions (Bufe & Korevaar, 2018) (Figure 1b). The provision of leaves was valorized here based on the authors' own assessment of production costs. Leaves are harvested in autumn, with a bunch sold to end-customers for 2.90 € (Der-renner.com, 2019). A *Miscanthus* field planted with 10,000 plants per hectare results in a potential value of 522,000 € ha^{-1} with 18 productive years over a 20-year cultivation period. The total production and harvest costs, including establishment, would amount to 160,027 €. For floristic use, the leaves need to be harvested by hand. For hand harvest it was assumed that one person cuts the plants, one person sheaves them and a third person drives a tractor with a trailer. Assuming a total cutting and sheaving time of 5 min per *Miscanthus* plant, the total harvest would take 6 weeks. The average florist wage in Germany is currently about 1,800 € per month (Ausbildung.de, 2019). Personnel costs for harvest would consequently amount to about 8,100 €, while the cultivation costs for a farmer are 125.49 €.

The annual attainable gross margin would be 18,099 € ha^{-1}. Factoring in 10% losses during harvest, transport, storage and selling would reduce this to 16,289 € ha^{-1} a^{-1}. Such large amounts of *Miscanthus* need to be sold to wholesalers, who take have an approximate share of 80% of end-customer prices. Hence, the estimated theoretical value of the ornamental resource provision is 3,258 € ha^{-1} a^{-1}. However, it is very unlikely that it would be possible to use an entire hectare for this purpose, as the market is very limited. Therefore, it is assumed that per hectare only 1% is used for the provision of ornamental resources. Consequently, a more realistic value for this category is about 33 € ha^{-1} a^{-1}. It should also be considered that this figure very much depends on (i) the size of the distribution area and (ii) how much *Miscanthus* is cultivated in the region. For this reason, it remains unclear how much *Miscanthus* can be sold as an ornamental resource per distribution area. The example given here should therefore be interpreted with caution when upscaling *Miscanthus* cultivation.

3.2. Regulating and Maintaining Services

3.2.1. Air Quality Regulation

Plants are among the most important regulators of the atmospheric and oceanic gas balance and consequently air quality. This ecosystem service includes the CO_2/O_2 balance, the O_3 concentration and the regulation of SO_x levels (Brenner Guillermo, 2007). Tianhong et al. (2010) valorized the gas regulation service provided by cropland in general based on the benefit transfer method and gave a value of 63.69 € ha^{-1} a^{-1}. This value was applied here as a fair approximation of this regulating service.

3.2.2. Climate Regulation

The climate regulation service of 1 ha of *Miscanthus* is calculated based on the CO_2 sequestration in the soil and the CO_2 substitution potential, when using *Miscanthus* as a feedstock for isobutanol production with the aim of substituting fossil petrol.

3.2.2.1. CO_2 Sequestration

Carbon accumulates in the topsoil under *Miscanthus* through leaf fall and dead roots and rhizomes (Clifton-Brown et al., 2007). Leaf fall ranges from 29% to 42% of the total aboveground biomass (Lewandowski et al., 2000). The annual average C accumulation in soils under *Miscanthus* can range between 1.0 and 2.2 Mg C ha^{-1} a^{-1} (McCalmont et al., 2017). Hence, a substantial amount of carbon from the atmosphere is stored in the soil in the form of humus.

For the valorization of this service, the amount of carbon is multiplied by the current price of CO_2 emission certificates of 26.83 € Mg^{-1} $CO_2{}^{-1}$ (EEX, 2019). This gives a value of 216.63 € for the CO_2 stored in the soil each year. Note that this value would be considerably higher if the price of CO_2 emission certificates was set at the level of the consequential costs of one ton of CO_2, that is, approximately 180 € Mg^{-1} $CO_2{}^{-1}$ (UBA, 2018).

3.2.2.2. CO_2 Substitution

The production of isobutanol from *Miscanthus* creates less CO_2 (26 g CO_2-Eq. MJ^{-1}), than the production of fossil petrol (95 g CO_2-Eq. MJ^{-1}) (Cai et al., 2018). For unit conversion from g CO_2-Eq. MJ^{-1} to Mg CO_2-Eq. ha^{-1} a^{-1}, an average heating value of 18.5 MJ kg^{-1} for isobutanol and 43.45 MJ kg^{-1} for fossil petrol (Brosse et al., 2012), and an average *Miscanthus* dry matter yield of 15 Mg DM ha^{-1} a^{-1} is applied. This results in a CO_2 emission saving of 19.1 Mg CO_2-Eq. ha^{-1} a^{-1} for the substitution of fossil petrol by isobutanol.

Multiplying these savings by a CO_2 emission certificate price of 26.83 € Mg^{-1} $CO_2{}^{-1}$ (EEX, 2019) gives the CO_2 saving potential a monetary value of 513.73 € ha^{-1} a^{-1}.

3.2.3. Waste Treatment—Reduced Nutrient Leaching

The reduction of nutrient leaching into the environment is currently a subject of debate in Germany with respect to the implementation of measures to comply with the "EU nitrate directive" (The Nitrates Directive, 1991). This directive aims at preventing the pollution of surface water and groundwater by nitrate from agriculture. In the federal state of Brandenburg, about one third of the surface water bodies are moderately polluted with nitrate, with maize being the most frequently cultivated bioenergy crop in this area (MLUL, 2018a, 2018b).

N fertilization of maize is about 150 kg N ha^{-1} and cultivation period (Herrmann et al., 2014), whereas the N requirement of the perennial crop *Miscanthus* is only about one-third of that amount (52 kg N ha^{-1} a^{-1}).

Consequently, the N leaching potential of *Miscanthus* is considerably lower. McIsaac et al. (2010) found significantly lower nitrate leaching rates under *Miscanthus* (3.0 kg N ha^{-1} a^{-1}) than for a maize–soy bean rotation (40.4 kg N ha^{-1} a^{-1}) (McIsaac et al., 2010). Ammonium losses in *Miscanthus* are less than 1 kg NH_4-N ha^{-1} a^{-1} and thus negligible (Christian & Riche, 1998). This makes *Miscanthus* cultivation a potential measure for the protection of surface and groundwater bodies to comply with the EU nitrate directive.

The savings through the reduced N leaching into the environment are calculated to be in the range of 0.3 to 1.3 € kg^{-1} N^{-1} (Matzdorf et al., 2010). Taking the average value (0.8 € kg^{-1} N^{-1} leached) and the potentially avoided N emissions (37.4 kg ha^{-1} a^{-1}), when cultivating *Miscanthus* instead of maize and soybean results in an economic advantage of 29.92 € ha^{-1} a^{-1}. However, it should be noted that this value would be significantly higher for regions with a higher nitrate load, such as large parts of northern Germany (SMUL, 2019).

3.2.4. Soil Fertility Improvement

The shift towards low-demanding perennial crops with a cultivation period of 10 to 20 years allows the soil to recover from annual, often intensive cropping (Clifton-Brown et al., 2017). Perennial biomass crops such as *Miscanthus* have recently also been proven to function as wind barriers, increasing both the environmental and economic performance of pasture growth (Littlejohn et al., 2019).

Miscanthus cultivation increases soil organic carbon by 0.42 to 3.8 Mg C ha^{-1} a^{-1}, thus improving soil fertility (McCalmont et al., 2017). Regular carbon inputs and the perennial cultivation with almost no soil disturbance improve soil structure, increase water-holding capacity (up to 100 to 150 mm), enhance floral and faunal abundance and diversity, and also reduce water run-off and erosion (Emmerling & Pude, 2017; Kahle et al., 2001; McCalmont et al., 2017). Earthworm community enhancement for example increases bioturbation of the soil and the formation of macro pores, which in turn increase the water infiltration capacity of the soil (Felten & Emmerling, 2011).

These beneficial effects of *Miscanthus* cultivation result in a higher long-term soil fertility (Clifton-Brown et al., 2017), which can potentially increase yields of the follow-on crops. To date however, very few studies have assessed these effects. Dufossé et al. (2014) compared the grain yield of wheat planted after a 20-year *Miscanthus* cultivation and that grown on an adjacent control plot and found no effect: Both sites yielded 9.8 Mg DM ha^{-1}. By contrast, data from the EU project "LogistEC" funded under the 7th Framework Programme indicate yield increases in winter wheat (+45%) and winter bean (+34%) grown after *Miscanthus* removal, compared to a conventional crop rotation where these crops were cultivated after winter wheat and winter bean (LOGISTEC, 2015). Winter wheat yielded 7.4 Mg ha^{-1} after *Miscanthus* removal and 4.1 Mg ha^{-1} after a previous winter wheat season. The same pattern was observed in the subsequent year, where winter bean after winter wheat after *Miscanthus* resulted in a yield of 3.2 Mg ha^{-1}, whereas winter bean following two seasons of winter wheat yielded 2.1 Mg ha^{-1}. However, it should be noted that (i) the higher yield after *Miscanthus* was due to pest infestations in both the winter wheat and the winter bean in the conventional crop rotation, and (ii) cultivation of these two crops on fallow land achieved higher yields than after *Miscanthus* (LOGISTEC, 2015).

Nevertheless, *Miscanthus* cultivation has multiple beneficial effects on soil fertility, which are likely to result in higher yields of the follow-on (annual) crops than in conventional annual crop rotations. Due to the lack of data, the yield increases in winter wheat and winter bean are used here as an estimation for the valorization of soil fertility improvement.

The current market price of wheat is 184.25 € Mg^{-1} (Markets Insider, 2019) and 289.01 € Mg^{-1} for beans (PGRO, 2019). A yield increase of 45% in winter wheat would thus result in an additional revenue of 611.37 € ha^{-1}, while a 34% yield increase in winter bean would create 317.91 € ha^{-1}. For the allocation of this benefit to *Miscanthus* cultivation, the average of these two estimations is divided by 20 years, giving an estimation for the soil fertility improvement of 23.23 € ha^{-1} a^{-1}.

3.2.5. Nutrient Cycling

When harvested after winter, *Miscanthus* is characterized by an efficient water and nutrient utilization (Lewandowski & Schmidt, 2006; Ruf et al., 2017; Yu et al., 2013). Nutrients are relocated at senescence internally via phloem translocation to the rhizomes as well as externally through leaf fall, stubble residues, and harvest losses (Ruf et al., 2017). Considerable amounts of nutrients are recirculated within the cultivation system based on these two pathways.

Nutrient recirculation is an important factor for economic cultivation, as fertilizer rates are reduced. Nutrient recirculation within the cropping system reduces nutrient removal through biomass harvest, thus substantially lowering fertilizer input for the following growth cycle (Yu et al., 2013).

This "service" provided by the perennial nature of *Miscanthus* is valorized by multiplying the amount of relocated nitrogen, phosphorous, and potassium by the current prices for the respective fertilizers (as single nutrient fertilizers). Based on the study of Ruf et al. (2017), direct nutrient translocation to the rhizomes, leaf fall, stubble residues, and harvest losses amount to 65.37 kg N ha^{-1} a^{-1}, 10.31 kg P ha^{-1} a^{-1}, and 16.76 kg K ha^{-1} a^{-1}. The current prices for these plant nutrients are 341 € Mg^{-1} urea, 398 € Mg^{-1} P_2O_5, and 347 € Mg^{-1} K_2O (Agrarheute.com, 2019). Consequently, the nutrients recycled within the cropping systems have an economic value of 48.46 € ha^{-1} a^{-1} for nitrogen, 9.40 € ha^{-1} a^{-1} for phosphorous and 7.01 € ha^{-1} a^{-1} for potassium, which sum up to 64.87 € ha^{-1} a^{-1}.

In addition, indirect nutrient relocation through leaf fall, stubble residues and harvest losses enhance the nutrient contents of the soil-plant system, leading to an improvement in soil fertility (Kahle et al., 2001). A comparison with annual crops shows, for example, that *Miscanthus* removes 49.0% N, 17.4% P, and 31.9% K of the nutrient removed by soy bean and only 3.7% N, 1.8% P, and 1.8% K of the nutrients removed by maize (Masters et al., 2016). Nutrient recirculation within the cropping system is a considerable asset of *Miscanthus* in terms of fertilizer demand and potential nutrient leaching when compared to other major (energy) crops such as maize and soy bean (Masters et al., 2016), as well as in terms of nitrogen use efficiency when compared to reed canary grass and triticale (Lewandowski & Schmidt, 2006).

3.2.6. Erosion Prevention

Soil erosion has the highest impact on crop productivity. The associated water and nutrient losses account for 50% to 75% of the reduced productivity (Pimentel et al., 1995). The permanent soil coverage achieved by perennial crops like *Miscanthus* considerably reduces soil erosion (Jankauskas & Jankauskiene, 2003; Lewandowski, 2016). Jankauskas and Jankauskiene (2003) report that perennial grasses prevent water erosion completely. Strip cultivation with other annual crops, such as cereals and energy crops, can reduce water erosion by 80% up to a gradient of 14° (Dauber & Miyake, 2016; Jankauskas & Jankauskiene, 2003).

The soil erosion reduction through *Miscanthus* is valorized using the TEEB database. The soil erosion avoidance costs of permanent grasslands were assessed by the Belgian Ministry of Agriculture, Nature and Food Quality as having a value of 42.75 € ha^{-1} a^{-1} (Van der Ploeg & de Groot, 2010) and applied here as a fair approximation for the cultivation of *Miscanthus*. This figure is taken as an average value—it would be higher on areas more susceptible to erosion and lower on other less susceptible areas (Table 1)—since it is assumed that distribution of erosion susceptibility is generally very heterogeneous on farmlands.

3.2.7. Moderation of Extreme Events

In addition to the advantageous effects on soil fertility, soil structure improvement, and reduced soil erosion described above, *Miscanthus* cultivation can play an important role in the moderation of extreme weather events. These include droughts, heavy rainfall, and flooding, all of which are expected to increase in both frequency and intensity due to climate change (Samaniego et al., 2018; Teuling, 2018; Von Cossel, Wagner, et al., 2019). While *Miscanthus* is not the best choice for drought-affected sites (Ramirez-Almeyda et al., 2017; Von Cossel, Lewandowski, et al., 2019), it provides many advantages for sites prone to flooding (Barbosa et al., 2015). The improved soil structure through the perennial crop cultivation increases infiltration and storage capacity of the soil by 100 to 150 mm (McCalmont et al., 2017). Higher bioturbation rates through soil biota create higher porosity (Felten & Emmerling, 2011) with beneficial impacts on water infiltration rates and groundwater storage, and the dense crop stands have higher evapotranspiration rates (McCalmont et al., 2017).

Thus, low-input *Miscanthus* fields are a potential agricultural use option for river flood plains. The modeling approach of Rosolova et al. (2010) revealed that *Miscanthus* acts like a "green leaky dam" which slows down the water flow on and upstream of the field and also the flood propagation across the flood plain. Both decrease the flood levels in the area downstream of the field. The model showed the largest effect when the whole flood plain is covered with *Miscanthus* (Rosolova et al., 2010).

The economic value of *Miscanthus* for the moderation of floods is estimated here based on values taken from a case study assessing the economic effects of flood plain management options for the river Elbe in Brandenburg, Germany (Grossmann et al., 2010). One of flood management options ranked highest was the relocation of the dike to create 35,000 ha of flood plain. This option had an overall economic benefit 3.1 times higher than the annual costs of about 18 million €. Covering this area with *Miscanthus* would avoid flood damage to houses, roads, bridges etc. (5 million € a^{-1}), save dike maintenance costs (6 million € a^{-1}), and support other measures introduced to fulfill the EU Water Framework Directive. These include the reduction of nutrient loads by restricting agricultural inputs and improving the cleaning efficiency of sewage plants (16 million € a^{-1}).

Cultivating 35,000 ha of *Miscanthus* on the river Elbe flood plain would create total benefits of 27 million € annually, corresponding to 771.41 € ha^{-1} a^{-1}. This service of course does not apply to areas not prone to floods and is thus omitted for the lower value of the range of total estimated annual monetary value of environmental services provided by 1 ha of *Miscanthus* (Table 1).

3.3. Habitat Services—Pollination and Biocontrol

Although *Miscanthus* does not produce nectar, both young and adult *Miscanthus* stands provide nursery services for pollinators and biocontrol agents. In addition, *Miscanthus* stands form suitable habitats for many forms of wildlife due to the low management intensity (Clifton-Brown et al., 2010; Emmerling & Pude, 2017; Fritz et al., 2009). Over a long period of the year they can replace the function of field trees and shrubs for open land animals like European roe deer (*Capreolus capreolus* Linnaeus, 1758) and brown hare (*Lepus europaeus* Pallas, 1778) (Fritz et al., 2004, S. 200). Deciduous trees and shrubs planted around fields are important wildlife habitats. A study by Pywell et al. (2015) demonstrated that up to 8% of arable fields can be converted into wildlife-friendly habitats in this way, while maintaining or even increasing the yield level of wheat, oilseed rape, and beans. The higher crop productivity through ecological intensification was attributed to habitat creation for flying and epigeal predators of crop pests (e.g., grain aphids), thus enhancing biocontrol and also to the higher abundance of pollinators (esp. important for beans).

Miscanthus stands also provide more nesting space than annual crops like maize. In Germany, eight different bird species were recorded in *Miscanthus* fields including European greenfinch (*Chloris chloris* Linnaeus, 1758), Eurasian sparrow hawk (*Accipiter nisus* Linnaeus, 1758), common quail (*Coturnix coturnix* Linnaeus, 1758), common linnet (*Linaria cannabina* Linnaeus, 1758), and the common buzzard (*Buteo buteo* Linnaeus, 1758) (Bellamy et al., 2009; Fritz et al., 2004).

The abundance of spiders and beetles is also higher in *Miscanthus* stands than in maize and the perennial crop common reed (Fritz et al., 2004). Haughton et al. (2009) reported a higher abundance of butterflies, esp. Satyrinae (Boisduval, 1833), in field margins around *Miscanthus* and short rotation coppices than around arable crops. Soil biota also benefit from the extensive management of *Miscanthus* fields, with an enhanced diversity of earthworm communities and a more balanced species composition (Felten & Emmerling, 2011).

The biodiversity value of *Miscanthus* fields is considered comparable to that of forests, grasslands and annual crops (Fernando et al., 2015). Thus for the valorization of the habitat and nursery services provided by *Miscanthus*, the average of the values listed for these three biomes in the TEEB database is taken (Van der Ploeg & de Groot, 2010). In the database, these values are listed separately for biocontrol and pollination services (Brenner Guillermo, 2007): Temperate forests have the highest pollination value of 353.53 € ha^{-1} a^{-1}, followed by temperate grasslands at 28.28 € ha^{-1} a^{-1} and cultivated land at 17.68 € ha^{-1} a^{-1}. Biocontrol services for the biomes listed above are 4.42, 26.51, and 26.51 € ha^{-1} a^{-1}, respectively. The average of the values for temperate grasslands and cultivated land (49.49 € ha^{-1} a^{-1}) is regarded a fair approximation of the pollination and biocontrol services provided by a *Miscanthus* field.

3.4. Cultural Services

3.4.1. Aesthetic Information

Landscapes also possess inherent aesthetic functions with opportunities for reflection, spiritual and cognitive development as well as an aesthetic experience (Brenner Guillermo, 2007). The use if *Miscanthus* fields as a close-to-nature flood plain allows an approximation of the aesthetic information of *Miscanthus* in the landscape.

Planting this low-input perennial crop with its reed-like appearance in this area, interspersed with typical flood plain trees such as willow and poplar, would be a viable option for a plant community in the riparian buffer of the river Elbe. This 35,000-ha landscape along the river was valorized at a figure of 30 million € a^{-1}, based on a choice experiment assessing the population's willingness to pay for the maintenance of these areas (Grossmann et al., 2010). This results in a total value of 857.14 € ha^{-1} a^{-1} for the aesthetic information of the close-to-nature *Miscanthus*-poplar-willow flood plain. However, since this value is highly dependent on the location of the land, the species composition of the plant community (*Miscanthus*, willow, poplar), the prevailing social attitudes, and the importance of tourism in the region, we therefore also added a minimum value of 0 € for this parameter (Table 1).

3.4.2. Recreation and Tourism

Recreational aspects of landscapes are important for tourism. In Brandenburg, the German Federal Ministry for Rural Development, Environment and Agriculture currently supports the development of new tourist activities of stakeholders along the agricultural value chain, for example, gastronomic activities, direct marketing of local products, and the creation of new products with local identity (MLUL, 2019). In this respect, the recreational value of the agricultural landscape in this area is important for tourism.

Brenner Guillermo (2007) estimated the recreational value of cropland along the Catalan coast, an important tourist area, by drawing on reference values. In another study, Alvarez-Farizo (1999) assessed the willingness to pay for the agricultural conservation of environmentally sensitive areas to maintain landscape quality in Scotland (Alvarez-Farizo, 1999). Seventy percent of the survey participants agreed with government payments of 36 £ ha^{-1} a^{-1} to farmers for landscape conservation. A similar study was carried out by Bergstrom et al. (1985), who assessed the willingness to pay for the scenic and nostalgic value of prime agricultural land in the United States. Here the households were willing to pay 13 $ ha^{-1} a^{-1} for the conservation of the agricultural land, instead of using the land for residential, industrial, or commercial purposes.

The average of these values from the latter two high-income countries is applied here as a fair approximation of the recreational value of agricultural landscapes for tourism. This results in a recreational tourism value of 26.69 € ha^{-1} a^{-1} of agriculturally used flood plains.

4. Recent Developments in *Miscanthus* Research and Production in Europe

The perennial C4 grass *Miscanthus*, with its 11 and 12 species, is native to Asia (in particular China, Japan, and Korea), Polynesia as well as South-East Africa (Anderson et al., 2011; Chung & Kim, 2012; Greef & Deuter, 1993). The sterile clone *Miscanthus* × *giganteus* (Greef et Deuter), a hybrid form of *M. sinensis* and *M. sacchariflorusis*, is the only genotype currently grown for commercial utilization in Europe and the United States (Kiesel & Lewandowski, 2017). Thanks to its robustness and adaptability (Ramirez-Almeyda et al., 2017), *Miscanthus* can achieve high dry matter yields in various locations within a number of climate zones (Brosse et al., 2012; Hastings et al., 2009; Tuck et al., 2006; Xue et al., 2016).

According to Ramirez-Almeyda et al. (2017), both dry matter yield and production costs of *Miscanthus* harvested in spring depend on the input level. As a perennial crop, *Miscanthus* generally requires less energy, material and labor than annual cropping systems, and is thus considered a low-input industrial crop (Von Cossel, Lewandowski, et al., 2019). However, a distinction must also be made between different input intensities for *Miscanthus* cultivation. In Europe, most locations require at least a medium input to achieve yields between 10–20 Mg DM ha^{-1} (Ramirez-Almeyda et al., 2017). A low input is only sufficient to produce a high yield in a few areas of Central Europe (Ramirez-Almeyda et al., 2017). In most cases high inputs are required to attain a yield of 25 Mg DM ha^{-1}. However, higher inputs often increase production costs up to 300 € Mg^{-1} DM^{-1} and reduce environmental benefits (Ramirez-Almeyda et al., 2017).

As land use competition with both food crops and biodiversity conservation need to be avoided in industrial cropping systems (Araújo et al., 2017; Caspeta et al., 2013; Fritsche et al., 2010; Tilman et al., 2009; Von Cossel, Lewandowski, et al., 2019; Wu et al., 2019; Wüstemann et al., 2015), marginal agricultural land should be taken into consideration for the location of *Miscanthus* cultivation (Von Cossel, Wagner, et al., 2019). "Marginal agricultural land" can be defined as the sum of "areas facing natural constraints" (Elbersen et al., 2017) which are available for agricultural utilization but unsuitable for food crop cultivation (Von Cossel, Lewandowski, et al., 2019). This implies that food crop cultivation is not economically feasible on this land as its overall performance is low. Indicators include, for example, low grain yield, grain quality, and environmental risks (Wu et al., 2019). The low performance of food crop cultivation on marginal agricultural lands can stem from one or more biophysical constraints (Terres et al., 2014; Van Orshoven et al., 2012, 2014). As a consequence, parts of these lands are subject to degradation or are in natural succession (Kalt et al., 2019). For this reason, it is important to consider on a case-by-case basis whether *Miscanthus* cultivation would be beneficial in social-ecological terms (Von Cossel, Wagner, et al., 2019). Literature sources cite the total area of marginal agricultural land distributed across Europe (EU-27) as between 446,000 km^2 and 646,833 km (Gerwin et al., 2018; MAGIC DSS, 2019; Von Cossel, Lewandowski, et al., 2019). The spatial distribution and regional densities of these marginal agricultural areas are given in Figure 2. These numbers reveal both the high economic and social-ecological relevance of an appropriate utilization of such areas (Galatsidas et al., 2018; Von Cossel, Lewandowski, et al., 2019; Von Cossel, Wagner, et al., 2019). For example, *Miscanthus* could be grown on approximately 12% (5.36 million ha) (Gerwin et al., 2018) to 73% (45 million ha) (MAGIC DSS, 2019) of European (EU-27) marginal agricultural land.

A comparison of the available constraint-specific thresholds (Terres et al., 2014; Van Orshoven et al., 2012, 2014) and growth requirements of *Miscanthus* (Ramirez-Almeyda et al., 2017; Von Cossel, Lewandowski, et al., 2019) shows that the crop could be suitable on several types of marginal agricultural land including sandy, saline and erosion prone sites (Alexopoulou et al., 2015; Cosentino et al., 2015; Nsanganwimana et al., 2014; Von Cossel, Lewandowski, et al., 2019). Additionally, *Miscanthus* could be suitable for a number of other less severe marginal sites (Von Cossel, Wagner, et al., 2019) and sites with multiple marginality constraints (Lewandowski et al., 2016; Ramirez-Almeyda et al., 2017; Terres et al., 2014; Van Orshoven et al., 2014; Von Cossel et al., 2018; Xue et al., 2016). Therefore, appropriate *Miscanthus* cultivation on European marginal areas can not only be of great economic advantage but also of great importance for environmental services, such as erosion mitigation and groundwater protection.

5. Discussion

This section first discusses the methods used in and results of the calculations, followed by possible social and ecological impacts of *Miscanthus* cultivation for isobutanol production. Finally, recommendations are derived.

5.1. Valorization of Environmental Services

The valorization of ecosystem services is important in order to understand the value ecosystems have for mankind (Abson et al., 2014; Haines-Young & Potschin-Young, 2018). Globally, ecosystem services can be valued at $ 140 trillion per year (Abson et al., 2014; Haines-Young & Potschin-Young, 2018), which is much higher than the 2018 global gross domestic product of about $ 85 trillion (Abson et al., 2014; Haines-Young & Potschin-Young, 2018). However, the services provided (e.g., clean water and air and pollination) and the negative impacts of agriculture on ecosystems that reduce the provision of these services are rarely valued on the market (FAO, 2015). Thus, there is often little awareness of them in public discourse and political debate. From 1997 to 2011, terrestrial land use change—mainly in form of deforestation of tropical forests and depletion of wetlands (including floodplains, swamps) to provide arable land—resulted in a loss of ecosystem services to the value of $ 20.2 trillion (Abson et al., 2014; Haines-Young & Potschin-Young, 2018). Consequently, the picture provided by assessments of agricultural system performance is far from complete. The predominant focus on crop yields does not appropriately address or assess the advantages and disadvantages of agricultural landscapes. The valorization of the external effects of agricultural crop production renders them more tangible and measurable in monetary terms. In this way, the conventional "production-only" assessment approach, which considers stocks, flows, outcomes, and impacts alone, can be made more holistic (TEEB, 2018).

The environmental services (referring to ecosystem services in agricultural landscapes according to Matzdorf et al., 2010) assessed here in an exemplary agricultural landscape amount to between 1,200 and 4,183 € ha^{-1} a^{-1} in total (Table 1). Of this, the provision of tangible products and services accounts for 210 to 1,522 € ha^{-1} a^{-1}, regulating services 913 to 1,727 € ha^{-1} a^{-1}, habitat services 50 € ha^{-1} a^{-1} and cultural services 27 to 884 € ha^{-1} a^{-1}. Consequently, non-use values (regulation, habitat and cultural services) can have a higher total value (990 to 2,661 € ha^{-1} a^{-1}) than the provision of biomass, drinking water, and genetic resources. Thus it is worth taking a closer look at regulating, habitat and cultural services in the assessment of agricultural production systems (Lead et al., 2010).

Similar service values for agricultural landscapes are reported from New Zealand. Here, a total annual environmental service value of 962 to 11,038 € ha^{-1} a^{-1} is attributed to conventionally managed agricultural fields and a higher value of 1,220 to 14,712 € ha^{-1} a^{-1} (Sandhu et al., 2008) to organically managed fields.

For the valorization of environmental services, *Miscanthus*-specific data were employed, wherever available. This was the case for the provisioning services (except genetic resources) and the services nutrient cycling, erosion prevention, soil fertility, and carbon sequestration. Where no specific data were available, comparable values were taken from the TEEB database as approximations of the services genetic resources, air quality regulation and nursery service. Where neither specific data nor comparable values were available, proxies and estimations were developed, drawing on existing data from contingent valuation and benefit transfer studies. This approach allowed an estimation of the service value of moderation of extreme events, aesthetic information, and recreation and tourism.

The valorization of provisioning services, also recognized in "production-only" approaches, is relatively straightforward and based on direct market pricing of tangible products. Here this refers to the harvestable biomass for the intended use, the ornamental use of leaves by florists, and the provision drinking water.

The provision of drinking water calculated as costs saved for water filtration through sediment passage is a highly important and tangible service for the public. The low-input crop *Miscanthus* with its well-established and active root system is suitable for ecological focus areas due to the low leaching and run-off into water bodies (Emmerling & Pude, 2017) This is one of the reasons why, in 2018, *Miscanthus* was added to the "greening" measures in the EU common agricultural policy (European Commission, 2018b). Christian and Riche (1998) recorded nitrate leaching rates under established *Miscanthus* stands comparable to the low levels of extensively managed grassland. This leads to improved groundwater quality (and environmental conservation). Mineral-N removal also takes place when *Miscanthus* is cultivated as bioenergy buffer strips. A 5-m-wide strip removed 63% and a 10-m-wide strip 80% of the incoming nitrate into the groundwater (Ferrarini et al., 2017). An increase in *Miscanthus* cultivation can thus help comply with the EU Water Framework Directive and at the same time reduce drinking water production costs (Bodensee-Wasserversorgung, 2019).

Some of the services assessed in valorization studies are often mutually exclusive. This is the case in this study for the provision of raw material (*Miscanthus* as feedstock for isobutanol) and ornamental use (harvest of leaves). It was assumed that only 1% of the leaves and flowers are actually harvested from a *Miscanthus* field, on the one hand due to the low market demand, on the other hand because leaf harvest and removal compromises nutrient cycling, soil fertility improvement, and CO_2 sequestration.

Other environmental services tend to be substitutional (in the sense of double accounting). Some degree of substitution is typical and tolerable in valorization studies, because ecosystems and biodiversity are subject to major nonlinearity and complex interactions (TEEB, 2018). Taking this into account requires a clear description of the service and the way it is actually assessed. In this study, the services recreation and tourism, aesthetic information, and moderation of extreme events appear to be interlinked and are thus substitutional. Recreational areas are usually in appealing landscapes favored by tourists for their high aesthetic information. The monetized services were distinguished in this study by allocating the willingness to pay for the conservation of agricultural landscapes to the recreation and tourism service to The residents' willingness to pay for the maintenance of a close-to-nature flood plain (instead of high dams channeling the river) was allocated to the landscape's aesthetic information. In addition, the service of extreme event moderation is estimated based on the costs of avoiding flood damage and of dike maintenance as well as savings from improved cleaning efficiency of sewage plants.

The valorization of environmental services in agro-ecosystems also takes into account the reduction and/or avoidance of negative external effects through farmers' decisions. Out of the 14 environmental services valorized here, only two (raw material, ornamental resource) would have been taken up by "production-only" economic assessments of *Miscanthus* production, automatically disregarding or "externalizing" additional values or services and thus negative impacts on the environment.

In addition, the environmental service “albedo-induced cooling effect” could not be monetized, as no data were available. A number of land use change scenarios have indicated that *Miscanthus* stands have a higher albedo effect during the vegetation period from May until the following March than, for example, the cereals wheat and barley (Cai et al., 2016; Jørgensen et al., 2014). In the period from harvest in March until canopy closure in May, the albedo effect of *Miscanthus* is still higher, because leaves that fall off during harvest cover the soil with a light mulch layer. Being brighter than bare soil, the mulch layer reduces soil warming and the subsequent terrestrial radiation into the atmosphere (Bernués et al., 2016; Jablonowski et al., 2017). Against the background of rising temperatures in a number of regions due to climate change, it is likely that the albedo-induced cooling effect of plant stands will be of increasing importance in future. Hence the albedo-induced cooling effect requires further research and, when data are available, should also be included in monetization studies.

Thus, the environmental services assessed include both distinct services and consciously avoided negative environmental effects, which need to be summed up to obtain the annual economic value of 1 ha of *Miscanthus*.

Provisioning, regulating, habitat, and cultural services are crucial for human welfare and some even for survival, such as air, drinking water, food, heating, and cooking fuel. Environmental services are characterized by somewhat complex interactions of biotic and abiotic factors that differ from place to place, thus creating different ecosystem successions (Lead et al., 2010). Valorization makes these services measurable and thus difficult to ignore in the public discourse on the sustainability of biofuels, agricultural value chains, and the growing biomass demand for the development of the bioeconomy. The holistic consideration of environmental services is of high importance, because agriculture's environmental footprint has increased exponentially over the past 25 years (FAO, 2016).

A survey conducted by Bernués et al. (2016) revealed that farmers working with and within agro-ecosystems are often well informed on and aware of environmental services. This applies in particular to knowledge on the regulating services like soil fertility, erosion prevention, air quality regulation, and gene pool protection, as well as their interactions and their relationship to agricultural practices. For the group of nonfarmers questioned in the survey, cultural services such as the aesthetic value of landscapes are of high importance, while the service “quality food” is equally important to both groups. Finally, the two groups are of the opinion that the provision of environmental services should receive more awareness in society and should also form the basis of agricultural subsidies (Bernués et al., 2016).

The environmental services valorized here are also applicable to other perennial crops, such as cup plant, Virginia mallow, switchgrass, giant reed, willow, and wild plant mixtures (Alexopoulou et al., 2015; Bufe & Korevaar, 2018; Fagnano et al., 2015; Fernando et al., 2016; Ferrarini et al., 2017; Jablonowski et al., 2017; Nabel et al., 2014; Stolarski et al., 2019; Von Cossel, Steberl, et al., 2019; Von Cossel & Lewandowski, 2016). Valorization of the various services however needs to be performed with crop-specific information and data, for example, for nutrient cycling, soil fertility improvement, CO_2 sequestration and erosion prevention. Some of these alternative perennial crops (cup plant, Virginia mallow, willow, and wild plant mixtures) fulfill an additional important environmental service that *Miscanthus* does not—the provision of nectar and pollen (Von Cossel, Wagner, et al., 2019). This service has become increasingly important due to rapidly decreasing pollinator abundances in agriculture (Hallmann et al., 2017; Isbell et al., 2017; Potts et al., 2016). Therefore, *Miscanthus* is less interesting from a biodiversity conservation perspective than cup plant (Bufe & Korevaar, 2018) or Virginia mallow. However, if harvested brown (in winter), *Miscanthus* can serve as habitat over a longer period of time and provided a range of open-land animals with protection from predators and the elements (Bellamy et al., 2009; Semere & Slater, 2007). This is not the case for cup plant which, as with maize, is harvested in autumn. For that reason, cup plant provides less habitat functions in winter than *Miscanthus*. The valorization of the multiple environmental services and the reduction of adverse environmental impacts provide information on the wider impacts of biomass production on an environmental, economic, and societal level and arguments for the integration of perennial biomass crops like *Miscanthus* into agricultural landscapes.

5.2. How to Best Integrate *Miscanthus* Into Agricultural Production in Order to Benefit From its Environmental Services

5.2.1. Diversification of the Agricultural Landscape

The long period of soil dormancy and the low use of pesticides and synthetic fertilizers in *Miscanthus* cultivation offers a number of ecological advantages (Heaton et al., 2008; Von Cossel, Lewandowski, et al., 2019), for both the cultivation site (agroecosystem) (Felten & Emmerling, 2011; Jørgensen et al., 2014; Williams & Feest, 2019) and adjacent ecosystems such as flowing or stagnant water bodies (Christian & Riche, 1998).

Miscanthus for isobutanol production is harvested on frozen topsoil in winter, allowing a more soil-friendly harvest compared to annual cropping systems (autumn harvest) (Von Cossel, Wagner, et al., 2019). The difference in harvest time diversifies conventional farm production systems and supports landscape heterogeneity (Huth et al., 2019). The large-scale maize cultivation for bioenergy, which in 2018 covered 7.5% of total crop land in Germany (FNR, 2019), creates a monotonous landscape that is negatively perceived in public opinion (Mockshell & Kamanda, 2017). A diversification through perennial crops with different growing cycles and harvest dates (e.g., in March for *Miscanthus*) could help to improve the image of bioenergy cropping systems (Borin et al., 2010; Daniel, 2001; Huth et al., 2019).

In addition, landscape heterogeneity is known to increase the resilience of agroecosystems (Tscharntke et al., 2012). In view of the severe climate change effects on agriculture expected in the near future (Pachauri et al., 2014; Samaniego et al., 2018; Teuling, 2018; Von Cossel, Wagner, et al., 2019), increasing the agroecosystem's resilience is highly relevant for adaptation strategies.

5.2.2. Strip Cultivation of *Miscanthus*

Site-specific strip cultivation of *Miscanthus* is a promising management strategy with economic and ecological advantages (Dauber & Miyake, 2016). The cultivation of *Miscanthus* on steep slopes or close to water bodies can help reduce the risk of both erosion and N leaching (Dauber & Miyake, 2016; Feldwisch, 2011). In addition, fields with awkward shapes could be economically optimized by realigning the field through planting *Miscanthus* in the odd corners (Clifton-Brown et al., 2017; Feldwisch, 2011). This field shape tuning could significantly improve the driving lane management and thus the costs of all measures that need to be performed in the vegetation periods of the annual crops grown on the main fields. The *Miscanthus* yield can compensate for the yield loss of the main crop.

Miscanthus integration, for example, in strips, creates habitats for insects and can connect surrounding habitats with each other (Dauber & Miyake, 2016). Additionally, the permanent strip vegetation on the field decreases erosion and evaporation (Dauber & Miyake, 2016). Furthermore, the average yields of the crops grown in between strip-cultivated *Miscanthus* can be significantly increased, as reported for a 2.5-m-high hedge-based strip cultivation system (Möndel, 2007).

These benefits decrease with field size, with habitat functions being provided in particular adjacent to or surrounding annual crop fields (Dauber & Miyake, 2016). Thus, large-scale *Miscanthus* production, for example, in the vicinity of an isobutanol biorefinery, has limited ecosystem service capacity. However, *Miscanthus* cultivation in strip cultivation only would extend the biorefinery's sourcing area and thus increase biomass transport requirements. Thus, in the overall concept of large-scale *Miscanthus* cultivation, strip cultivation should be seen as one important factor for the enhancement of environmental services in agricultural landscapes.

5.2.3. Social Implications of Crop Management

In temperate zones, the harvest of the main agricultural crops (often annual crops) takes place in the same time periods. These periods create various social burdens for the rural population (in particular children), including noise, traffic jams, dirt on roads, and dust in the air (Karr, 2012). Although these burdens also apply to *Miscanthus* harvest, the advantage is that it takes place in late winter. This is a less outdoor-oriented phase of social life, thus lowering direct exposure to the burdens mentioned above. However, a brown *Miscanthus* harvest also implies that leaves are shed during winter, long before the harvest, and depending on the main wind direction, can be blown across public or private properties (gardens, parks, roads etc.) and might need frequent removal. This can cause negative social impacts and pose a threat to *Miscanthus*' image. Therefore, when planning *Miscanthus* cultivation areas near villages, the main wind direction needs be considered to avoid negative effects for the local community. In this way, the benefits of its low management intensity and uncommon harvest date can be taken advantage of.

5.2.4. Income Creation

The creation of new income sources in rural areas has become highly relevant, since many regions have experienced migration and deprivation in the last decades (Jokisch, 2002; Kahane et al., 2013; Satterthwaite et al., 2010). This is linked to the lack of jobs in rural areas other than those in the primary sector. The development of the bioeconomy may be able to counteract this trend. Biorefinery concepts (European Commission, 2018a) are likely to be implemented in rural areas where the biomass is produced. This is because the transport of biomass (with its high water content) is usually more demanding than the transport of a refined product. The development of *Miscanthus*-based isobutanol biorefineries thus holds great potential for job creation and new income opportunities in rural areas.

6. Conclusions

The inclusion of environmental services in the design and assessment of agricultural systems offers a change of focus from a production-only to a more holistic perspective. In addition, this approach reveals the necessity for farmers to consciously reduce the adverse environmental and societal impacts of agriculture. The valorization of both the provision of these services and the reduction of negative impacts makes them explicitly tangible and accountable. Monetary values are the common denominator understood by all stakeholders in the political and societal discourse on the sustainability of agricultural biomass production.

Modern biofuel production from perennial biomass crops, such as *Miscanthus*, provides a promising option to stimulate a continued development of the currently stagnating biofuel sector in Europe. The environmental services provided by *Miscanthus* can improve soil fertility and thus the long-term crop productivity of marginal lands. Hence the cultivation of perennial biomass crops on marginal areas constitutes a substantial measure in the sustainable intensification of agriculture. Not only can considerable amounts of feedstock for biofuel be produced during the period of land restoration, but the process may also render the land economically viable (again) for food and feed production.

Putting this value-chain strategy into farming practice needs to be supported by political incentives. However, to date, farmers in Europe are not acknowledged for the provision of environmental services to society. This aspect needs to be addressed in the new EU Common Agricultural Policy (CAP) currently under development, which includes the development of the bioeconomy as one of its objectives. In this way, EU member states would benefit from more options in the design and implementation of national CAP Strategic Plans. This could stimulate the production and supply of sustainable biomass, a key challenge in the development of national bioeconomies. As already concluded by several other studies (Grethe et al., 2018; Neumann et al., 2017; Pe'er et al., 2014), this would be an important step forward towards sustainable agriculture. Another option would be a remuneration model in the form of a “common goods bonus” (Grethe et al., 2018; Neumann et al., 2017) that pays farmers for the provision of ecosystem services. This would compensate farmers for yield reductions and provide an incentive to adopt an environmental-service-based farming approach.

This conceptual study shows that the perennial biomass crop *Miscanthus* can provide the following services: air regulation, drinking water filtration, flood prevention, biodiversity, improved soil fertility, N_2 fixation, soil erosion reduction, and creation of more diverse landscapes with recreational value. Through the sustainable cultivation of perennial biomass for isobutanol biorefineries and the restoration of marginal land, environmental-service-based farming can help turn the food-agriculture-environment trilemma into a promising opportunity. In addition, it can contribute to the achievement of the 10% biofuel target by 2030 (International Energy Agency, 2019) to support the sustainability transition in the transportation sector.

Data Availability Statement

Data sets for this research are included in the references compiled in Table 1.

Conflict of Interest

The authors declare no competing interests.

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5. General Discussion

In this chapter the research findings are discussed to elaborate contributions of the IREPA approach (Chapter 5.1), urban agriculture (Chapter 5.2) and the environmental service monetarisation in agricultural production systems (Chapter 5.3) for the sustainable supply and consumption of agricultural products.

This finally merges in a novel concept that integrates rural and urban agricultural systems for the sustainable provision of biomass for the 4F's, renewable energy (RE) and environmental services along the rural-urban gradient involving (smallholder) producers and (urban) consumers in the sustainability transition towards the bioeconomy (Chapter 5.4).

5.1. Contribution of smallholder renewable energy production in developing and emerging economies to the sustainability transition towards the bioeconomy

In the first part of this chapter, the IREPA approach and the methodological contributions of participatory, bottom-up case-study research to support the bioeconomic sustainability transition (Chapter 5.1.1 and 5.1.2) are discussed.

Subsequently, the determining factors for RE production in smallholder agricultural systems are discussed, based on the two IREPA applications (Chapter 5.1.4 and 5.1.5). These insights uncover the perspective of smallholder family farmers in terms of drivers for and barriers to agricultural RE production for the bioeconomy development in rural areas in countries of the South.

5.1.1. Evaluation of the IREPA approach based on the state-of-the-art in participatory, case-based sustainability research

The local potential for smallholder RE production was assessed effectively in both case studies in rural South Africa and India, based on the IREPA approach. This can be attributed to the interdisciplinary combination of the assessment of the biophysical resource base (natural science) with the participatory exploration of locally relevant sustainability criteria (social science) and the integration of both in multi-criteria decision analysis (MCDA) for the selection and planning of locally appropriate RET. These three main IREPA steps are methodologically assessed based on the case studies experiences and the current state of the art in the field in order to improve the approach for supporting the supply of agricultural products from smallholder systems.

Assessment of the biophysical renewable resource base

Nowadays, various digital sources for the power densities of solar, wind, hydro, geothermal and bioenergy exist. These sources allow for the assessment of the biophysical resource and the subsequent selection of suitable RET including system dimensioning. Solar irradiance data with global coverage is available for free from the *HelioClim-3 solar radiation* database (soda-pro.com, n.n.), the *NASA surface meteorology and solar energy* database (NASA SMSE, n.n.) and the *NASA Earth Observations (NEO)* database (NASA Earth Observation, n.n.).

Global wind speed data is available from the Danish Global Wind Atlas (Global Wind Atlas, n.n.). These sources have been employed for IREPA, while additional sources are available today, e.g. the *IRENA Global Energy Atlas*, the *Renewable Energy Explorer Website*, the *National Solar Resource Database*, the *Lawrence Berkeley National Laboratory Map RE*, and the *World Bank Group Global Solar Atlas* (Cox et al., 2018).

For the biomass potential assessment, the local net primary productivity (NPP), obtainable from the NEO database, is a suitable indicator for assessing the biomass productivity of the respective area. The average crop yields on country level are available from FAOSTAT (FAO, n.n.).

Wind and hydroenergy data are very site-specific and thus need to be explored on local to national level, e.g. from government departments e.g. on RE, environment, agriculture or statistics as well as from national weather stations. In both case studies valuable information was obtained (charged or free) from such sources, e.g. the discharge timelines of adjacent rivers (DWEA, 2012) and average wind speed densities at different hub heights and terrain roughness classes at the researched area (WASA, 2012). In case no information is available about the researched area and for assessing the geothermal potential, one must rely on explorations that may have already been conducted and published elsewhere, like it was the case in South Africa (Banks and Schäffler, 2006) and in India (Chandrasekharam and Chandrasekha, 2015; Parua, 2010). Other major data sources are the scientific literature, project reports and other local grey literature (information sources need to be evaluated).

Based on the biophysical resource base, the theoretical REP can be assessed. Based on that those RET, where the power densities were found to be below the benchmark for technical and economical RE generation can be excluded from further assessment.

In both cases, the average wind speed was below the threshold level (4 m s^{-1} at 10m height) of even the smallest commercially available wind turbines (Kumar et al., 2010). Accessible geothermal sources were neither available in South Africa nor in India. The hydropower potential of the Hooghly River, a branch of the Ganga, was found to be huge, but the hydroenergy inaccessible for the smallholders. Therefore, in both cases solar and bioenergy applications were found to be possible, while in South hydro power was an additional option.

This initial exploration and the potential exclusion of irrelevant RE generation pathways reveal an advantage of local studies and the bottom-up assessment approach. The renewable energy potential assessment (REPA) studies, reviewed in Chapter 2.1, typically apply large spatial resolutions, which are unsatisfactory for the assessment of the technical, economic and implementation potential (Angelis-Dimakis et al., 2011). Local shading objects for solar energy or local wind breaks (e.g. hills, adjacent trees, other buildings) cannot be taken into account. This is a major source over- or underestimation of the RE potentials on the ground. The biomass potential can only be assessed based on the locally prevailing crops in combination with the yield level, the crop-residue ratio and other competing uses. In both IREPA applications the renewable resource base could be assessed on local level. This was possible and feasible by drawing on existing online data bases. Today, even more digital data sources with global coverage are available (Cox et al., 2018), with many of them accessible free of cost. These renewable resource databases allow for proper technical selection and dimensioning of appropriate RET for local application. Through the integration of RE production, smallholder farming increase their resource-use efficiency, which is a main goal in the development of the bioeconomy (BMEL, 2020; EC, 2018). Such Integrated Food and Renewable Energy Systems (IFRES), based on locally adapted technology, can increase the productivity of the whole production system (FAO, 2011, 2010) in countries of the South, where highest agricultural productivity gains need to be achieved (Bruinsma, 2009; OECD-FAO, 2009).

Participatory exploration of locally relevant sustainability criteria and decision making

Technically suitable RET also need to match the energy demand of smallholder households in terms of quantity and quality to be appropriate. Therefore, smallholder farmers and other relevant stakeholders, including local government officials, traditional leaders, government and municipality departments, extension services, NGO members, etc., were involved in the IREPA studies from the beginning through participatory learning and action (PLA) research methods (Chambers, 1994; Hart, 2008). In the following a brief summary of the methods applied in both case studies, the respective type of information obtainable and the complementarity of these PLA methods is provided to ease data collection in further IREPA studies:

- *Open-ended, semi structured interviews with members of smallholder farming households*

From such interviews precise information can be obtained about household and village characteristics (including demographic factors, gender roles, health, education, skills, jobs, household income and sources, decision making, household and communal hierarchies, openness to new technologies and practices), the prevailing agricultural systems and the production methods, land ownership, current energy supply along with additional demand (quantity and quality), environmental aspects such as concerns, access to natural resources and their use, and the current knowledge about RE among the household members. The open-ended questions allow for a follow-up about individual aspects, e.g. about specific RET and potential applications. This is useful in case the information provided was not detailed enough. Further information from other sources can be cross-checked, e.g. about local power relations and decision making. Therefore, interviews with household members are deemed crucial for the selection of appropriate RET on household or farm level.

- *Key-informant interviews*

In-depth knowledge about specific aspects, e.g. available RET support schemes, as well as information about the general context, e.g. local agricultural development, can be provided by key-informants. Such persons are typically experts in relevant fields and include agricultural extension and NGO workers, scientists, local companies, craftsmen, politicians e.g. from government or municipality, and traditional leaders. Key-informants support the understanding of the local context through in-depth knowledge and are thus also valuable sources for triangulation and interpreting the information obtained from other PLA methods.

- *Transect walks and village mapping*

Transect walks support the understanding of the village structure in terms of terrain, soil types, solar irradiance on the ground, wind distribution patterns and existing infrastructure, e.g. transport, sanitation, health, field sizes and distribution and craftsmen shops (as indication for locally available skills and technologies). Village maps aid the informed planning of potentially suitable RET based on the renewable resource distribution on the ground.

- *Participant observation*

The behaviour of the people, daily routines and how certain tasks are performed can be observed. Especially, socio-cultural aspects, like e.g. gender roles and the related work distribution, local power relations and individual sub-groups, and those aspects which are often not verbalised like informal jobs, religion and spirituality or alcohol misuse, can be discovered. Further, observations can confirm interview information or uncover discrepancies about what was told and what is actually done, e.g. men stating that agriculture is their sole responsibility, while watching women weeding. Of particular importance are daily routines related to energy, including the types of energy, their respective utilisation (if possible including amounts/duration and costs) and the household member in charge of it. This allows for the estimation of the energy demand (e.g. in form of daily power curves) and the subsequent adequate dimensioning of RET while considering seasonal patterns in the resource availability.

- *Visits of other development projects in the research area*

Insights into other local development projects can support the overall understanding of the socio-economic and socio-cultural context. In some cases, it is also possible to obtain and draw on already existing information for triangulation, easing data assessment for mutual benefit. Further, contacts to overseen, but relevant stakeholders can be revealed and subsequently established.

To date, participatory learning and action (PLA) research methods are typically applied in case-based research in the broad field of sustainability transition studies (Fischer et al., 2020; Köhler et al., 2019). Sustainability transition studies explore in-depth information about a sustainability problem on local, regional and / or national level and the surrounding (enabling) policy landscape (Fischer et al., 2020; Köhler et al., 2019; Wittmayer and Schäpke, 2014), e.g. in the fields of energy (Lennon et al., 2019), agriculture (Lairez et al., 2020) and participatory epidemiology (Fischer et al., 2020). Participation of stakeholders is fundamental for agriculture-related sustainability assessments in countries of the South (Schindler et al., 2015), because information relevant for science and society can be gathered from relevant stakeholders (Wittmayer and Schäpke, 2014). PLA is therefore considered the "*mode-2 knowledge production and transdisciplinarity*" (Wittmayer and Schäpke, 2014, p. 484), in contrast to mode 1, which refers to knowledge created under academic settings by professionals (Levin and Greenwood, 2008; Wittmayer and Schäpke, 2014).
For the selection of RET and the design of IFRES both types of knowledge are required. While mode-1 knowledge refers the techno-economical and methodological knowledge, the participation of local stakeholders in a "mode-2" bottom-up process is crucial for the local appropriateness and the integration of new technologies and practices in the daily routines of household members.

Today, the scientific discourse in participatory research has moved from data acquisition methods towards (i) the researcher, its influence and its role in PLA research (Schwanen, 2018; Wittmayer and Schäpke, 2014), (ii) the scale of application (micro vs. macro level) and (iii) the integration of data from the large pool of case-based studies into macro analysis for deriving more generic insights for accelerating sustainability transitions (Geels et al., 2017; Köhler et al., 2019; Lang et al., 2017).
These discourses inform the following IREPA evaluation for deriving insights allowing for improving the approach for further applications in other settings.

Role of the researcher

Stakeholder engagement, multiple perspectives and the complexity of the sustainability problems changed the role of the researchers considerably (Wittmayer et al., 2017; Wittmayer and Schäpke, 2014). Today, researchers need to be skilled in guiding learning processes and in mediating conflicts, while it is expected that the researcher as person represents the change who puts sustainability into action (Wittmayer and Schäpke, 2014). In IREPA, the researcher is integral part of the highly interdisciplinary research process. Hence, researchers applying IREPA have to be aware of and be skilled with respect to the following:

Ownership of the problem

The ownership problem is a normative issue. In many cases researchers identify sustainability problems in society. During the research process the researcher needs to guide data acquisition, analysis, formulation of solutions and implementation in such a way that the ownership of the problem and the research process moves gradually to the participants. They need to become the owners of the solution and become empowered to implement it (Wittmayer and Schäpke, 2014).

The multiple researcher roles have been realised during the first IREPA application in South Africa. This lead to the development of a dedicated workshop concept for REP assessment and RET selection in a project work, supervised by the author of this thesis (Polcher and Wurster, 2015). A complete workshop agenda guides the researcher from the preparation phase, including the selection of stakeholders and framing their expectations, to the moderation of a one-day workshop with brainstorming exercises, mappings, expert groups and focus groups (Polcher and Wurster, 2015).

The co-construction and demonstration of potentially suitable RET as part of the workshop, is an important methodological element for capacity development and building ownership, because it allows for mutual learning about (unknown) technology in a given context (Barry et al., 2011). The highest learning success rates are achieved from do-it-yourself exercises (90%), compared to what is memorized from what was read (10%), seen (20%) listened to (30%) and the combination of the three (50%) (Klein, 2016). RET co-construction was included in the IREPA approach after the application in South Africa and was applied in the Indian case. This allows for knowledge and skills exchange for setting up a new technology (for the participants) in a new context (for the researcher), providing a fruitful basis for RET implementation.

Sustainability concept

Todays' transition management approach considers sustainability as the starting point of the processes, referring to the Brundtland definition (Wittmayer and Schäpke, 2014). Process-oriented PLA research, however, emerged before sustainability mainstreaming and sources value from human development, emancipation, democracy and the empowerment of the stakeholders involved (Wittmayer and Schäpke, 2014). The application of PLA methods in sustainable development research is based on these values, guiding the open-ended process of defining sustainability context-specific and elaborating case-based solutions (Wittmayer and Schäpke, 2014). In IREPA a shared understanding of sustainability and the sustainability targets related to agricultural production and RE are developed during the research process on context-specific basis.

Action

The goal has changed in PLA research from merely providing research results for the scientific community, towards ‘action’ in terms of developing practical solutions for daily life. The researcher has multiple roles in this respect, including facilitation of the process of finding solutions, support in policy formulation, information analysis and networking (Wittmayer and Schäpke, 2014). This issue was experienced, as IREPA is basically an approach for project planning, not considering the actual RET implementation. Hence, for further IREPA applications, the approach should be completed by elements that guide, facilitate and analyse also the implementation and uptake of the developed RE solutions. For engaging citizens and multiple stakeholders in the implementation process, follow-up surveys and workshops, exhibitions, websites and social media, online stakeholder consultations and the living lab approach are considered suitable formats (Gerdes et al., 2018). Living labs are be conceptualised as public-private-people partnerships for open innovation and co-creation through stakeholders from the same geographical area (Gerdes et al., 2018). For IREPA the living lab approach is very suitable as subsequent action-oriented process after the RET selection, fostering ownership of the problem, RET uptake and capacity building.

Power

Power, group dynamics and inherent politics need to be recognised by the researcher. It has to be considered in participant selection and group composition, in facilitating the research process, in the analysis of the outcomes and during sharing the benefits of the solution (Fischer et al., 2020). This issue requires a conscious reflection on the participants’ power relations and group dynamics as well as a self-reflection about the personal role within this setting (Wittmayer and Schäpke, 2014). Power also refers to a participants’ ability of being heard or being able to guide the outcomes towards self-benefits (Fischer et al., 2020). The researcher hereby needs to organise an inclusive research process making sure that ‘silent voices’ (considering gender, age, social hierarchy, ethnic groups) are recognised (Fischer et al., 2020; Lemke and Claeys, 2020). This aspect is also taken up in the IREPA workshop concept (Polcher and Wurster, 2015), e.g. by organising gender-selective focus-groups and interviews with female translators or researchers.

Language

The PLA methods in IREPA were all applied with translator in the local language. The vocabulary in the mother tongue is best capable for expressing oneself and understanding new information, while the researcher and / or translator need to be good listeners (Fischer et al., 2020).

Geography

The unidirectional way of innovations and strategies developed in the Western world with subsequent knowledge and technology transfer to developing countries diminishes more and more today (Henao et al., 2012; Jolly et al., 2012; Köhler et al., 2019). Today, sustainability innovations co-evolve at multiple locations (Köhler et al., 2019; Schwanen, 2018).

Consensus vs. plurality

The researcher needs to decide whether the sustainability problem tackled requires a single best-solution or rather a package of several solutions and subsequently design the research process accordingly (Fischer et al., 2020). IREPA is based on the pluralistic approach with the aim of conceptualising multiple RETs with different RE sources as research output for matching diverse energy needs in agricultural production and the smallholder households at the same time.

For identifying locally appropriate RET with IREPA, the information obtained from the PLA research, is subsequently analysed, interpreted and translated into local sustainability criteria. For technology selection the multi-criteria decision analysis (MCDA) method *Analytical Hierarchy Process* (AHP) (Saaty, 1990) was applied in South Africa. The application with farmers was challenging, giving the large number of pair-wise comparisons. In the Indian case the *Simple Multi-Attribute Rating Technique* (SMART) (Chen et al., 2010) was employed. In addition, an adapted version of the AHP using criteria clustering (Stewart and van den Honert, 1998), thereby reducing the number of pair-wise comparisons. SMART is based on straightforward ranking of both selection criteria and technology options, instead of the pair-wise comparisons, and thus easier to comprehend and faster in the application. The latter, however, was experienced as disadvantage compared to the AHP. The pair-wise comparisons require thoughtfulness and concentration of the participants, which may result in more informed decisions as compared to SMART.

The advantages of the AHP method in terms of scalability and adaptability to individual decision problems make it the most frequently applied decision making method in the field of environmental sustainability (Colapinto et al., 2019). Other areas of frequent application include manufacturing, logistics and transportation as well as in construction, agriculture, forestry and land use (Colapinto et al., 2019). The number of MCDA studies published was about 1400 in 2016/17. Within the field of sustainable energy, the number of studies multiplied from one in 1999 to 77 in 2017 (Siksnelyte et al., 2018).

Important for informed choices in the final step of IREPA is the preparation, explanation and presentation of the sustainability criteria to the participants. In both case studies, the MCDA methods were successfully applied for criteria ranking and RET ranking. Therefore, no adaptation or renewal is required in the MCDA-based RET assessment and selection process. Today, MCDA methods are state-of-the-art in environmental and sustainability studies (Colapinto et al., 2019; Marinis and Sali, 2020; Siksnelyte et al., 2018). MCDA methods are important for structured decision making in sustainability research for the development of the bioeconomy, because they allow for the integration of multiple disciplinary perspectives.

5.1.2. Up-scaling of case-based research for the sustainability transition towards the bioeconomy

To date sustainability research takes place either on macro level, elaborating the theoretical landscape of drivers and barriers for system change, based on theories, frameworks of analysis and modelling employing big data approaches (Geels et al., 2017; Lang et al., 2017; Sovacool and Walter, 2019), or on micro-level based on participatory case-based research (Fischer et al., 2020; Schwanen, 2018) and sustainability assessments of technologies and practices (Schindler et al., 2015). Taking this into account, the following conclusions can be drawn for further IREPA applications, in order to widen the level of application and informing the broader sustainability transition.

Socio-technical innovations can induce transitions when they link up, reinforce and gain momentum supported by the wider landscape level (Geels et al., 2017). For example, the energy transition in Germany builds on technological advancements that lowered solar, wind and bioenergy generation costs, industrial coalitions (e.g. machine building and farming), subsidies through the EU RE directive and a positive public image of RE, due to the rising opposition against nuclear power after the Fukushima accident (Geels et al., 2017). Consequently, RE production in smallholder agricultural systems should not only focus on the energy-related aspects, but additionally address agricultural sustainability challenges and support solving them by creating win-win situations between agricultural production and RE production (Zeweld et al., 2017).

Therefore, IREPA could benefit from an explicitly stated focus on the design of IFRES in future applications. More farmers might become interested in RE production, when the relations to agricultural production are more obviously communicated in terms of co-benefits that support solving agricultural sustainability as well as household challenges. For example, the co-benefits of biodigestion include climate change mitigation (replacement of fossil fuels), deforestation reduction (replacement of traditional biofuels), increase in soil fertility and thus food security (digestate application as fertilizer), increase in resource-use efficiency (utilisation of residues and wastes) and household energy security (biogas utilisation). Hence, several synergies arise with the agricultural production system, when biodigestion is implemented.

Agricultural manures, residues and household wastes are valuable feedstocks for bioenergy production. Hence, farmers intentionally collect, store and use them instead of burning on the field or discharge them with other wastes (like e.g. in the South African case). This increases the resource-use efficiency and nutrient circularity on the farm. Further, the digestate has to be removed and is ideally used as organic fertilizer for improving soil fertility and increasing agricultural productivity.

This example can be considered a narrative of the biogas production in smallholder farming systems. Narratives are frequently used to disseminate case-study results (Köhler et al., 2019; Schwanen, 2018). The abstraction and purification of case-based results to derive more general results (based on selection, simplification, reworking and exclusion of cast study results) renders the information more interesting for a broader readership, while blurring the results' context (Schwanen, 2018). Traditionally, meta-analyses and reviews are conducted for generalizing and extrapolating case-based research results for informing the wider political sustainability transition context (Köhler et al., 2019). Therefore, the inclusion of institutional factors and the political setting in sustainability assessments and case studies is crucial, but remained an overseen in studies conducted in the past (Schindler et al., 2015). IREPA includes institutional factors, as these can be important drivers for or barriers to specific RET and thus frame the technology selection factors in the broader context.

The transferability of research results from a specific context, innovative technologies and practices developed as well as the information generated in numerous case-studies needs to be strengthened for supporting the sustainability transition towards the bioeconomy. The increase in case-based data and information (Fischer et al., 2020; Schwanen, 2018) creates the opportunity for novel methodological approaches that strive for generic insights across cases to support scientific theory building for the global sustainability transition (Köhler et al., 2019). Recent attempts of generalising case-based research results, are replicated case studies applying the same methodology in other geographical areas and socio-cultural contexts (Köhler et al., 2019), like it was done with IREPA. Embedding case study research in global or regional models could support the identification of suitable case-study regions and socio-economic contexts. This strategy of stratified sampling, based on the anticipation of impacts, would result in more comparable results. The data and information obtained from such a strategic approach can improve models to explore the generalisability, scalability and transferability of the results and thus increase the wider impact of case study results (Lang et al., 2017). The bioeconomy is to a large extent based on decentralised biomass production in agricultural systems and thus needs to reach and involve multiple stakeholders. This could be accelerated by the structured up-scaling of case-based research results, e.g. by replicated IREPA applications following a stratified sampling approach, based on regional to global models (Köhler et al., 2019; Lang et al., 2017). Suitable case-study locations can be identified, based on various indicators like e.g. the renewable resource base, availability of similar institutional support schemes or the access rate to modern energy. Consequently, a general concept for IFRES can be planned and subsequently adapted for implementation based on the IREPA approach. A stratified-sampling approach based on IREPA case studies, could support the increase in agricultural productivity in countries of the South and involve the large group of smallholder famers in the sustainability transition towards the bioeconomy.

5.1.3. *Summary:* The methodological contributions of integrated assessment approaches and case-based research and for the sustainability transition towards the bioeconomy:

The following methodological considerations are derived from the development of the IREPA approach and its applications in two case studies, with the aim of providing guidance for further agriculture and RE based sustainability research in smallholder farming systems in countries of the South:

Methodological considerations for sustainability transition research:

- Sustainability research has to be regarded an open-ended process that defines sustainability context-specific instead of applying general definitions (e.g. Brundtland) (Wittmayer and Schäpke, 2014).
- Solutions for sustainability problems need to be appropriate in the local context. Often multiple solutions (plurality) (Wittmayer and Schäpke, 2014) that address interlinked challenges, e.g. related to agriculture and energy, need to be combined (Zeweld et al., 2017). Finding these solutions, requires flexibility in conducting case-based research and thus in the regulatory research funding frameworks.
- The co-evolvement of sustainability solutions at multiple locations requires case-based, inter- and transdisciplinary research approaches, such as IREPA, that builds on stakeholder participation from the beginning (Fischer et al., 2020; Köhler et al., 2019). Thus, the foundation of sustainability transition research towards the bioeconomy is a holistic bottom-up perspective with sustainability being defined context-specific.
- The interlinkages of sustainability solutions with each other, with people's livelihoods and the environment need to be explored, explicitly stated and enhanced (i) to integrate several technologies and processes to enhance overall performance on systems level (e.g. agricultural productivity, resource-use efficiency, residue and waste recycling, etc.), and (ii) to ensure the applicability to local livelihoods without negative impacts and environmental trade-offs.
- Information and data exploration need to capture the local context and therefore be based on participatory learning and action research methods, which are nowadays state-of-the-art in sustainability transition research (Fischer et al., 2020; Köhler et al., 2019).
- Digital databases with global coverage (and often free access) facilitate the exploration and assessment of the local natural resource base (bio-physical data) (Cox et al., 2018) for RE production (e.g. NASA SMSE), primary productivity (e.g. NASA Earth Observation) and agricultural productivity (e.g. FAOSTAT). Appropriate technologies and practices can be planned based on

local bio-physical data following cascading and circular approaches to optimise the use efficiency of natural resources.

- MCDA methods, like e.g. AHP and SMART (Chen et al., 2010; Saaty, 1990), allow for structured decision making and the determination of locally appropriate sustainability solutions, based on quantitative and qualitative (sustainability) criteria and the involvement of multiple stakeholders from various disciplines in decision making (Colapinto et al., 2019; Siksnelyte et al., 2018).
- For successful implementation, the ownership of the sustainability solution needs to be with the local stakeholders. If the identification of the solution was not initiated by local stakeholders, the ownership transfer needs to be part of the research process, e.g. through participatory identification of problems and the co-design of solutions e.g. in practical workshops or living labs (Gerdes et al., 2018).

The multiple roles and required skills of researchers in the sustainability transition:

- Interdisciplinary, cross-sectoral perspective and collaboration skills for the identification of appropriate technologies based on the holistic consideration of locally relevant social, environmental, technical, economic and institutional factors.
- Language skills and / or cooperation with a translator and good listening skills.
- The ability to identify and manage local power relations (e.g. gender roles, minorities), group dynamics, inherent politics and conflicts in stakeholder involvement (e.g. in focus group composition) during the research process, the analysis of the outcomes and sharing the benefits of the solution (Fischer et al., 2020; Lemke and Claeys, 2020; Wittmayer and Schäpke, 2014).
- Authenticity of the researcher and practical knowledge, e.g. for technology co-construction or policy formulation, for putting the sustainability change into action (instead of providing research results for the scientific community only) (Wittmayer and Schäpke, 2014)

These methodological recommendations can guide and lead the transition from a centralised fossil resource exploitation, based on techno-economic considerations, towards a decentralised provision of biobased and renewable resources using locally appropriate technologies and production systems while involving multiple stakeholders in the bioeconomy.

For stakeholder involvement the sustainability transition towards the bioeconomy, their perspective needs to be explored and subsequently taken up for the targeted formulation of political development strategies. Therefore, the following chapter focuses on the perspective of smallholder farmers on agricultural RE production.

5.1.4. Smallholder farmers' perception on agricultural renewable energy production: drivers and barriers for implementation

In the past, energy transitions emerged from the exploitation of new energy resources, without considering impacts on the environment or society and were controlled almost monopolistic by energy corporations (Lennon et al., 2019). Today's ongoing energy transition, however, is based on decentralised RE systems, because of spatial and temporal fluctuations of renewable resources (Arndt et al., 2019). Decentralisation implies the involvement of multiple stakeholders from the private and the public sectors as well as the society. This changed the role of individuals from being regarded (passive) consumers and customers towards becoming main actors in the concurrent energy transition (Lennon et al., 2019; Wirth et al., 2018). The same applies to the sustainability transition towards the bioeconomy, where agricultural products, including energy, are to be produced in a decentralised way in multiple agricultural systems. In countries of the South access to modern and clean energy is a crucial driver for rural development and for increasing agricultural production (FAO, 2014a, 2011; Kaygusuz, 2012). Therefore, the drivers for and the barriers to agricultural RE production in smallholder farming system are explored to inform the formulation of targeted political strategies for increasing the supply of agricultural products for the growing bioeconomy.

Energy situation in countries of the South

Globally, smallholder family farmers represent about 475 million households, who manage 53% to 75% of the total global agricultural land including its natural resources (Graeub et al., 2016; Lowder et al., 2016). The majority of farms (84%) are smaller than 2 hectares and 72% are smaller than 1 hectare (Lowder et al., 2016). Only 4% of these farms are in high-income countries, while the majority is located in lower-middle (36%) and upper-middle income countries (47%) (Lowder et al., 2016).

Rural areas of Latin America, Asia and Sub-Saharan Africa entail the largest potentials for increasing the supply of agricultural products and RE (Moriarty and Honnery, 2012; OECD-FAO, 2009; Teske et al., 2019). In these areas, the number of people without access to electricity dropped from nearly 1 billion people in 2017 to 860 million in 2018, while 2.6. billion people still remain without access to clean cooking fuels (IEA, 2019). In 2018, Sub-Saharan Africa showed an electrification rate of 45% (world average 88.7%), while only 17% have access to clean cooking fuels (IEA, 2019). As elaborated in Chapter 2.1 and Chapter 2.2 of this thesis, the implementation of the huge RE potential in countries of the South, depends mainly on the inclusion of the large societal group of smallholder farmers. The selection of locally appropriate RET for harnessing these potentials, depends on multiple and complex interactions of local social, environmental, technical, institutional and economic factors (Tab. 1) - posing drivers for and barriers to smallholder RE production and the development of IFRES:

Table 1: Locally relevant factors for the assessment of the renewable energy implementation potential and the selection of locally appropriate renewable energy technologies at the case study areas Mgwenyana (South Africa) and Ghoragaccha and Baikunthapur (India)

<table>
<tr><th>Mgwenyana (South Africa)</th><th>Ghoragachha and Baikunthapur (India)</th></tr>
<tr><td colspan="2">Economic factors</td></tr>
<tr><td colspan="2">Investment costs and energy expenditures</td></tr>
<tr><td>Operation and maintenance (financial aspects)</td><td></td></tr>
<tr><td colspan="2">RE business models</td></tr>
<tr><td colspan="2">Institutional factors</td></tr>
<tr><td colspan="2">Government support (financial and for operation and maintenance)</td></tr>
<tr><td colspan="2">Technical factors</td></tr>
<tr><td colspan="2">Energy security and reliability
Operation and maintenance (technical skills and knowledge)</td></tr>
<tr><td colspan="2">Environmental factors</td></tr>
<tr><td>Protection of soil, water, air and biodiversity</td><td>Environmental Conservation</td></tr>
<tr><td colspan="2">Social factors</td></tr>
<tr><td>Food and nutrition security
Access to clean water
Gender aspects
Social cohesion and stability
Social benefits and increased well-being</td><td>Ease of daily activities
Education and development of new skills</td></tr>
</table>

Economic factors

Achieving universal electricity access requires investments of about $400 billion between 2020 and 2030 (IEA, 2019), which is exactly the amount of subsidies the fossil energy sector (still) receives annually (REN21, 2020). Nevertheless, RE generation has been growing faster than expected in the last years (Arndt et al., 2019). Global annual investments reached $301.7 billion in 2018 (REN21, 2020). Currently, the cost decrease of solar (-87%) and wind (-62%) energy technologies between 2010 and 2017 made RE competitive with fossil energy and thus accelerates further RE deployment (Arndt et al., 2019), also in smallholder farming systems.

Investment costs and energy expenditures

The investment costs of modern RET pose a major barrier for smallholder farmers, as revealed in the South African and Indian case studies. Mandelli et al. (2016) reviewed 350 off-grid rural electrification studies in countries of the South and came to the same conclusion. A potential way ahead is to focus on RET that are dimensioned to produce the required energy at lower costs than the currently used energy form. This can reduce household energy expenditures, making financial resources available for investing into new technologies.

In South Africa, 94% of the households rely on social grants as major income source. Less than half (44%) additionally receive financial support from migrated family members. The (low) agricultural produce is almost entirely self-consumed. The monthly household income ranges from about ZAR 500 to ZAR 1500 (about 25 – 75€ per month). Therefore, only RET with very low investment costs are considered suitable. RE systems were planned and the amortisation time estimated based on the monthly savings through the omission of expenditures for the currently used energy alternatives. A simple solar-PV light system (10W, 4x LED bulbs) takes 8.7 years for amortisation, while a PE-bag biodigester would amortise within one year (assuming fuelwood is purchased) and remove the need for fuelwood (Ritter, 2013).
The same RET planning approach was applied in India. The economic assessment of solar-PV home systems (500 – 1500 Wp) showed that the investment costs for a 1000Wp PV system are on the same level as the average annual household income of INR 115068 (about 1325€). This solar system could be paid off within nine to eleven years (operation and maintenance costs not included), through the saved expenditures for grid-electricity. Similar solar PV amortisation times are found in Europe with pay-off periods ranging from six to seven years in Spain to about twelve years in Norway. The European average pay-off period is just below 10 years (Whitlock, 2019).
The cost decrease for solar and wind technology (Arndt et al., 2019) is lowering the investment-barrier considerably. Since 2020, decentralised RE systems show the lowest energy generation costs in rural areas in countries of the South, thus accelerating RE production (Arndt et al., 2019; REN21, 2020).

Operation and maintenance (financial aspects)

Initially, simple and cheap, (partly) self-built RET were found to be favourable options for both case study areas. This, however, implies that smallholders are also responsible for operation and maintenance, including the purchase of spare parts at an unpredictable time (Terrapon-Pfaff et al., 2018). Such a 'do-it-yourself' strategy is supported by the high smartphone penetration rate of about 91% in South Africa in 2019 (Gilbert, 2020) and the observed daily smartphone utilisation of the younger generation in India. Today, ample do-it-yourself manuals and videos (important in case of illiteracy) for nearly all RET are available online for free e.g. on *youtube* or *Appropedia*. Further, these and multiple other sources provide information about sustainable agricultural practices, technologies and management. Further, institutional support can be provided e.g. by raising awareness among farmers about these information sources or through the creation of open-access online manuals and practical step-by-step videos based on the local context and in local languages.
A recent study in India concluded that capacity building is the major driver for the uptake and utilisation of smartphones by smallholder farmers in India (Landmann et al., 2020). Some interviewed farmers in the Indian case study reported the use of smartphones for obtaining information about

farming, e.g. about crop-specific fertilizer application rates or for improving biogas productivity. Hence, the increasing smartphone and associated internet access rates globally, support access to open-source information. This enables do-it-yourself RET setups including operation and maintenance.

The roll out of electricity grids to rural areas in countries of the South usually follows major roads and connects adjacent villages only (Mandelli et al., 2016). In these villages, often public buildings (e.g. schools, health centres), enterprises and household who can afford the grid-connection (with up to 10-times higher electricity costs compared to urban areas) gain electricity access (Mandelli et al., 2016). For the remaining households, decentralised RE systems are today the most viable energy access option (Mandelli et al., 2016; REN21, 2020). Several RE business models emerged in the last years, tailored to the needs of often low-income rural households (Mandelli et al., 2016; Terrapon-Pfaff et al., 2018).

RE business models

RE business models were not part of the IREPA applications, but provide a lucrative and thus feasible option for smallholder farmers to produce RE. Medium to large-scale RE production is becoming an opportunity especially for those smallholders living in areas where the national grid has already expanded or will expand soon (Asian Development Bank, 2015). Public-private partnerships or multi-party ownership models provide the chance for farmers to lease land and / or sell biomass feedstock, thereby omitting own technology investments as well as the operation and maintenance responsibility (Asian Development Bank, 2015). In India for example, Thapar et al. (2017) estimate the farmers' equity share to be up to 15% in community RE projects, which can result in an additional income of up to $4000 per year. Such medium to large-scale projects can further attract private-sector investments, which are currently higher in countries of the South than in the North (Frankfurt School-UNEP Centre/BNEF, 2020).

On small-scale, lease or hire business models are tailored to the needs of poor households. Complete RE systems, e.g. solar-home systems, are leased or hired for regular payments including operation and maintenance service. The dealer credit model combines RE system selling with microloans in one-stop-shops. Individuals buy an RE system based on a microloan, which is payed back based on regular instalments. After the pay-off period, the purchaser owns the RE system, but without additional service (Asian Development Bank, 2015). These pro-poor business models surpass the upfront investment costs, increasing access of smallholders to RET considerably. In a similar way, lease or hire as well as dealer credit models could also support smallholder mechanisation, e.g. irrigation pumps and equipment, tractor access and post-harvest storage facilities, with the aim of increasing agricultural productivity. Recently, several machinery sharing business models emerged, e.g. *HelloTractor* in Nigeria and Kenya or *farMart* in India (Daum and Birner, 2020). Digital tools bring farmers and tractor owners together. Shared utilisation options increase financial viability of tractors by increasing the utilisation rates and lower the risk of purchasing agricultural technology (Daum and Birner, 2020). Such business models can support the implementation of modern agricultural and RET, in order to increase resource-use, land and labour efficiency, and reduce post-harvest losses, while offering new income opportunities in rural areas of the South.

From an economic perspective, the cost digression of RET together with large investments from the private sector foster RE business models in rural areas in countries of the South, removing economic barriers for smallholder RE production and fostering rural bioeconomic development. For smallholder RE production, the following options arise:

- Household RETs should be selected and planned based on the premise that the investment can be paid off through the savings of replacing the previously used energy source(s). Agricultural technologies for increasing productivity should be implemented in a similar way, allowing smallholders to pay-off the investment costs based on productivity gains or production cost reductions.
- The participation as shareholder in public-private partnerships or multi-party ownership RE business models provide the opportunity for smallholders to by-pass the investment as well as the operation and maintenance barrier, thus creating an additional income (Asian Development Bank, 2015; Thapar et al., 2017).
- Digital technology-sharing applications can increase affordability and lower the risk of high upfront investment costs for farm mechanisation (Daum and Birner, 2020) and thus support the uptake of agricultural technology to increase agricultural productivity in smallholder farming systems.
- RE and agricultural projects need to focus on capacity building and technology trainings (Terrapon-Pfaff et al., 2018; Wirth et al., 2018).
- The increasing smartphone penetration enables access to open-source information for do-it-yourself RETs, operation and maintenance as well sustainable agricultural practices and agricultural knowledge (e.g. *youtube* or *Appropedia*). Institutional support should raise awareness and educate farmers about finding relevant information online. Further digital extension services could provide locally relevant information in local languages.

<u>Institutional factors</u>

Globally, financial support schemes remain the crucial driver for the RE transition (Arndt et al., 2019). In 2019, 172 countries had RE targets and 161 countries had RE policies in place (REN21, 2020). This evidence from the RE sector highlights the importance of institutional support also for the development of the bioeconomy, where already 49 countries have currently strategies in place that guide the national research agenda, set development targets and foster the deployment of new biobased technologies (Bioökonomie.de, 2021; German Bioeconomy Council, 2018).

The focus in South Africas' RE policy and support landscape remains on large-scale RET through the 'Renewable Energy Independent Power Producer Procurement Programme' (REI4P), as described in Chapter 2.1. The programme is considered very successful, with each bidding round attracting numerous consortia willing to install RE production capacity (Fontana and Wing, 2019). In 2016, the Income Tax Act was reformed and allowing now for accelerated depreciation of solar PV systems with less than 1MW in one year, thus promoting small-scale projects for increasing energy security with low environmental impact (Fontana and Wing, 2019). Further, the Carbon Tax Act came into law in 2019 charging 120 ZAR for every tonne $CO_{2\text{-eq.}}$ emitted until 2022. The overall tax rate is expected to be 6 – 42 ZAR per tonne $CO_{2\text{-eq.}}$, with 60% of the emissions as basic tax-free allowance (Fontana and Wing, 2019). The tax reform renders decentralized solar PV projects in rural areas of South Africa more lucrative as fossil energy prices will likely increase in the next years.

Furthermore, the importance of local institutions was revealed in the South African case study. Traditional leadership and community hierarchies need to be considered in RE project planning and RET selection, because local leaders can hamper actions by individuals (in case the chief is not interested in RE) or motivate whole communities to produce and use RE (in case the chief is interested).

In India, the energy success story began in September 2017 with the launch of the *Saubhagya* scheme, aiming at providing grid-electricity access to all (willing) un-electrified households until the end of 2018 (in remote areas through solar-PV systems) (Government of India, 2017). In April 2018 it was announced that the goal was reached, with only few remote villages being unconnected (IEA, 2020b). According to the official *Saubhagya* website, 99.99% of all Indian households were electrified in September 2020 (saubhahya.gov.in, 2020) - based on the premise that a village is considered electrified, when 10% of the households and all public buildings are connected (IEA, 2020b). Since 2000, India provided electricity access to 750 million people (IEA, 2020b). This is a huge step forward in rural development, indicating the power of long-term political strategies and their resolute implementation that is backed up with sufficient financial resources.

Currently the expansion of the RE production capacity to 175GW in 2022 is challenged by a needed increase in the electricity transmission capacity, which is important for intermitted solar and wind energy. Further, insecurity about upcoming RE policy reforms as well as slow progress in land acquisition of RE production sites is slowing down progress. The increase in RE production capacity to reach the 2022-RE target in rural areas requires about 200,000 hectare of land, and in case of bioenergy, biomass as feedstock (Buckley, 2020; Thapar et al., 2017). This represents a bottleneck, as it was found in the Indian case study that virtually all land is in use. The majority of smallholders (82%)

surveyed in the case study prefer to cultivate food and feed crops on their land in order to secure the basic income source. The remaining 18% of farmers would be willing to include RE production, if it provides additional income. Typical for early adopters, the farmers willing to take up new opportunities are those who have sufficient resources to take the associated risk in case of failure (Rogers, 1983). The launch of the *Saubhagya* scheme in 2017 fostered communal RE projects based on public-private partnerships with smallholders as shareholders (Thapar et al., 2017). Furthermore, multiple RE support schemes for small to large scale applications are in place, supporting the developments of solar (electricity, heat, light), wind, small hydro and biogas e.g. National Biogas and Manure Management Programme (MNRE, 2020) in the country.

India and China are the largest growth markets for RE in the world with substantial progress (REN21, 2020). In India ample opportunities emerge that seem to allow smallholders to participate and benefit from the RE transition. On the contrary, the policy landscape in South Africa does not consider smallholder RE production. Hence, smallholder farmers in areas without favourable institutional conditions, need to take own initiative through business models or do-it-yourself solutions:

- RE support strategies are a main driver of the global RE transition (Arndt et al., 2019), consequently the growing number of countries implementing bioeconomy strategies set the scene for the global bioeconomy transition.
- In both countries, India and South Africa, the current focus is on medium to large-scale RE projects, while India supports small-scale RET since decades (Buckley, 2020; Fontana and Wing, 2019; Government of India, 2017; MNRE, 2020). Thus currently community or collective RE production tend to have a higher chance of being financially supported through government schemes, private investments or a combination of both.
- In areas with high pressure on land like in India, smallholders tend to be reluctant of leasing or selling land for RE production, because of the associated risk of being deprived from the livelihood basis. Consequently, RETs need to be linked to and combined with agricultural production, e.g. through the creation of IFRES that aim on increasing overall productivity of the smallholder farming systems.
- Traditional community hierarchies, like e.g. in South Africa, may foster or hamper individual smallholders to take initiative or participate in the increasing number of RE projects in rural areas. Therefore, political strategies and development projects need to take the local socio-cultural context and local community leadership into account by applying participatory research methodologies.

Technical factors

Access to sufficient and clean energy can substantially increase agricultural productivity in rural areas in countries of the South (Daum and Birner, 2020; Mandelli et al., 2016; World Bank, 2017). In these areas, the energy demand in agricultural production (e.g. planning, mechanisation, irrigation) is currently supplied by manual labour (65%) or animal power (25%), while only 10% is energised. Energy is especially required for post-harvest operations (like e.g. cleaning, drying), food storage, preservation and food preparation (World Bank, 2017). Globally, energy poverty results in post-harvest grain loss of 10-20% or $ 4 billion (World Bank, 2017). To date 80-100% of the energy is used for cooking, water boiling and, in colder climates, for space heating. Most of this energy is supplied from traditional biomass, collected and handled typically by women (Mandelli et al., 2016; World Bank, 2017).

Energy security and reliability

Energy security and reliability is one of three common factors found in both case studies. It implies the reliability and quality of the energy supply. In terms of electricity, frequent and sometimes long last power cuts hamper the utilisation of electricity (reliability), while fluctuations in voltage can damage the appliances connected (quality). Other energy carriers such as diesel, kerosene or LPG are not always available in rural areas, due to transport and trade constraints (Mandelli et al., 2016; World Bank, 2017). Mandelli et al. (2016) suggest that 'a few hundred Watts' are often sufficient for meeting the household energy demand. Consequently, rather small RET systems, as suggested in the South African and the Indian case, are appropriate to meet the daily life energy needs. Even smaller RET systems can considerably reduce indoor-air pollution, the burden of fuelwood collection for women (Terrapon-Pfaff et al., 2018) and food losses due to limited storage and preservation possibilities (World Bank, 2017).

Meeting the energy demand of project beneficiaries in terms of quantity and quality provides the foundation for the wider uptake of RET (Terrapon-Pfaff et al., 2018). Terrapon-Pfaff et al. (2018) concluded, after evaluating the outcomes of 30 RE project in countries of the South that successful RE projects trigger replications of the RET within the community (77%) and the surrounding communities (65%). This highlights that *appropriate RET* need to supply the amount and quality of energy required by smallholder farming households at the right time. Consequently, there is a strong tie between technical and social factors that likely applies to other agricultural technology as well.

Operation and maintenance (technical skills and knowledge)

Limited knowledge and skills for operation and maintenance are often the reasons why already installed RET systems, e.g. through development projects, are not operated in the long term (Mandelli et al., 2016; Terrapon-Pfaff et al., 2018). In India for example, a farmer abolished the use of his biodigester after he changed the production system from cattle towards vegetables. The household switched back to LPG for cooking, because of the lack of manure and the lack of knowledge that various other biomass sources can replace manure as biogas feedstock. When service and spare parts are unaffordable and / or unavailable in rural areas, the lack of knowledge and skills leads to overall RE system breakdown (Mandelli et al., 2016). RE workshops and service providers were available in India at the time of the case study in 2015, but not in the South African case in 2012.

RE development projects usually take up this issue through technology-based education programmes for operation and maintenance as well as sustained contact between the project staff and the participants after implementation (Terrapon-Pfaff et al., 2018; Wirth et al., 2018). In addition to the new digital possibilities for do-it-yourself solutions, introduced above, RE development projects should foster the creation of networks by disseminating the experiences, the knowledge and the lessons learned to the wider audience in the region, including surrounding villages, local authorities, government bodies and NGOs. Further, a sustained contact between the project team and the beneficiaries is important for RET maintenance and potentially necessary technology adaptations. In 73% of the projects, evaluated by Terrapon-Pfaff et al. (2018), networking and partnership creation were part of the project agenda. In a previous evaluation in 2014, only 44% of the projects focused on networking activities (Terrapon-Pfaff et al., 2018). These activities do not only trigger the wider RET uptake, but develop technical capacity for further RE deployment (Terrapon-Pfaff et al., 2018).

Technical drivers for and / or barriers to smallholder RE production include energy security and reliability as well as skills and knowledge for operation and maintenance:

- Appropriate RET for smallholders have the highest impact when the household energy demand can be met in terms of quantity (often < 1kW), reliability and quality (Mandelli et al., 2016), highlighting the strong tie between technical and social factors in the RE as well as the sustainability transition towards the bioeconomy.
- Women are responsible for household-related tasks and thus a gender-sensitive research approach is needed when selecting appropriate RET in smallholder farming systems.
- Knowledge and skills for operation and maintenance (including access to service) need to be considered already during RET selection.
- Knowledge dissemination, networking and partnerships support operation and maintenance, and stimulate RET uptake in the region (Terrapon-Pfaff et al., 2018; Wirth et al., 2018).

Environmental factors

Environmental factors were found to be highly relevant for smallholder farmers and the selection of locally appropriate RET in both case study areas. This can be attributed to the direct impact of changes in the weather and climatic conditions on the agricultural production system. The smallholders at Mgwenyana (South Africa) reported changes in the weather patterns, manifested e.g. as changes in the seasonal precipitation patterns and the need for watering crops which were grown rain-fed in the past. In this case study, basically the negative implications of a changing environment on the daily life (e.g. more thunderstorms damaging traditional clay-houses) and agricultural activities (e.g. yield losses or reductions through drought) were reported, which resulted in the RET selection factor '*Protection of soil, water, air and biodiversity*'. At Ghoragachha and Baikunthapur (India), several environmental concerns were expressed. A decline in soil fertility and an increase in waste disposal and air pollution was reported. In addition, several concerns were expressed about observed changes in local weather conditions, including shorter rainy seasons, hotter temperatures in the non-monsoon seasons, a decline in rainfall frequency and intensity during the whole year. These changes lead to crop yield reduction. In contrast to the South African study, almost 30% of the Indian farmers attributed the emissions from fossil fuel and wood burning as causes to these changes.

Another important aspect was revealed. Indian smallholders produce food for self-consumption in organic home gardens. The Block Development Officer reported that the food produced on the fields with mineral fertilizers and pesticides is not for self-consumption, but for selling only, because the farmers consider these inputs averse to their health. Three of the interviewed smallholders considered the conversion to organic farming, because they observed negative impacts of mineral fertilizers and pesticides on soil fertility and thus productivity. Further, higher revenues for organic crops on the markets in Kolkata trigger the conversion to organic production.

In both cases several environmental concerns were raised that directly affect smallholder livelihoods negatively and thus force the farmers to adapt the production system and their livelihoods accordingly. The environmental concerns were found to be a strong motivational factor for sustainable energy and agricultural practices, like organic farming in India. Consequently, environmental factors determine the selection and uptake of new technology and practices in smallholder agriculture to a large extent. Indian farmers pursue already for more sustainable technologies and agricultural technologies to adapt to climate change and re-build soil fertility after input-intensive farming since the Green Revolution.

The elaboration of strategies for coping with climate change on local level requires the co-production of environmental knowledge, pairing local farmers' knowledge and expert knowledge from relevant disciplines (Kusnandar et al., 2019; Oliver et al., 2020; Zarei et al., 2020). Based on the combination of local and expert knowledge, climate change adaptation strategies in agriculture, specific to the local context, can be elaborated (Zarei et al., 2020). Thereby, all sustainability dimensions as well as institutional factors need to be explored and considered in a participatory learning process (Kusnandar et al., 2019; Oliver et al., 2020). The strategy of knowledge co-production was e.g. successfully applied

for the adaptation of the agricultural system to water-scarcity in Iran (Zarei et al., 2020), for the development of aridity-adapted rangeland management schemes in Patagonia (Castillo et al., 2020) and adapted farming-practices in a karst region in China (Oliver et al., 2020).
Hence, for securing and increasing agricultural productivity and smallholder biomass supply for the growing bioeconomy, a combination of both local farmers' knowledge and expert knowledge (e.g. researchers, extension workers) is required.

Smallholder farmers depend on the natural resource base and seasonal patterns. In both case studies, environmental concerns were raised by farmers, which push and motivate them to adapt and improve the production system through the utilisation of RET.

- Ongoing changes in the local environment (including soil, water, forests, biodiversity) and climate change push and motivate the farmers to take up sustainable technologies and agricultural practices in order to secure their livelihoods.
- Smallholder farmers in the researched areas consider those RETs appropriate that support both agricultural productivity and livelihoods.
- The co-production of environmental knowledge by smallholder farmers and experts from relevant disciplines provides the basis for adapting the agricultural system as well as the livelihoods to climate change supported by locally appropriate technologies and practices (Kusnandar et al., 2019; Oliver et al., 2020; Zarei et al., 2020).

<u>Social factors</u>

Both IREPA applications revealed a variety of social factors and their importance for appropriate RET selection. Social factors are often closely related to other factor categories. Social factors, for example, determine the utilisation of energy and the related technologies in the daily life, which in turn is influenced by environmental factors.
In the South African case, social factors constitute around access to sufficient water, food security as well as gender aspects and the social community structure. The surveyed smallholders expect an improvement in water and food security through RET implementation. Food security should be improved through additional income (or expenditure savings) or higher agricultural productivity. In rural areas in countries of the South, access to basic human needs, such as water and food, depend mainly on agricultural and related activities (Mandelli et al., 2016). Further, the social cohesion in the community shall not be altered through new technologies and associated practices, e.g. through an unequal distribution of RE benefits among households. Therefore, traditional or local leadership needs to be involved from the beginning to guide the community members throughout the RET selection

process. This helps ensuring that social well-being through access to modern and affordable energy is increased in a socio-cultural acceptable way on community level.
In the Indian case, the ease of daily activities through modern and affordable energy was the most important selection criteria. RETs need to match with the energy demand in terms of quantity and quality, considering both household and agricultural energy demand. The pursue towards a modern lifestyle was attributed to access to modern energy and thus serves as main motivation for the Indian smallholders to utilise RET. Modern information and communication devices want to be used and these require electricity. Also negative impacts on health and the burden of collection of traditional biofuels were reported and motivate for a change. Further, also education and the development of new skills was important to the farmers. The implementation of RET should always be accompanied with capacity building and skills transfer about new technologies and practices (Terrapon-Pfaff et al., 2018). This is not only important for operation and maintenance, but as well for the creation of new jobs and income sources e.g. by providing service for RETs or selling energy to other households.
The production and utilisation of modern RE in smallholder agricultural systems has therefore great potential to accomplish the basic human needs (water and food), ease daily activities, contribute to income creation and rural welfare and thus support sustainable agricultural development in countries of the South.
Social factors as well as stakeholder engagement and empowerment are essential for sustainable agricultural development, and if neglected, can lead to opposition and project failure (Kusnandar et al., 2019; Lemke and Claeys, 2020; Oliver et al., 2020). For successful agricultural development projects in rural smallholder systems, the following social factors have to be taken into account:

- New technologies and practices need to match the lifestyle and the livelihood needs on local level and thus requires the comprehensive assessment of relevant social factors.
- Social impacts and benefits associated with the use of an individual technology (like e.g. RETs) need to be explored, assessed and explicitly linked to the particular technology (Wirth et al., 2018).
- Capacity building based on participatory processes is a key-driver for rural development projects on agriculture, energy and the environment and should encompass all relevant social, environmental, technical, institutional and economic aspects (Kusnandar et al., 2019; Schindler et al., 2015; Terrapon-Pfaff et al., 2018).

5.1.5. *Summary:* The perspective of smallholder farmers on agricultural RE production and the learnings for the sustainability transition towards the bioeconomy

Today, the development of sustainability innovations takes place simultaneously in multiple locations globally (Köhler et al., 2019). For accelerating the sustainability transition, best-practice examples of technology and practices can be transferred to other areas, where an adaptation to the local context is required. This provides a shift from top-down technology transfer perspective, whereby innovations have been created in industrialized countries and are subsequently implemented in countries of the South, towards a bottom-up co-creation of locally appropriate solutions (Köhler et al., 2019).

The research on RET implementation into smallholder agricultural systems revealed the importance of matching new technologies and practices with the local context, based on a participatory exploration of social, environmental, technical, institutional and economic factors. Some of these factors support changes and act as drivers. These need to be taken up in the research process to reach and motivate local stakeholders. Some other factors pose barriers, which can be overcome by adapting the proposed solutions accordingly (e.g. high investment costs can be overcome by small, yet efficient technologies and do-it-yourself solutions) or reveal unsuitable technologies that should be removed from further assessment (e.g. in the South African case, the fear of using (bio-)gas for cooking or RETs that only benefit few community members and thus alter the social community structure).

The following drivers and barriers reveal the perception of smallholder farmers in rural South Africa and India on agricultural production, RE and environmental conservation, which are integral part of the sustainability transition towards the bioeconomy:

Barriers:

- High upfront investment costs of new technologies
  - Decreasing technology prices for RET (esp. solar and wind) (Arndt et al., 2019) break down this barrier. Consequently, those technologies are preferable where economies of scale have lowered the prices already.
  - Technology investment costs should be paid off through monthly savings of the replacement of the previously used energy carriers in case of RE or based on higher revenues / savings from a production cost reduction in case of productivity increasing agricultural technologies. By-passing loans for investment costs can increase the implementation rate of new technologies and involve more smallholder households.
  - Initially, rather simple and self-assembled RETs (with educational purpose) sufficient for covering the often low household energy needs (few hundred Watts) are preferable (Mandelli et al., 2016).

  - Where applicable, smallholders can become shareholders in different business models for medium to large-scale decentralized RE production, thus omitting technical investments (Thapar et al., 2017).
  - Dealer credit as well as hire or lease business models provide the option for smallholders to utilise modern technologies such as RE (Asian Development Bank, 2015) or farm mechanisation equipment (Daum and Birner, 2020).
- Lack of skills, knowledge and financial resources for operation and maintenance
  - Increasing smartphone and internet penetration in rural areas in countries of the South provide the chance for do-it-yourself RET and grant access to information about operation and maintenance as well as agricultural practices at the time it is needed.
  - Institutional support for open-access online manuals and practical step-by-step videos based on the local context and in local languages should be strengthened.
  - Capacity building and networking needs to go along with technology implementation for advertising the benefits of sustainable technologies and practices to involve further smallholders in the region (Terrapon-Pfaff et al., 2018).
- Land-use competition
  - Land is the basic source of income and thus smallholders tend to be reluctant of changing the land-use as well as leasing or selling land, e.g. for RE production. Therefore, the involvement of smallholders in medium to large-scale RE projects as shareholders or as (contracted) biomass producers is a potential pathway for not depriving smallholders from their land while still engaging them as stakeholders in rural development.
  - Areas around the houses and roofs are often available for RE production.
  - Smallholders with higher incomes and access to more land show higher willingness to implement new technologies and practices. These smallholders should be targeted first, as they can serve as practical example to subsequently attract further farmers.

<u>Drivers:</u>

- Environmental (and climatic) conditions
  - Smallholder livelihoods are directly impacted by climate change effects (e.g. change in seasonal patterns, droughts, etc.). This provides a strong intrinsic motivation to take up new technologies and practices. Smallholders consider those technologies (e.g. RET) and practices appropriate that support the adaptation of the agricultural production system and the farmers' livelihoods towards climate change.
- Institutional support

  - Government support schemes, private investments or a combination of both are crucial funding sources for the often low-income smallholders.
  - Government support schemes tend increasingly towards community or village RE projects, but should also provide incentives for household-based solutions in rural areas.
- Energy security
  - RE systems that increase energy security and reliability on household and farm level have higher chances of implementation and continued utilisation.
- Traditional community structure
  - Traditional community hierarchies and structures need to be explored and recognised in technology selection and implementation.
  - Local authorities (e.g. traditional leaders) need to be involved from the beginning. In the South African case traditional leaders were critical to project success.
- Gender sensitivity
  - Women are responsible for several household and agriculture-related tasks and thus a gender-sensitive research and capacity-building approach is required.
- Ease of daily living
  - New technologies and practices need to improve the lifestyle and benefit the farmer's livelihoods. Associated benefits of technologies and related practices need to be explored in the local context and explicitly communicated to increase understanding, while motivating multiple smallholders with different needs.

The production of RE in smallholder agricultural systems provides a promising pathway towards the sustainable increase in the supply of agricultural products (Daum and Birner, 2020; Mandelli et al., 2016; World Bank, 2017). Participatory bottom-up approaches provide crucial insights into the local context and provide the basis for the targeted formulation of agricultural development policies for involving the large number of 475 million smallholder households (Graeub et al., 2016; Lowder et al., 2016), in the sustainability transition towards a bioeconomy.

5.2. Contribution of urban agriculture and urban consumer behaviour to the sustainability transition towards a bioeconomy

Urban agriculture provides new cultivation areas and links the growing urban population to agricultural production. In this chapter, first the contribution of urban farming for increasing food production is discussed (Chapter 5.2.1), and secondly the potential of urban gardening to encourage a sustainable consumer behaviour (Chapter 5.2.2).

The Worldwatch Institute estimates that globally 15-20% of the food is produced in urban and peri-urban areas (Artmann and Sartison, 2018), while urban production alone accounts for 1-5% (Clinton et al., 2018). "*Most broadly, urban agriculture refers to growing and raising food crops and animals in an urban setting for the purpose of feeding local populations*" (Sanyé-Mengual et al., 2019, p. 2).
Urban agriculture re-emerged as trend in the US in the past two decades and is now becoming part of the urban lifestyle and city development in countries of the North. In countries of the South, it has ever since been required and been practiced for food security (Chatterjee et al., 2020; Clerino and Fargue-Lelièvre, 2020; McEldowney, 2017; Orsini et al., 2013; Paganini and Lemke, 2020). For example, in Kinshasa (Democratic Republic of Congo) and Dakar (Senegal), 65-70% of the vegetables consumed are produced within the cities (Clerino and Fargue-Lelièvre, 2020).
Urban agriculture is practiced in a wide variety of ways. In this thesis the focus is placed on two types of modern urban agriculture in the countries of the North and their societal role forthe sustainability transition towards the bioeconomy:
(i) Commercial high-tech, indoor production systems referring here to 'urban farming', and
(ii) 'urban gardening' activities of individuals or as community on available public and private areas including balconies, roofs, yards and other vacant areas.
Urban gardening is usually soil-based, utilizing garden plots, raised beds, mount cultures, pots and containers on almost any possible area outside for plant and crop cultivation (Chatterjee et al., 2020; McEldowney, 2017). Urban farms instead, often apply soilless hydroponic, aeroponic or aquaponic cultivation systems, combined with modern controlled indoor-environments to cultivate crops vertically in stacked systems (Al-Kodmany, 2018; Kalantari et al., 2017).

5.2.1. The potential of urban farming for increasing food supply

Globally, modern soilless cultivation systems play a major role in greenhouse cultivation since decades and recently moved into cities as indoor, vertical or roof-top farms (Kalantari et al., 2017; Shamshiri et al., 2018). Soilless cultivation has a better cost-effectiveness, a higher water- and nutrient use efficiency, a larger space productivity and a rather low weight of the cultivation systems (Barrett et al., 2016). Soilless systems make efficient use of available spaces, including rooftops, walls, yards and indoor areas for urban food production from small to large scale (McEldowney, 2017).

Vertical farming

On the large scale, the number of commercial high-tech vertical farms is increasing with the aim of producing a substantial amount of food calories for the growing urban population at the place of consumption (Al-Kodmany, 2018). Prominent examples include *Aerofarms*, who produce nearly 1000 tonnes of greens in Newark (US) annually, claiming to be 390-times more productive than conventional open field agriculture on square meter basis, while using 95% less water and no pesticides (Aerofarms.com, 2020); and *Sky Greens*, one of the first vertical farms in Singapore, which is operating since 2012, using a very space-efficient cultivation system based on hydraulic rotating tiers attached to nine meter high A-shaped towers. The area productivity is announced to be 10-times higher than monolayer farming (skygreens.com), producing about 10% of Singapore's vegetables (Benke and Tomkins, 2017).

Despommier, the founding father of the vertical farming concept, roughly estimates that a 30-floor vertical farm with a ground area 5 acres (about 2ha) could supply food to up to 10.000 people (Despommier, 2011). The vertical farm feasibility study of the German Aerospace Centre (DLR) estimated that a 1936m² (44m x 44m) vertical farm with 37 floors (167.5m height) has the potential to produce as much food as 216 ha of agricultural land (Zeidler et al., 2013). Considering the global average cropland footprint of 2000m² (0.2ha) per person and year (Schutter and Lutter, 2016), this exemplary vertical farm could roughly supply the food for 1080 people annually - on the cropland footprint of one person. Thus there is great potential for vertical farms to produce fresh and healthy food to the surrounding households in a decentralised, people-centred and demand-driven food system.

This could raise food self-sufficiency of cities, while reducing food miles substantially. For example, Berlins' food is produced to 72% on domestic land, to 7% in other EU countries and to 21% in non-EU countries (Hönle et al., 2017). Especially, the imported share of food could be reduced by vertical farms. In controlled indoor-environments even those crops can be cultivated which are not cultivatable outside under the given climatic, geographic or pedologic conditions.

However, the creation of artificial cultivation conditions, including photosynthetic active radiation, temperature and humidity control, fertilizer dosage and the building or greenhouse itself, requires large technical efforts and energy inputs. Irrespective of the high productivity and resource-use efficiency, vertical farms are often not economically viable. Reasons are the high investment, energy and labour costs (Al-Kodmany, 2018; Benke and Tomkins, 2017; Kalantari et al., 2017). The investment costs are estimated to be about $15 million for a modern vertical farm with controlled environment conditions, compared to the cost of a controlled environment greenhouse with about $280.000 (Toledano, 2019). These high costs result in a current production price of one kilogram of leafy greens in a vertical farm of about $33. The same amount of food can be produced on organic farms for $23 (Toledano, 2019). Further, the high energy demand is a threat to vertical farm sustainability. For example, lettuce grown in a vertical farm has a two to five times higher energy demand and thus CO_2 emissions compared to conventional farming (Al-Chalabi, 2015).

It is expected that technological advancements will decrease production costs considerably, making vertical farming a viable and resource-efficient option for urban food production (Al-Kodmany, 2018; Benke and Tomkins, 2017; Despommier, 2011; Shamshiri et al., 2018). Considerable advancements in vertical and indoor farming technologies are expected in the areas of cover materials (e.g. radiation transmittance), light control and artificial lights (e.g. LED), microclimate controllers (e.g. mechanical ventilation), indoor environment monitoring (e.g. wireless and cloud-based sensor networks, IoT-based monitoring and data sharing), energy efficiency (e.g. RE, energy and indoor environment optimisation models) and management (e.g. decision support models) (Shamshiri et al., 2018). These technical innovations are required because the existing greenhouse technology, does not fully fit the setups and conditions of vertical indoor farms (Al-Kodmany, 2018; Shamshiri et al., 2018).

Considering that these technological improvements are achievable within the next decade, vertical farms might be capable of producing substantial amounts of food for the growing urban population at the place of consumption, thus increasing the sustainability of urban food supply systems.

Rooftop and building integrated farming

On a medium scale, soilless cultivation systems are often applied in rooftop greenhouses and building integrated systems (Sanyé-Mengual et al., 2015). Both can subsequently be integrated into or onto existing builds e.g. on or in unutilized roofs, storeys and rooms. Modern cultivation systems can be connected with the building infrastructure, thus increasing the energy efficiency through combined heating/cooling, (grey) water recycling and gas exchange (CO_2/O_2) (Sanyé-Mengual et al., 2015). A special form of soilless cultivation systems at this scale are aquaponics, combining fish and crop production in recirculating systems. The aquaponic cycle maximises the nutrient and water use efficiency by drawing on synergies between both elements. Aquaculture effluent serves as nutrient solution for hydroponic crop production (Goddek et al., 2019). The cleaned water flows back into the aquaculture. The nutrients of the fish feed, which are only consumed to 25-35% by the fish, additionally nourish the crops (Goddek et al., 2019). The direct combination of both parts in one water cycle can reduce the water demand by up to 90%, compared to both system parts running individually (Goddek et al., 2019). However, the two parts in combination are not able to achieve the same productivity as stand-alone aquacultures and hydroponic systems (Kloas et al., 2015). A recent Bachelor thesis (co-supervised by the author of this thesis) revealed that the production costs of tomatoes and tilapia fish in a small aquaponic system on top of a parking lot in Stuttgart are about 80% higher compared to the purchase of organic tomatoes and tilapia filets (Mobayed, 2020). For increasing productivity, Kloas and colleagues (2015) developed a double recirculating aquaponic system. Two independent recirculating units allow for optimal water quality for the fish as well as for optimal pH levels for bacterial biomass decomposition (pH 7.0 – 9.0) and nutrient availability for the crops (pH 5.8 – 6.2) (Kloas et al., 2015). Plant nutrient deficiencies can be avoided by targeted fertilizer doses, thus increasing fish and crop productivity to almost the same level as of stand-alone systems, to achieve economic viability without harming the fish (Goddek et al., 2019; Kloas et al., 2015).

Consequently, modern soil-less urban farming, either in the form of vertical farms, roof-top or building-integrated systems can contribute substantially to food production in cities. New cultivation areas are exploited, while the cultivation systems show very high water and nutrient use efficiency, little food-miles and job-creation potential (Al-Kodmany, 2018; Benke and Tomkins, 2017; Goddek et al., 2019; Sanyé-Mengual et al., 2015). Consequently, urban farming is an important pillar for the growing bioeconomy, contributing to the biomass production of the 4F's in future.

Further development of vertical and indoor farming, however, needs to overcome the barriers of high investment costs, energy consumption and labour demand (Al-Kodmany, 2018; Shamshiri et al., 2018). The high production costs forced several vertical farms to stop operation in the past years, because the consequently high prices aggravated marketing of the food and uptake by the consumers (Specht et al., 2019). For example the largest European roof-top farm in The Hague (Netherlands) faced bankruptcy in 2018, after only two years of operation (Sijmonsma, 2018). A social barrier is posed by the fact that soil-less cultivation systems remain largely unknown by the public (Specht et al., 2019). Soil-less cultivation is often perceived futuristic and unnatural, because of the complex high-tech production systems. Many consumers still imagine their food being produced on small, diverse farms using organic methods in the nearby environment (Specht et al., 2019). Despite of the pesticide-free production and organic nutrient solutions in aquaponics, an organic certification, a measure often contributing to trust and consumer acceptance, is not granted so far for soil-less cultivation systems (Specht et al., 2019).

The integration of several sub-systems into decentralised circular production systems, based on natural ecosystems cycles and the direct involvement of the customers, e.g. through consumer-integrated business models, might contribute to overcoming the techno-economic and social barriers of modern high-tech production systems in urban areas.

Circular production systems

The integration of urban farming systems into the urban metabolism serves both the highly efficient use of inputs (including organic waste) and areas as well as the consumer – producer link (Clerino and Fargue-Lelièvre, 2020). Circular production systems go beyond the synergies of water, heat and gaseous exchange of roof-top and building integrated systems (Sanyé-Mengual et al., 2015). Despommier (2011) already sketched the vision of urban food production being connected with the surrounding building, collecting rainwater, harvesting solar energy, recycling organic wastes, grey-water and food wastes. Al-Kodmany (2018) briefly described a concept for a 'closed-loop system', whereby crop, fish and algae production is combined with a biodigester for nutrient recovery from organic residues and wastes, and bioenergy for supplying energy for the artificial cultivation environment. Such systems can be embedded in the city infrastructure for converting organic wastes, e.g. from food wholesalers, breweries and gastronomy into high-value and diverse food products for supplying businesses and consumers (Al-Kodmany, 2018).

Like in smallholder farming systems, the integration of RE production allows for the sustainable supply of (at least a part of) the energy required by vertical farms, through solar PV, solar-thermal, wind, bioenergy and combined heating/cooling concepts with adjacent buildings (Al-Kodmany, 2018; Kalantari et al., 2017). The space-use efficiency increases through the installation of RET on roofs and walls of vertical farms. RE increases sustainability of the farm and may lowers operation costs or increase revenues.

In particular, the integration of biodigestion provides multiple benefits. Organic wastes and residues can be converted into bioenergy, while at the same producing plant nutrients, humus and water – all of which can directly be re-utilised for biomass production (Stoknes et al., 2016). A combined heat and power unit (CHP) supplies RE to the building or greenhouse surrounding this circular food system. Also here novel approaches decrease the energy demand. For example, Stoknes et al. (2016) apply a novel approach to greenhouse insulation, whereby soap-bubbles between two greenhouse foils reduce the heat transmission substantially. Only 74% of the produced heat from the CHP was sufficient for greenhouse heating. Overall, the closed-loop system requires about 80% less energy than conventional greenhouse cultivation (Stoknes et al., 2016).

Circular production systems are based on the natural matter cycles and a cascading decomposition of biomass into several valuable products and thus fulfil two major bioeconomic goals. Past research in this field has focused mainly on combining two different production systems (e.g. aquaponics) or converting organic wastes and residues into products like e.g. algae as food, insects as food and feed, and mushrooms as food (Fig. 2). More recent research enlarged the focus to the integration of multiple components to make efficient use of organic wastes and residues.

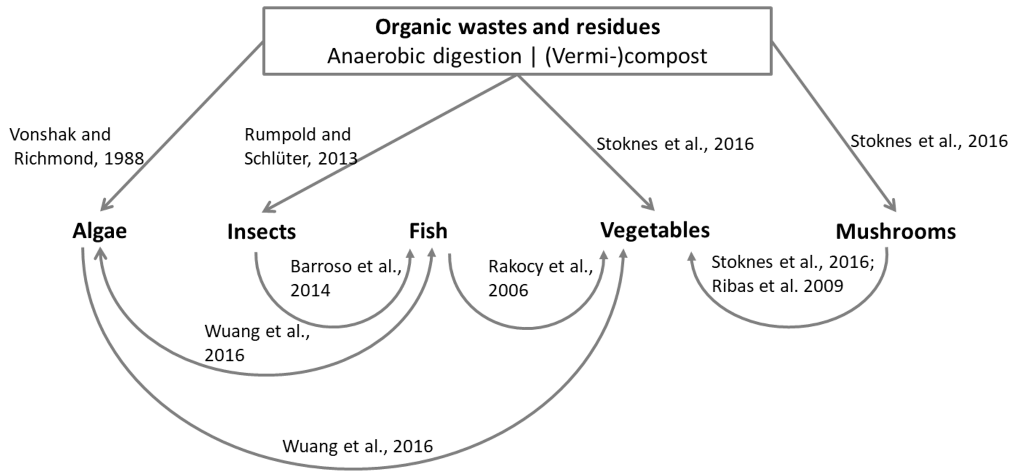

Figure 2: Result of a literature review on the feasibility of integrating algae, inset, fish, vegetable and mushroom production into a circular organic production system based on organic wastes and residues
(References represent researched links between individual components and the arrows the use direction; (Barroso et al., 2014; Rakocy et al., 2006; Ribas et al., 2009; Rumpold and Schlüter, 2013; Vonshak and Richmond, 1988; Wuang et al., 2016))

Stoknes et al. (2016) developed a pilot 'Food-to-waste-to-Food' system in Norway. Organic household and garden wastes are collected separately. The household waste is biodigested and the digestate separated into solid and liquid phases. One share of the solid digestate is vermicomposted and another share is mixed with paper waste, straw and chicken manure. Thereby the digestate is turned into cultivation substrate for edible mushrooms. The spent mushroom substrate is subsequently re-used for vegetable cultivation by mixing it with (vermi-) compost as well as solid and liquid digestate. Numerous experiments with varying ratios of mixtures revealed that the nutrients received from the organic waste and the liquid digestate fraction are sufficient to cultivate vegetables without any additional fertilizer. Moreover, the more natural cultivation substrate even showed higher yields e.g. of tomato, cucumber, lettuce and parsley, compared to soilless cultivation in a hydroponic system with mineral fertilisation (Stoknes et al., 2016).

Hence, circular food-to-waste-to-food production systems open up a new field of highly resource-efficient food production based on available resources and waste. Such systems are independent of arable land, climatic conditions and system size (as shown below) and are thus applicable to almost any location where sufficient amounts of organic waste arise.

Moreover, the sustainability of circular production systems is remarkable. Direct methane emissions can be reduced by 98% compared to landfilling of organic waste. The CO_2 emissions of tomatoes can be reduced by 95% compared to conventional greenhouse production. Potentially, no mineral fertilizers and pesticides are needed. Spent cultivation substrate waste (e.g. rockwool) from greenhouse production, can be reduced by 32kg m^{-2} a^{-1}. Instead, 157 kg of organic waste can be recycled per square meter food cultivation area annually. Water recycling can decrease the water-footprint by 80% compared to conventional greenhouse horticulture (Stoknes et al., 2016).

These figures of this pilot system are stunning and reveal the great potential of circular urban production systems for urban food production, supporting the vision of the EU of turning cities into bioeconomy hubs with focus on organic waste recycling (EC, 2018).

For the scale-up of such circular systems, further interdisciplinary research is necessary to explore and understand the microbiology and the processes involved in order to overcome existing challenges related to high variations in pH and EC levels and nutrient trade-offs between nitrate, phosphorous and chlorine (Stoknes et al., 2016). Based on that appropriate management systems of the microbial food web needs to be established to scale-up circular production systems that are based on organic waste and residue recycling (Stoknes et al., 2018). These early stage developments of circular production systems point out their great potential for the urban bioeconomy. The 'Food-to-waste-to-Food' system was capable of producing equal or even higher vegetable yields under research conditions, at a minimum of the water, the nutrients, the pesticides and the energy inputs of state-of-the-art greenhouse crop production (Stoknes et al., 2018).

Utilising organic waste and residues as main resource for food production in circular production systems contrasts with modern soilless greenhouses and vertical farms. The basic premise of soilless approaches is that the technology provides the vital resources (e.g. LED light with defined spectra, fertilizer, water) directly to the plant in an abiotic environment e.g. under cleanroom conditions like in vertical farming (Al-Kodmany, 2018). This can be considered a *technology-2-plant* approach.

Circular production systems, however, use modern technologies to create the conditions for diverse natural growth and decomposition processes, thereby providing a biotic environment for the plants to grow. This approach can be considered a *technology-2-growth-condition* approach, which comes closer to natural conditions. In natural ecosystems plants grow and interact with various abiotic and biotic factors in growth and decomposition cycles of food webs. 'Nature-based solutions' (see Chapter 5.3.1) explore and draw on natural principles and biologic processes (EC, 2020c) that emerged through plant-environment interactions over the past 420 million years (Pflanzenforschung.de, 2013). Therefore, bioeconomic research should focus on natural and biological solutions, in order to increase resource-use efficiency and cut negative environmental impacts of agricultural biomass production. Natural solutions had much more time to develop, compared to human agricultural (technology) development, which has 'just emerged' since 12000 years (Pflanzenforschung.de, 2013). Understanding natural resource cycles and the biology involved, offers ample solutions for sustainability problems, because natural processes utilise resources most efficient in close and wide cycles without producing any (hazardous) waste.

Modern technology developments and manufacturing seek for inspiration in biological processes (e.g. lightweight construction, biomechanics) and are already capable of integrating biological systems into technical systems (Miehe et al., 2020), like it is the case in controlled-environment urban farming.

Circular production systems develop these systems further by replacing chemical and technical processes by biological processes. Bio-integrated systems (Miehe et al., 2020) and biorefinery concepts (Cherubini, 2010) provide the backbone for the development of the bioeconomy.

The circular terrabioponic garden systems (see Chapter 2.2 and Chapter 3), developed by the author of this thesis, follow natural principles and thus rely only on natural resources available in urban areas. These include sunlight, (rain-)water and organic household wastes. Through two modular designs, terrabioponic gardens fit on small spaces for example on balconies, flat roofs and in interior yards in cities – thereby creating a natural ecosystem for urban gardeners to cultivate, interact and learn about natural ecosystem processes and cycles. Therefore, circular production systems can raise awareness about sustainable agricultural production and at the same time about sustainable consumer behaviour thus supporting the sustainability transition towards the bioeconomy.

5.2.2. The potential of urban gardening for supporting a sustainable consumer behaviour

In addition to the provision of diverse agricultural products including RE, the consumption patterns and thus the consumer behaviour is of crucial relevance for a sustainable use of natural resources in a growing bioeconomy (EC, 2018). The importance of addressing and connecting the supply and demand site is reflected by '*Sustainable Development Goal 12*: Responsible Consumption and Production' (UN DESA, 2020). How urban gardening can influence the consumer behaviour and act as a potential starting point for a more sustainable lifestyle, is discussed in the following section.

The demand-site problem of food waste

To date an enormous amount of food is wasted - including land, water, nutrient, energy and labour resources used for its production. A recent study revealed that the amount of food wasted by consumers on global scale has been underestimated by a factor greater than two (van den Verma et al., 2020). Based on an energy gap and consumer affluence approach, it was found that 19% of the food calories produced for consumption are wasted by consumers (527 Kcal day^{-1} $capita^{-1}$), instead of the previously assumed 8% food wastes (214 Kcal day^{-1} $capita^{-1}$) – based on the identical FAO dataset from 2005 (Kummu et al., 2012). Adding the food lost along the supply chain, the total food loss and waste accounted for 614 Kcal day^{-1} $capita^{-1}$ or about 25% of the food calories produced globally in 2005 (Kummu et al., 2012). Kummu et al. (2012) further estimated that the 25% food losses also 'waste' 24% of the agricultural land, 23% of the fertilizer and 23% of the water resources. Thus the potential of reducing food waste is huge. The food wastes could instead feed about 1 billion people (Kummu et al., 2012). Unfortunately, the amount of food wasted even increased from 2005 to 2011 to 727 Kcal day^{-1} $capita^{-1}$ (van den Verma et al., 2020).

Food waste is strongly correlated with the income level, which are highest in North America, Europe and Australia. At a per capita income above \$6.70 day^{-1}, politicians in countries of the South should put measures in place to avoid food waste (van den Verma et al., 2020).
The issue of the still growing food waste shows that a theoretical reduction of food waste to zero could supply about 25% (or more) of the projected 70% food demand increase. This high share of food wasted by consumers points out the urgent need of a responsible consumption behaviour, which is required for the sustainability transition towards the bioeconomy.

Approaches for increasing sustainable consumer behaviour – the case of urban gardening

In 2019, 79 countries had policies in place promoting sustainable production and consumption patterns (UN DESA, 2020), for example in Europe, the FOOD 2030 policy framework and the Updated Bioeconomy Strategy (EC, 2018, 2016). Political strategies often raise awareness about sustainable consumer behaviour through sustainability standards and information provision (EC, 2018; Pekkanen et al., 2018). The basic premise of this top-down approach is that unsustainable behaviour is grounded in a lack of knowledge. Standards guide consumers while the provided information illustrates in various formats 'what consumer should do' (Grilli and Curtis, 2021). Waste and energy are currently the topics addressed by most behaviour change studies, while the food waste issue was only addressed by few studies so far (Grilli and Curtis, 2021).
The motivations for and the impacts of urban gardening go far beyond food production. The demography and the backgrounds of the urban gardeners are manifold and include (as explained in detail in Chapter 3) on social level e.g. awareness about healthy and sustainable nutrition, food security, local recreation, meeting places supporting communication and community feeling; on environmental level e.g. habitat creation, improvement of city climate, climate change mitigation; and on economic level e.g. productive utilization of unused spaces, new forms of private-public partnerships and new income sources (Chatterjee et al., 2020; Clerino and Fargue-Lelièvre, 2020; McEldowney, 2017).
Basically, urban crop and plant cultivation turns the growing number of consumers in cities into producers, confronting them with the need of acquiring the necessary knowledge and skills about how to actually grow plants. Urban gardeners gradually engage with the basic plant growth requirements such as soil (or substrate), nutrients and water, the utilisation or disposal of plant residues, pest and disease management and local cropping calendars (Fig. 3). Through plant cultivation these aspects become part of the daily life. Thereby the gardeners are confronted with multiple questions, options and choices. For example, from the question of how to sustain and increase soil fertility, they might learn about humus and its functions. From its formation through CO_2 sequestration, the topic of climate change arises. This way, the links between urban plant cultivation, natural processes and the

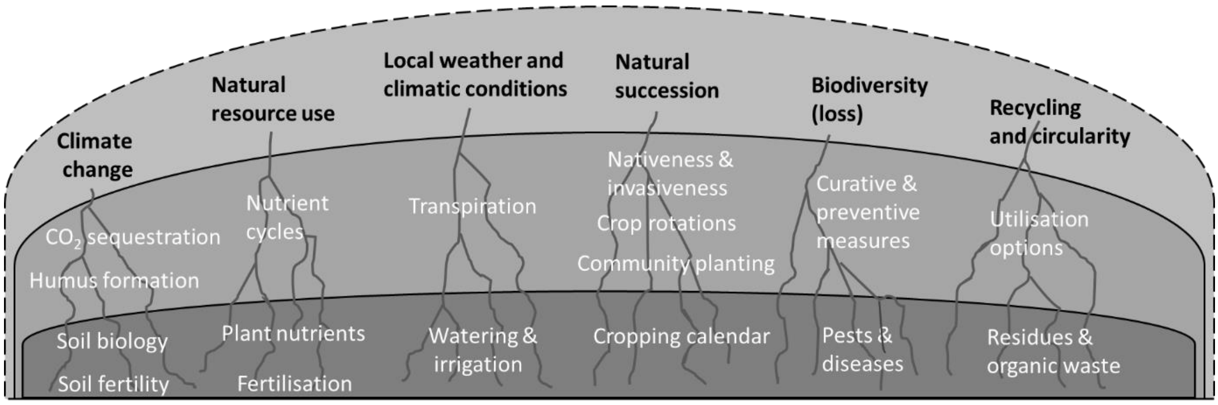

Figure 3: Emerging links of urban plant cultivation with natural processes and the societal challenges of the 21st century

societal challenges of the 21st century may arise and become visible (Fig. 3). Similarly, fertilisation options (mineral / organic) lead to the topic of plant nutrients and to an understanding of nutrient cycles and the broad topic of natural resource use. The water demand of a plant depends on its physiology, determining the transpiration rate in the local cultivation environment. Supplying sufficient water is based on the interplay with the local weather and climatic conditions, determining the watering or irrigation strategy. Further, urban gardeners need to stick to seasonality and local cropping calendars. When gardening on smaller patches or raised beds, multiple plants are cultivated next to each other and in sequence. Community planting and crop rotations become eminent to the gardeners. This planning procedure requires at least some knowledge about plant characteristics, which in turn are determined by their native growing area and the functions of the plant in the respective natural succession. For pest and disease management, the gardeners might apply curative and / or preventive measures. For both, the right timing of application is crucial, opening up the fields of, for example, insect development stages, suitable growing conditions for fungal diseases or vectors of viruses and thus the topics of food webs and biodiversity. Once the plants have been harvested, residues are left. Several utilisation options are available, including composting, mulching, animal feed or disposal, from which the gardeners need to derive an appropriate management strategy, which brings the topics of organic waste recycling and circularity on the table. These emerging links from garden level to societal level may made the German urban gardeners more conscious about food production and more sustainable food consumption choices, like found in Chapter 3.

In literature, five approaches are distinguished for fostering a pro-environmental behaviour (Grilli and Curtis, 2021). These approaches are applied (unintentionally) in urban community gardens and may explain the transformative potential of urban gardening for the sustainability transition towards the bioeconomy:

(i) *Education and awareness:* The emerging links of gardening towards the wider sustainability aspects described above fall into this category. Information provision methods are frequently applied due to their comparably low costs, but lead to a success in only 60% of the cases (Grilli and Curtis, 2021). Information and education are in particular suitable for people who have already an interest in environmental issues and willingness to apply sustainable behaviour (Grilli and Curtis, 2021). These people, who are rather female than male, are characterised by openness to change, self-transcendence and self-direction (Pekkanen et al., 2018). For example, people who consider sustainability labels in product purchase choices are receptive for information (Pekkanen et al., 2018). These characteristics are also reflected by the urban gardeners and the self-driven information exploration about plant cultivation. Urban gardening requires and supports information uptake and renders dedicated *education and awareness* methods effective in this context. Digital information acquisition and exchange are also emerging in the urban gardening community. In Germany, 33% of the urban gardeners utilise internet fora, while 18% are interested in supportive smartphone-apps (Chapter 3). In addition, online gardening and do-it-yourself manuals, compilations of gardening hints and webinars on various topics are increasing, e.g. on the website of '*die anstiftung'* - the largest urban gardening community in Germany (die anstiftung, 2020). An interactive step-by-step guideline in form of a smartphone app might turn additional people into urban gardeners. Interactive guidelines might be suitable for beginners to familiarize them in a playful way with gardening and support a successful harvest for a motivating experience.

However, bare education and awareness approaches are less likely to initiate a change in the consumer behaviour by people with mind-sets building on tradition, conformity and security as well as self-enhancement, depicting power, achievement and hedonism (Pekkanen et al., 2018). For such people, interactive and guiding formats of gardening assistance, e.g. through smartphone apps, might increase conformity (many people use it), security (easy accessible gardening know-how on smartphone), self-enhancement (obtaining new knowledge) and achievement (successful harvest) for gardening beginners.

(ii) *Nudges:* An interactive urban gardening app can also serve as *nudge* for initiating a sustainable consumer behaviour. Nudges are subtler methods compared to explicit information about do's and don'ts, aiming at altering the decision context of individuals in a desired way (Grilli and Curtis, 2021). Examples include appealing and large recycling bins or the energy utility that normally supplies RE electricity, unless customers demand fossil energy. Nudges are often successful and gain popularity, but often come along with high costs, e.g. due to additional materials for more or larger recycle bins or the software development costs of an app. In addition, nudges have a manipulative dimension as the free-choice of individuals is influenced partly obscured. Therefore, nudges are often combined with direct and open methods (Grilli and Curtis, 2021). To make education and awareness methods more effective, the point of information and the way it is delivered is important, to overcome the 'implementation gap'. This gap refers to the disparity between the opinion of people, who e.g. state in surveys that the purchase of biobased products is very important for protecting nature and climate

(31%), and the actual behaviour, where e.g. only 10% actually purchase biobased products (Lang, 2019). Obtaining the information directly at the point of purchase or having it easily at hand on the smartphone in this moment, increases sustainable product choices (Grilli and Curtis, 2021). Consequently, the digital provision of information about gardening can satisfy the knowledge and skills needs, may attract other societal groups to participate in urban gardening activities and allows for having the information at hand when required.

(iii) *Social influence:* In contrast to digital and thus non-personal offers, the personal information provision or a tailored feedback on consumption choices show a stronger influence on changing the consumer behaviour (Grilli and Curtis, 2021). Personalised information and feedback are able to transfer the (sustainable) behaviour from one person to another. Thereby the influence is higher the closer the personal relationships or the social groups are. Sustainable behaviour changes can be induced through members or leaders of social groups acting as positive example, through public commitment making (e.g. self-sufficiency of vegetables), through reference models practising a certain behaviour (e.g. organic gardening methods) and through feedback interventions (e.g. no use of pesticides in the urban community garden). The success of these methods is attributed to the link of behavioural changes with personal relationships (Grilli and Curtis, 2021). Like shown and discussed in article 3, the communities formed in urban gardens are a crucial driver for the overall urban gardening trend. Gardening communities have the capacity to create a new neighbourhood feeling and lasting relationships, bridging heterogeneous groups of people with different power and social statuses (McIvor and Hale, 2015; Rogge et al., 2018). Consequently, the social influence in urban community gardens for building pro-environmental consumer behaviour among the members can be considered high.

(iv) Outreach and relationship building: Similarly, to social influence, 'outreach and relationship building' comprise various methods and actions that foster personal relationships and community building. Often methods from *education and awareness* as well as *social influence* converge in a rather long-term process of relationship building through several interactive group-meetings, e.g. in workshops, trainings, focus-groups and community-building exercises. Thus, outreach and relationship building processes are the methods with the highest success rates for behaviour changes in the long term. Due to high costs of interactive group-meetings, these are typically applied when several sustainability challenges want to be tackled (Grilli and Curtis, 2021). The already high level of social influence in urban community gardens can be strengthened and accelerated through formalised outreach and relationship building programmes, e.g. offered by municipalities or regional governments as part of the city development plans. For manifesting the multiple benefits of urban gardening, municipalities start to offer support programmes. Examples include *Parisculteurs* in Paris with the aim of creating an urban gardening area of 100ha (Ville de Paris, 2020) or *'urban green'* in

Stuttgart fostering the improvement of the city climate (Stadt Stuttgart, 2020). Outreach and relationship building methods are in these two pioneer cases combined with organisational support (e.g. finding suitable cultivation areas) and direct funding for initiating and maintaining urban gardens (Stadt Stuttgart, 2020; Ville de Paris, 2020).

(v) *Incentives* comprise subsides, direct payments and discounts (monetary) as well as free materials, gifts and coupons (non-monetary) to influence a certain consumer behaviour as often applied in government schemes and programmes (Grilli and Curtis, 2021). The method itself and its success is questionable, because the awareness of consumers is distracted from the sustainability problem towards people's welfare. Hence, the effect of an incentive-induced behaviour change might only last until the incentive is removed. Incentives are thus mainly applied in public-service domains including waste, energy and water management (Grilli and Curtis, 2021), where e.g. a separation of waste reduces the costs of municipal recycling facilities while increasing the recycling rates. For increasing the impact of urban gardening to foster a sustainable consumer behaviour, municipalities and city governments should subsidize *outreach and relationship building* actions of urban community gardens, in order to attract more people to urban gardening.

Consequently, urban gardening represents a very promising trend that fosters a more sustainable consumer behaviour by applying four out of five behaviour change incentives (often unintentionally). Especially, personal engagement and relationships within social (garden) groups, are known to be most effective in inducing a behaviour change (Grilli and Curtis, 2021), because real life consumption choices take place embedded in social structures and rules affecting the consumer (Pekkanen, 2020). This can partly explain the 'implementation gap' between the consumers' opinion about sustainable behaviour and the real choices made in a particular social setting (Pekkanen et al., 2018).

For supporting sustainable consumer behaviour on societal level, urban gardening projects should receive more attention and (financial) support from cities, municipalities and governments. On the one hand, political support in form of *social influence* on local to national government level is required to raise awareness among municipality departments and politicians about the benefits of urban gardening. This might lower the administrative barriers for establishing an urban gardening project on public spaces, for which often permissions from multiple city departments are required. On the other hand, cities and municipalities should fund and subsidise the various activities of urban gardens, in particular outreach and relationship building as well as education and awareness, like the pioneer cities Stuttgart and Paris have implemented already (Stadt Stuttgart, 2020; Ville de Paris, 2020).

Sustainable behaviour is prolonged and spreads further, the more it is embedded in practices and daily-life actions, which are shaped by institutional structures and meaningfulness in the socio-cultural context of the consumer (Pekkanen, 2020). Through urban gardening, people engage in a community with several real-life sustainability problems, based on own interest and willingness to change. This way, several social (e.g. social cooperative farms, community roof-top gardens) and technical innovations (e.g. indoor farming, domestic and commercial aquaponics, integrated roof-top greenhouses) are born that solve sustainability problems from local to global level (Sanyé-Mengual et al., 2019). In turn, cities and municipalities benefit greatly from the social, environmental and economic sustainability outcomes of urban community gardens on multiple levels (Clerino and Fargue-Lelièvre, 2020; Sanyé-Mengual et al., 2019). Therefore, urban gardening is part of three major city development aims: increased well-being, increasing food security and achieving sustainable cities and communities (SDG 11) (Ambrose et al., 2020) and is thus a strong driver of the societal sustainability transition.

Urban gardening supports the bottom-up transition towards a sustainable bioeconomy

Urban gardening not only supports a sustainable consumer behaviour, but has multiple other benefits for sustainable cities and thus the development of the bioeconomy in urban areas. The majority of participants joined community gardens in Germany because urban gardening '*represents something bigger'*. Urban gardens are spaces that create communities consisting of people with a wide variety of backgrounds e.g. in terms of demographics, educational level and social classes. Aspects related to environmental conservation and sustainability, social community, health, social inclusion and political activism motivate the inhabitants to spend their time in a meaningful way, encompassing self-enhancement, collaboration with others and involvement in city and block development while addressing and tackling the societal challenges of the 21st century.

The main motivation, found in Chapter 3 for German gardeners, is the joy and happiness associated with gardening activities. A recent study from the US revealed that urban home gardening strongly supports emotional well-being (Ambrose et al., 2020). Highest emotional well-being was reported by female and lower-income study participants and for vegetable gardening compared to ornamental gardening. Further, gardening was among the top-five leisure time activities (out of 15) across the assessed categories (net affect, average happiness and peak happiness) without being statistically different from the other high ranked activities such as recreation/leisure, biking and eating out (Ambrose et al., 2020). This might be attributable to the intrinsic desire of humans to re-connect with nature ('re-grounding') (Borgstedt, 2012), which becomes possible on daily-life basis for the urban population through urban gardening.

Environmental sustainability is another strong motivation for and objective of urban gardening in countries of the North. The strong association of urban gardening with the environment and sustainability was revealed by numerous studies from various countries including the US (Grebitus et al., 2020; Opitz et al., 2016), the UK (Miller, 2015), Germany (Borgstedt, 2012; Rogge et al., 2018;

Sanyé-Mengual et al., 2019), France and Spain (Sanyé-Mengual et al., 2019), Italy (Gasperi et al., 2016; Sanyé-Mengual et al., 2019; Sanyé-Mengual et al., 2018), Switzerland (Lewis et al., 2018) and Croatia (Gulin Zrnić and Rubić, 2018). Typically, the urban gardeners aim to tackle several sustainability challenges including "*climate change, food security, biodiversity and ecosystem services, agricultural intensification, resource efficiency and land management*" as summarized by Artmann and Sartison (2018, p. 1) who reviewed the sustainability dimensions of (peri-) urban agriculture in the global North. In addition, green (garden) areas in cities provide ecosystem services with a global value of $88 to $164 billion, thus substantially increased well-being of urban inhabitants (Clinton et al., 2018).

Finding solutions for the multiple societal sustainability challenges drives the global development of the bioeconomy. The sustainable bioeconomy should be based on natural matter cycles and conciliate economic growth with environmental conservation and climate change mitigation (BMBF, 2014; BMBF & BMEL, 2014). Initially, the development of the bioeconomy is mainly driven by top–down approaches in form of policy agendas and research strategies focusing on technical innovations and processes that aim at the substitution of fossil resources with biomass and the creation of green business models (Leipold and Petit-Boix, 2018; Peltomaa, 2018). Nowadays, more emphasis is put on the inclusion of the society and the role of the consumer in the development of the bioeconomy (Lang, 2019), like described e.g. in the updated bioeconomy strategy of the EU (EC, 2018) and the national bioeconomy strategy of Germany (BMBF & BMEL, 2020). Therein the civil society and societal stakeholder groups are directly addressed, e.g. through stakeholder workshops, consumer-integrated product development, acceptance studies and public outreach activities such as the 'Science Year Bioeconomy 2020/21' in Germany (BMBF, 2020). The societal transition towards the bioeconomy can be supported by combining existing trends from the green and sharing economy with integrative components such as citizen science and urban gardening (BMBF & BMEL, 2014).

Like elaborated in this chapter, urban gardening plays a key-role for the societal transition towards a bioeconomy from bottom-up. Urban gardening engages the growing urban population in food production and promotes sustainable consumer behaviour.

5.2.3. *Summary*: Urban farming can support urban food production, while urban gardening triggers sustainable consumer behaviour

Urban agriculture supplies much more than just food. The diverse functions of urban farming and urban gardening support the sustainability transition of cities for the development of the bioeconomy:

(i) Urban farming - Soilless crop cultivation systems under controlled environment in vertical farms

- Vertical indoor farming shows very high productivity levels and demonstrated to increase the land use efficiency by 10 to 1100-times (!) (Aerofarms.com, 2020; Zeidler et al., 2013), depending on the location, design and type of the production system. This entails great potential for a substantial urban food production in a resource-efficient and sustainable way (Al-Chalabi, 2015; Al-Kodmany, 2018; Shamshiri et al., 2018).

- To date high investment costs, a very high energy demand for the controlled-environments and high manual labour efforts challenge economic feasibility and sustainability of this new farming approach (Al-Kodmany, 2018; Shamshiri et al., 2018; Specht et al., 2019), requiring further research on soilless crop cultivation and technological advancements.

(ii) Circular production systems – Integration of multiple biomass and renewable energy production systems

- The integration of several production systems (e.g. vegetables, mushrooms, fish), RE (e.g. solar, wind, biogas) and further technical advancements increase the resource use efficiency, economic feasibility and sustainability of modern urban farming (Al-Kodmany, 2018; Zeidler et al., 2013).
- Circular production systems are designed and planned, based on natural matter cycles and processes, including self-supporting functions and the recycling of organic wastes and residues. Based on that, multiple valuable products, including food, feed, RE, water and nutrients are produced in multiple cascading sub-production systems. External inputs such as fertilizer, water and energy are minimized through resource circulation (Al-Kodmany, 2018; Despommier, 2011; Stoknes et al., 2018; Stoknes et al., 2016).
- The integration and combination of biological processes in technically-controlled production systems provides a promising approach for modern technology and efficient manufacturing (Miehe et al., 2020), the development of biorefinery concepts (Cherubini, 2010) and sustainable (urban) agricultural systems.

(iii) Urban gardening - Community gardens fulfil multiple functions in addition to food production

- Urban gardening engages 'urban consumers' in food production thus creating awareness in the society for the sustainability challenges of the 21st century, including climate change, biodiversity, ecosystem services and natural resource use (Artmann and Sartison, 2018).
- Urban gardening supports sustainable consumer behaviour, by (unintentionally) applying multiple approaches (*education and awareness, social influence*, *nudges, outreach and relationship building)* that encourage pro-environmental behaviour (Grilli and Curtis, 2021).
- The growing sustainable consumer behaviour has great potential to reduce consumer food waste thus lowering the pressure for increasing agricultural food production by up to 25% (van den Verma et al., 2020).

- The increase in emotional well-being (Ambrose et al., 2020), the re-connection with the environment (Borgstedt, 2012) and supportive digital gardening applications are strong drivers for engaging even more urban inhabitants in urban gardening, making it an integral part of sustainable city development (SDG 11) (Ambrose et al., 2020).
- The multiple social, environmental and economic benefits of urban gardening should be stronger acknowledged and supported by cities and municipalities for fostering the urban sustainability transition towards the bioeconomy.

5.3. Contribution of environmental service monetisation in agricultural systems to the sustainable intensification of biomass production

In this chapter the contribution of the environmental service assessment and monetisation for a sustainable intensification (SI) of agricultural production is discussed with the aim of determining an SI pathway for the growing bioeconomy.

First, the concept and the drivers of SI are explored (Chapter 5.3.1); second, the new measures of the European Common Agricultural Policy (CAP) are examined with respect to their contribution towards increasing sustainability in the European agriculture (Chapter 5.3.2); and third a pathway for sustainable agroecologic intensification is outlined, based on the enhancement und utilisation of environmental services in agricultural systems (Chapter 5.3.3).

The individual environmental services as well as their assessment and monetisation approaches have been discussed in Chapter 4 of this study, thus the discussion here focuses on the implications of environmental service assessment and monetisation for rendering agricultural biomass production more sustainable.

The exploration, analysis and monetisation of environmental services in agricultural systems and landscapes alters the perspective from the ‘production only’ approach of conventional, input-based industrial production systems (TEEB, 2018). In these systems, the focus is limited to the production elements of biomass value chains, including stocks, flows, outcomes and impacts that are tangible and have a market value (TEEB, 2018). Acknowledging, measuring and valorising the currently invisible environmental services in agricultural systems, provides the basis for conserving and enhancing these services inevitable for human life (TEEB, 2010) and for reducing negative impacts of these agricultural systems on society and the environment (Matzdorf et al., 2010).

5.3.1. Pathways of sustainable intensification in agriculture

The sustainable biomass production is a crucial prerequisite of the development of the bioeconomy in Germany (BMBF & BMEL, 2020), in Europe (EC, 2018) and should be the goal globally (Lewandowski, 2015). The concept and policy approach of SI aims at a pathway for increasing biomass production for the 4F’s (including food waste reduction) on existing agricultural land (Garnett et al., 2013). A key-feature of SI is the conservation and enhancement of biodiversity and the services of natural ecosystems. Further, the natural resource base has to be utilised within the planetary boundaries, while mitigating climate change (Garnett et al., 2013; Steffen et al., 2015).

The SI concept framed the goal for the future of agriculture, but the approaches and measures to reach this goal were (Garnett et al., 2013) and are still not defined (Cassman and Grassini, 2020). Cassman and Grassini (2020) recently made an attempt to determine the SI research agenda, based on the definition of (i) the time frame, (ii) the expected biomass demand increase and (iii) the required improvement in environmental performance of agriculture. Subsequently, the (iv) locations with the highest productivity gains, and the (v) suitability of different agricultural approaches for achieving this goal can be explored on local level. This results in (vi) the priority areas for further SI research and development (Cassman and Grassini, 2020).

Following this approach, the typical time frame until 2050 (Cassman and Grassini, 2020), e.g. used by FAO, OECD and the UN is suitable (FAO, 2009b; OECD-FAO, 2009; UN DESA, 2013). Based on the robust global food demand projections by Tilman et al. 2011, an annual yield increase of 1.55% is required to meet the future food demand in 2050. This translates into a total yield increase of about 50% on the existing agricultural land in the upcoming 30 years, focusing on those areas with the highest yield gaps (Cassman and Grassini, 2020). These areas need to be identified based on bottom-up yield gap assessments based on local data on soils, cropping systems and climate (Cassman and Grassini, 2020). Participatory approaches like IREPA can inform and support local data exploration (chapter 5.1.2), may be embedded in a stratified sampling structure of consecutive case studies in order to derive generic insights on regional level based on modelling approaches (Köhler et al., 2019).

Futhermore, Cassman and Grassini (2020) propose a 50% reduction of negative environmental impacts. The 50% value refers to the required N load reduction of the Mississippi watershed to reduce hypoxia in the Gulf of Mexico and is thus considered reasonable for the prioritization of the SI research areas (Cassman and Grassini, 2020).

SI research should target those crops with the highest current demand and those agricultural systems already well-researched and known today (Cassman and Grassini, 2020). Given the rather short time frame of 30 years for achieving the SI target, it is unlikely that disruptive technologies, new crops and new cropping systems are being developed within three decades that are able to boost agricultural productivity in the order of magnitude required (Cassman and Grassini, 2020). Therefore, the development of SI solutions requires a holistic approach that not only stems from basic and applied agricultural science, but from an interdisciplinary cooperation across multiple sectors (Cassman and Grassini 2020) and clearly determined sustainability targets that focus on systemic solutions based circularity, high-resource use efficiency and the involvement of all relevant stakeholders along biobased value nets, as outlined in Chapter 1.4, and the (urban) consumer perspective (Chapter 5.2).

According to Cassman and Grassini (2020), important sectors and disciplines for agricultural development include computational science and digitalisation (e.g. big data analysis), molecular biology (e.g. genetic engineering) and landscape ecology. These sectors will be explored in the following section.

Digitalisation and computational science

Key-technologies developed in the area of computational science and digitalisation comprise e.g. autonomous vehicles, robotics, artificial intelligence (Gordon, 2018), sensor-systems and internet-of-thing applications as well as digital information and management systems (Wolfert et al., 2017). These digital applications were transferred gradually in the agricultural sector over the past two decades and it is likely that this gradual development will continue in the next decades, without bringing up disruptive technologies or process (Gordon, 2018).

To date no distinct impact of a digital key-technology on the annual yield increases of about 1% of the major crops wheat, corn and soy has been recorded so far (Cowen and Southwood, 2019). The great transformative change of digitalisation on business models took place before 2006 (Gordon, 2018) and was achieved mainly through the miniaturisation of computing. This lead to the breakthrough of personal computers, internet, tablets and smartphones (Mokyr, 2018). These advancements allowed businesses to increase the speed of data collection and information exchange as well as selling and buying inputs and products globally. The largest impact of digitalisation, however, was on the consumer side, with the development of a digital environment consisting of multiple social networks, messenger and streaming services and online shopping (Gordon, 2018).

Nevertheless, digitalisation has an important facilitating role for the SI of agriculture, especially through information access, networking and selling/buying inputs/products globally. Farmers benefit from this development, like introduced in Chapter 5.1.4, e.g. through having access to required information at the time it is needed, for sharing best-practice examples and innovative approaches globally as well as selling agricultural products across countries. Furthermore, precision farming and sensor-based management systems support farmers in utilising inputs more efficient, e.g. through plot-specific fertilisation based on N-sensors, thereby increasing productivity and sustainability of agricultural systems, thus supporting the development of the bioeconomy.

When aiming at increasing sustainability, however, it is important to consider and anticipate technology and innovation “bite-backs”, referring to the real costs of an innovative technology on the environment and the society that often manifested years or decades after the innovation was taken up (Mokyr, 2018). Prominent examples include Chlorofluorocarbon having deprived the ozone layer, the insecticide DDT that accumulates at the upper end of food webs and impacts on negatively on health, antibiotics in animal production leading to multi-drug resistance and the eutrophication of water bodies through mineral fertilisation (Mokyr, 2018). Therefore, SI research and the selection of new and innovative technologies and processes for the growing bioeconomy need to undergo rigorous risk assessments to reveal the long-term sustainability performance.

Molecular biology and genetic engineering of perennial biomass crops

The molecular biology sector, including biotechnology and genetic engineering, is another key-area for increasing agricultural biomass production (Cassman and Grassini, 2020). These sectors contributed to a large extent to the productivity increases of the major agricultural crops in the past (Fuglie, 2012; OECD-FAO, 2009). However, despite the great success of genome sequencing and editing, allowing for the manipulation of living beings, green genetic engineering might not be able to provide a breakthrough within the next 30 years in the areas of current research, including photosynthesis rate, nitrogen-use efficiency or drought resistance (Cassman and Grassini, 2020). Unlike crop disease and insect resistance, the aforementioned traits are controlled by numerous genes. Manipulating these genes results in various trade-offs. Understanding the roles of the multiple genes and finding ways for engineering approaches requires time and large investments (Cassman and Grassini, 2020). These are currently and will likely not be provided in the near future, because the success of increasing photosynthesis rate, nitrogen-use efficiency and drought resistance of the main food crops is highly uncertain (Cassman and Grassini, 2020).

Genetic engineering and breeding approaches can adapt crops, especially perennial industrial crops important for material and energetic use in the bioeconomy, to the various bio-physical constraints of marginal agricultural land (Pancaldi and Trindade, 2020). Like elaborated Chapter 4 of this thesis, the production of perennial biomass crops can provide relief to both the competition for land between the different biomass utilisation pathways and the decline of arable land by restoring and enhancing soil fertility through the environmental services provided by perennial cropping systems. Perennial biomass crops, comprising tall grasses such as miscanthus, switchgrass and different reed species as well as fast growing trees such as poplar, willow, Siberian elm and eucalypthus (Pancaldi and Trindade, 2020), are thus a potential solution for the food-energy-environment trilemma. Adapted perennial crops (through breeding) are able to ameliorate marginal land (e.g. depleted soils) within their lifetime. With increased soil fertility, these areas might become again available for food production (Cossel et al., 2019). Such a land-restoration approach might be most suitable on marginal land areas that have been degraded through the intensive cultivation of annual crops in conventional agricultural systems in the past decades. On these areas the climatic conditions have been suitable for rain-fed agriculture in the past and might likely be under climate change with specifically selected crops and adapted varieties through breeding. Taking depleted as well as other marginal land areas (back) into agricultural production has great potential for re-increasing the arable land for the future without jeopardizing e.g. natural forests, savannah areas and wetlands for arable land expansion and the valuable services and habitats these ecosystems provide.

Therefore, sustainable non-food biomass cropping systems should be primarily established on marginal lands, in order to enhance soil fertility, biodiversity and environmental services (Cossel et al., 2019). Another option is the integration of perennial biomass crops into the typically annual food production systems. Diverse multi-cropping systems increase the resilience of the production system for climate change adaptation while enhancing biodiversity and environmental services (Cossel et al., 2019). Consequently, breeding industrial biomass crops, in addition to the major food crops, provides a promising option for producing large quantities of biomass for material and energetic use for the growing bioeconomy, while at same time ameliorating degraded agricultural land for future food production. Moreover, this approach of integrating perennial crops into typically annual crop based monoculture agriculture increases biodiversity and ecosystem services as well as their utilisation in agriculture.

Landscape ecology and nature-based solutions

The integration of perennial biomass crops into agricultural systems can enhance both biodiversity and landscape aesthetics while not competing with, but rather supporting food production through the provision of multiple ecosystem services such as pollination, pest and disease control and soil fertility improvement (Cossel et al., 2019). This landscape ecology approach that is based on the dynamics of biodiversity, ecosystems and their services, can support solving the food-energy-trilemma through sustainable perennial-based cropping systems, as described in chapter 4. Furthermore, landscape ecology, and in particular the ecosystem services provided to society, and landscape aesthetics is important for the public acceptance of new agricultural biomass production systems (TEEB, 2018).

For increasing the biomass production sustainably, soil fertility and increasing humus levels is a key area. At the same time, natural carbon sequestration in the soil is a crucial measure to mitigate climate change (Aertsens et al., 2013; Minasny et al., 2017). Humus is formed by soil fauna on macro (e.g. earthworms and insects), meso (e.g. springtails, enchytraeids) and micro (e.g. nematodes, protozoa) level through the decomposition of various biomass (Ruiz et al., 2008). Options for increasing soil fertility, and thus for marginal land restoration, include the establishment for leguminous cover crops, green manure crops, perennial biomass cropping systems and multi-cropping systems that include perennials (Altieri and Nicholls, 2012; Cossel et al., 2019). Recently, Kalt et al. (2019) investigated a new approach, by comparing the carbon sink potentials of bioenergy from short rotation coppices and ‘natural succession’ on arable land. Within the first 20 to 50 years the spontaneous vegetation sequestrates more carbon in the soil than the replacement of liquid transport fuels or natural gas-based electricity from short rotation biomass. Consequently, natural succession is a natural carbon sink with multiple benefits for soil fertility, biodiversity and the enhancement of environmental services at minimal costs (Kalt et al., 2019).

Such nature-based solutions (NBS) become increasingly recognised and draw on or apply natural principles with the aim of creating benefits on environmental, social and economic level in a very cost-effective way (EC, 2020c). Typically, NBS are locally adapted and enhance the resource-use efficiency through natural functions, processes and features in various aspects of daily life in rural and urban areas. (EC, 2020c). Like concluded in chapter 5.2.1, drawing on, learning from and integrating biological solutions and processes in technically-controlled production systems (Miehe et al., 2020) provides a very promising approach for the SI of agriculture. Hence, for SI of agricultural biomass production an interdisciplinary research approach is required to explore and develop systems-level solutions based on natural principles and the integration of natural processes into the agricultural sector to enhance and make efficient use of ecosystem services.

The main lessons drawn from the past for the future of innovations for a sustainable increase of the biomass production for the bioeconomy are that (i) there is no technical reason for economic welfare growth and equal distribution to slow down (Mokyr, 2018), but at the same time (ii) there are no innovations anticipated in the areas of digitalisation or molecular biology that are able to boost (agricultural) productivity like the second industrial revolution between 1920 and 1970 did (Gordon, 2018), despite the fact the number of agricultural researchers working today on the major crops increased 23-times (Bloom et al., 2020).

Therefore, the SI pathway has to focus on the intelligent integration of already existing and soon-to-come innovations from digitalisation and breeding into agricultural systems. Furthermore, NBS derived from natural ecosystems provide key-solutions to re-connect agriculture with the surrounding (natural) landscapes. The introduction of perennial (biomass) crops into agricultural systems increases diversity and environmental services of agricultural systems, with the latter providing benefits for the production systems (e.g. soil fertility increase) and the society (Cossel et al., 2019; Möndel, 2007; Rosati et al., 2020). For the implementation of new technologies, practices and crops in the local context, case-based and participatory research is required as proposed for sustainability transition research (Köhler et al., 2019; Lang et al., 2017)

Furthermore, the focus of SI research on the uptake of agricultural practices and technologies that increase resource-use efficiency and sustainability, while reducing GHG emissions, require collaborative governance and long-term agricultural policies (OECD, 2019). The EU has recognised the great potential of NBS and intends to invest considerably in research and development of tangible pilots and demonstrations that increase well-being and welfare at lower monetary and environmental costs than technical solutions (Maes and Jacobs, 2017).

Bridging the gap between agriculture and nature is central to the European Green Deal and the current reform of the Common Agricultural Policy (CAP) of the EU in order to cope with and identify solutions for the fundamental societal challenges of the 21st century (BMEL, 2020; EC, 2020f).

5.3.2. CAP reform for sustainable agriculture in the European Union

The reform of the EU CAP aims at strengthening the link between agriculture and natural ecosystems. The new CAP (which is during the writing of this thesis at the stage of the trilogue between the European Parliament, the Council of the European Union and the European Commission) is based on the Green Deal and the related new strategies including the ‘Farm-to-fork-strategy’, the ‘EU Biodiversity strategy for 2030’, the ‘Updated Forest Strategy’ as well as the upcoming ‘Zero Pollution Action Plan’ and an ‘EU climate law’ (EC, 2020a, 2020b, 2020f). For agriculture, the main goals are 50% reductions in the use of pesticides and the use of antibiotics in animal husbandry (including aquacultures) as well as a 20% reduction in mineral fertilizer use (EC, 2020a, 2020f). The fertilizer reduction aim can be attributed to the Nitrate Directive and the EU Water Framework Directive, which came into law already in 1991 for ensuring good ecological conditions of the water bodies in the EU (EC, 2020e). The EU aims are thus very similar to those presented by the US-based researchers Cassman and Grassini (2020), also referring to the protection of water bodies and biodiversity, when proposing 50% less environmental impacts by agriculture until 2050.

For achieving these aims, the CAP builds on a ‘green architecture’ and includes a new ‘conditionality’ of direct payments, combining cross-compliance and greening measures as mandatory rules for direct per hectare payments (pillar one), and a new ‘eco-scheme’ that is backed up with 20% of this first pillars’ budget. With these new key-measures, the EU ties the direct payments to environmental actions of farmers (BMEL, 2020; EC, 2020d). Consequently, farmers have to fulfil higher environmental standards for receiving the direct payments of the first pillar (80% of budget), while 20% of the first pillars’ budget is shifted to the new eco-schemes (BMEL, 2020) promoting sustainable agricultural practices and measures that explicitly enhance environmental services (BMEL, 2020; EC, 2020d).

However, multiple environmental organisations (including Greenpeace, WWF Europe, Birdlife Europe, Agricultural and Rural Convention, and Friends of the Earth Europe (Matthews, 2020), as well as over 3600 scientists (Pe'er et al., 2020) argue that the ambitious aims of the Green Deal are by far not reflected in the CAP reform and that the current targets and budget allocation schemes are basically continuing business-as-usual (Matthews, 2020; Pe'er et al., 2020). In the proposed form, the new CAP still pays 80% of the budget to the 20% largest farms (and land owners) claiming minimum environmental standards, while marginalising the large number of the EUs’ small farms (Pe'er et al., 2020). The allocation of 20% of the pillar one budget is insufficient and at least 30% are required to increase environmental sustainability of agriculture in the EU (Pe'er et al., 2020).

On political level the CAP reform as well as the new strategies mentioned above provide a break-through for sustainable agriculture in Europe. On practical level the newly introduced eco-schemes provide the farmers at least with some financial incentive to test and evaluate sustainable practices that increase biodiversity, enhance environmental services and mitigate climate change.

For taking environmental service provision really into account the goal has to be based on direct payments on the monetised values of environmental services on farm level, like argued in Chapter 4. Nevertheless, until 2027 the measures that are supported by the eco-scheme, including agroecology, agroforestry and high nature value farming (e.g. semi-natural habitat creation and enhancement) (EC, 2021) provide a starting point to bridge the gap between agriculture and nature. The recent update of the Ecosystem Services Valuation Database (ESVD) complemented "The Economics of Ecosystems and Biodiversity" (TEEB) database to a total number of 4,042 monetary values for ecosystem services, including environmental services in agricultural landscapes (Groot et al., 2020). For environmental services from agriculture a dedicated database needs to be developed as basis for incentivising payments to farmers either from public budget like the EU CAP or from consumers e.g. in form of an ecosystem service certificate.

Therefore, the new CAP can be considered a starting point for the SI of agriculture in Europe triggering the sustainability transition on farm level. Inputs such as mineral fertilizers and pesticides need to be considerably reduced (e.g. through integrated pest management, leguminous crops, residue management) and subsequently be replaced by organic agricultural practices, ecosystem services and other nature-based solutions.

5.3.3. Sustainable agroecologic intensification

The agricultural measures of the new CAP rely on the scale-up of well-known existing solutions, like suggested by Cassman and Grassini (2020) for the development of the SI research agenda. Until 2030, the arable land under organic agriculture should rise to 30% (EC, 2020b) from 7.5% in 2018 (Eurostat, 2020). However, organic and conventional agricultural systems are both intensive and highly-specialised. Both rely on to a large extend on monocultures for the cultivation of predominantly annual crops or the husbandry of one or a few animal species (Rosati et al., 2020). The difference between the two systems is the kind of input. Organic farming is thus an input substitution approach to conventional agriculture without striving for real diversification (Andrade et al., 2020). For solving the societal challenges of the 21st century, however, a fundamental re-design of the agricultural system appears to be required (Altieri and Nicholls, 2012; FAO, 2014b; McIntyre, 2009; OECD-FAO, 2009; Rosati et al., 2020). Therefore, new and alternative approaches that are based on natural principles and environmental services become more and more in focus in the sustainability transition of agriculture. Such systems include already quite well-known agroforestry systems (Damant and Villela, 2018; Möndel, 2007; Reeg, 2009; Rosati et al., 2020) and agroecology (Altieri and Nicholls, 2012; Pretty and Bharucha, 2014) as well as the emerging field of regenerative (Gosnell et al., 2019; LaCanne and Lundgren, 2018; Lal, 2020; Newton et al., 2020) and syntropic agriculture (Andrade et al., 2020; Cossel et al., 2020; Schulz et al., 1994).

Agroecology: Environmental service based agriculture in countries of the South

To date, agroforestry is still the main land-use in the tropics and has been in Europe for centuries until it got replaced by conventional farming systems. Considering all forms of agro-forestry, including silvopastoral, silvoarable and agrosilvopastoral systems, it is currently practised on about half of the global agricultural area (Rosati et al., 2020). Agroforestry is considered an agroecological approach that is based on diversification as well as temporal and spatial stratification of the agricultural system (Rosati et al., 2020). Agroecology draws on natural principles and processes in order to develop and apply nature-based solutions adapted to the local conditions with high resource-use efficiency instead of external inputs (Altieri and Nicholls, 2012). Agroecologic approaches aim at minimizing water, energy and nutrient losses from the system through enhancing the natural cycles of biomass growth and decomposition through biotic activity for increasing soil fertility. Diversity, interactions and biological synergies provide the basis for diverse environmental services and resilient agricultural systems (Altieri and Nicholls, 2012; Pretty and Bharucha, 2014).

The development and performance of agroforestry and agroecologic systems is based on agro-biodiversity and the inclusion of perennial crops (Altieri and Nicholls, 2012; Rosati et al., 2020; Wanger et al., 2020), such as trees, shrubs, grasses (e.g. industrial biomass crops). Perennial crops fulfil multiple functions for several years and thus considerably enhance environmental services, including:

habitat provision for a wide range of animals, insects and birds; alteration of microclimate through shading (thus lower evaporation and higher dew formation), reduction in wind speed (and thus less wind erosion), less temperature fluctuations and protection against climate extremes; permanent soil cover through canopy layers leading to higher water infiltration and less surface run-off (thus reducing water erosion of top soil and nutrient losses); litter fall of deciduous crops and root biomass turnover provide nutrient and water inputs that circulated within the system; nutrient uptake from different and deeper soil layers; allopathic effects of litter and root exudates (Möndel, 2007; Reeg, 2009; Rosati et al., 2020).

Agroforestry systems typically have a higher abundance and diversity of insects, soil arthropods and birds thus improving natural pest and disease control as well as pollination (Rosati et al. 2020). These beneficial effects also lead to higher yields of adjacent crops. For example in Germany, a 6% higher grain yield of winter rye was obtained on 5% less cropping area, due to the environmental services provided by a tree/hedge row on the field (Möndel, 2007). In addition, also the trees or shrubs generate a yield (depending on species) while the reduction in inputs and labour due to a smaller field improve the overall system productivity and financial profitability (Möndel, 2007).

In another example from the US the pest abundance in insecticide treated maize fields was 10-times higher than in maize fields managed agroecologically. Whereas the grain yield on agroecologic farms was found to be 29% lower, the overall profit of these farms was 78% higher compared to conventional maize farming. Reason are the substantial reductions in labour, energy, machinery and input costs after adopting agroecologic practices. The study further showed that the profitability of the ten agroecologic farms assessed, was correlated with particulate organic matter and not with yield (LaCanne and Lundgren, 2018). Hence, agroecology tends to be profitable, despite of lower yields, because the costly inputs are replaced by the enhancement of ecosystem services and soil fertility.

Farming plots with agroecologic practices face less erosion and have 20-40% more topsoil with higher soil moisture content than adjacent conventional plots, as it was shown by a large data set of 360 communities in Guatemala (Altieri et al., 2012). Aertsens et al. (2013) reviewed the carbon sequestration potential of agriculture in the EU-27 and found agroforestry to be most effective with a technical potential of 2.75 tonnes of carbon per hectare and year (1.5 to 4.0 t C ha^{-1} a^{-1}), compared to cover crops (0.16 t C ha^{-1} a^{-1}), hedge-rows and no till (each 0.1 t C ha^{-1} a^{-1}) (Aertsens et al., 2013). The C-sequestration of agroforestry has a value of 282 € per hectare and year (Aertsens et al., 2013), which is lower but within the range of the value estimated for miscanthus (217 € ha^{-1} a^{-1}) in chapter 4. The extrapolation of the average C-sequestration value of agroforestry (2.75 t C ha^{-1} a^{-1}) to the agricultural area in Europe (about 140 million hectares), reveals a technical C-storage potential in biomass and soils of on average 1566 million tonnes $CO_{2\text{-eq}}$ annually (Aertsens et al., 2013). This would account for more than half (55%) of the total emissions of CO_2 equivalents in the EU in 2019 (IEA, 2020a), while at the same time increasing soil fertility.

Agroecologic approaches have great potential to mitigate climate change while enhancing environmental services (e.g. CO_2 sequestration) and biodiversity for the production of diverse yields at minimum negative environmental impacts (Hathaway, 2016; LaCanne and Lundgren, 2018; Möndel, 2007; Reeg, 2009; Wanger et al., 2020).

However, the lower corn yields reported by LaCanne and Lundgren (2018) are in line with the argument against organic agriculture, considered unable to produce sufficient food for the growing world population. The organic yield of the major cereal crops (wheat, wheat, maize, rice, barley, rye and oats) are about 81% of the cereal yield achieved in conventional farming (Tittonell, 2014). Therefore organic farming could benefit greatly from the inclusion of agroecologic approaches and practices that enhance environmental services, while retain the benefits of modern agriculture including mechanisation and high labour-efficiency (Rosati et al., 2020).

Organic as well as agroecologic approaches focus on building up soil fertility over time. Consequently, also the crop yields are likely to increase gradually with improved soil fertility. Like shown by LaCanne and Lundgren (2018), in agroecologic farming the productivity is strongly correlated with soil organic matter, which takes years and decades to build up. A meta-analysis of agroecologic approaches implemented by 10.4 million African smallholder farmers revealed on average a 2.13-fold productivity increase (Pretty et al., 2011). Brazilian maize farmers increased the yield level by 60% through agroecologic practices (Altieri et al., 2012). A large-scale example for yield increases through agroecologic practices is Cuba, where the use of agrochemicals got reduced by 77% due to the US-embargo in the 1980s. Initially the productivity dropped between 1988 and 1994 (vegetables -65%, roots and tubers -45%), but re-increased considerably for both crops until 2007 to 145% of the 1988 levels through the adoption of agroecologic practices (Rosset et al., 2011).

This example shows that it takes time until agroecologic practices come to fruition fully, as the soil, flora and fauna needs to adapt and build up under new management forms.

Another important aspect is the energy efficiency of the production system. Smallholder farmers in Cuba feed 10 to 15 people from one hectare based on manual labour. The energy efficiency of the agroecologic production system is about 10:1 (output : input) (Altieri et al., 2012). When animal power is used the energy efficiency drops to 3.1 : 1 to 4.3 : 1, like reported from smallholder farmers in Mexico and Guatemala. The application of mineral fertilizers and pesticides further decrease the energy efficiency to less than 2.5 : 1 (Altieri et al., 2012). Consequently, the higher the inputs of a farming system, the less energy efficient it is. For mitigating climate change, however, the energy efficiency of the biomass production needs to increase in order to reduce energy-related GHG emissions.

These references on the productivity and energy efficiency of agroecology (for more see e.g. (Altieri et al., 2012; Pretty et al., 2011), however, originate from smallholder farming in countries of the South, where the highest agricultural productivity gains can be achieved (Bruinsma, 2009). There agroecological production methods prove to substantially enhance biomass productivity, biodiversity and soil fertility while reducing external inputs to a minimum. Therefore, a transfer and adaptation of agroecologic principles, best-practice examples and environmental service management knowledge to temperate climates is required (Cossel et al., 2020; Rosati et al., 2020).

Regenerative agriculture: Sustainable intensification in Countries of the North

In recent years the term ‘regenerative’ agriculture emerged in countries of the North. In the book ‘*Growing a revolution*’ US-Geologist David R. Montgomery stated that regenerative agriculture will be 5th agricultural revolution that transforms the unsustainable conventional agricultural system of today into sustainable biomass production systems for the future (Montgomery, 2017). Starting from the domestication of plants and animals (1st revolution), soil management and crop rotations (2nd revolution), industrialisation and mechanisation (3rd revolution) and the ongoing 4th biotechnological revolution, now the focus of the 5th revolution is on restoring soil fertility and setting agriculture within ecosystems based on a holistic perspective (Montgomery, 2017).

To date the term ‘regenerative agriculture’ is used inconsistently in literature and remains undefined (Newton et al., 2020). According to Newton et al. (2020), who reviewed 229 scientific articles and 25 practitioner websites that refer to regenerative agriculture, concluded that it comprises approaches that aim on the reduction of negative and the enhancement of beneficial (net positive) environmental and/or social impacts (Newton et al., 2020). Regenerative agriculture basically refers to the broad field of agroecologic agriculture, including biodynamic agriculture, carbon farming and alternative agriculture. Specific emphasis is on storing carbon from the atmosphere in biomass and soil (Lal, 2020). The number of studies on regenerative agriculture increased since 2015 and practitioner websites emerge to provide information about regenerative agricultural practices (Newton et al., 2020). This can be considered the beginning of agroecologic farming and the research-based assessment of agroecologic practices and agroforestry systems in temperate climates in the Countries of the North (Cossel et al., 2020; Rosati et al., 2020).

Today, however, it is difficult for farmers to find research-based information about individual measures and their implications on their particular agricultural system. The newly established eco-schemes can support practical application of agroecologic measures and agroforestry by providing a financial backup to support farmers with the exploration of agroecologic practices at a comparably low risk. At the same time research into regenerative agriculture increases and thus supports the development of new production systems and practices in countries of the North.

Recently, a five-year project, funded by the Federal Agency for Nature Conservation, was initiated in the Federal State of Brandenburg in Germany. The project aims at the assessment of the biodiversity and scalability potential of five different agroecologic forest-garden systems on total area of 11 hectare (BfN, 2020). Another project was co-initiated by the author of this thesis in 2019, to assess the potential of 'regenerative' syntropic agriculture (explained below) as renaturation measure for a stone quarry site in the Federal State of Baden-Württemberg. On two demonstration plots with stony soil, a management plan is under development that aims at guiding natural successional processes in direction of accelerated soil fertility improvement and environmental service provision thus allowing for food production at this marginal land in few years only. The approach is published as communication article to engage with the wider scientific and practitioner community (Cossel et al., 2020).

From entropy to syntropic agriculture for the bioeconomy

Syntropic agriculture, a specific form of agroecologic farming, gained in popularity after the 21st United Nations Framework Convention on Climate Change (COP21) in Paris in 2016. Syntropic agriculture applies agroecologic principles (Altieri and Nicholls, 2012) and embeds them in a management path of temporal and spatial stratification striving for maximising photosynthesis and thus biomass productivity per area (Andrade et al., 2020). The syntropy approach has been developed by the swiss farmer Ernst Götsch over 45 years in Brazil (Andrade et al., 2020; Götsch, 1995; Schulz et al., 1994).

The guiding term '*syntropy'* refers to the natural process complementary to entropy. In thermodynamics the law of entropy refers to energy dissipation, while syntropy is the accumulation and concentration of energy (Andrade et al., 2020). The mathematician Luigi Fantappie found, while studying the equation that unites quantum mechanics and special relativity that the positive mathematical solution to the equation is entropy, while the negative solution to the equation is syntropy. The properties of the law of syntropy are concentration of energy, differentiation, order and organisation. Syntropy thus basically describes the fundamentals of life and all living systems (Vannini and Di Corpo, 2011). The term 'bioeconomy' was formulated as antonym to the economic system based on unlimited growth, which exceeds the planetary boundaries and is contradictory to the natural law of entropy (Bonauiti, 2015). The counteracting natural law of syntropy may provide the guiding principles of natural order and organisation of agricultural systems for a sustainable increase in biomass production for the bioeconomy.

Applying syntropy to agriculture means to focus on natural succession and stratification in order to concentrate energy in form of biomass within the production system (Andrade et al., 2020). In practice this refers to the selection of diverse plant species (perennial and annual) and the arrangement of these plant species in canopy layers (like in agro-forestry) mimicking the natural strata. An optimal layer distribution gets denser from top to bottom for optimising photosynthesis and thus biomass growth. This also leads to a temperature gradient with the lowest temperatures at the bottom. Combined with continuous soil cover (e.g. litter fall, harvest residues and dedicated mulch plants) evaporation, erosion and weed pressure is considerably lowered, while nutrient cycles, soil life and biodiversity are enhanced (Andrade et al., 2020). Syntropy is about the concentration of radiation energy from the sun within the production system for fuelling all biological processes and *"placing each cultivated plant in their 'just right' position in space (strata) and in time (succession)"* (Andrade et al. 2020, p. 22). The abiotic conditions and thus the natural resource base at each location will be utilised optimally through its biological parts that also build up and organise (self-)regulating environmental services.

The syntropy approach complements the agroecologic principles by aligning the focus from 'minimizing' losses of water, nutrients and energy (Altieri and Nicholls, 2012) towards maximisation of photosynthesis and thus biomass productivity based on the location-specific, optimal arrangement of the crops in space and time (Andrade et al., 2020; Schulz et al., 1994). Syntropic agriculture is based on the following three basic principles:

(i) Optimisation of photosynthesis: Regular pruning and cutting enhances light penetration into the multi-story cropping system (Götsch, 1995; Schulz et al., 1994). Plant removal should take place immediately before their maturity, because afterwards allopathic growth reducing effects hamper the growth of neighbouring plants. In turn, a production system should contain young plants, which can accelerate vegetative growth of adjacent crops (Schulz et al., 1994). Further, native plant species should be incorporated. These usually perform optimally under the local conditions, thus increasing overall biomass productivity and energy accumulation. This enhances biodiversity and various biotic processes that provide environmental services for the agricultural system (Götsch, 1995; Schulz et al., 1994);

(ii) Constant soil coverage: Regular mulch application avoids erosion and enhances water infiltration, soil fauna, nutrient cycling and humus formation. Pruning material and residual biomass is typically coped and applied to the soil, woody trunks are additionally split in half. All biomass and its nutrients, water and energy remains within the system, except the harvest for consumption, based on the premise to keep and circulate as much as possible within the production system in order to accumulate energy (Damant and Villela, 2018; Schulz et al., 1994).

(iii) Species selection and temporal and spatial stratification: The selection and arrangement of the main perennial crops are based on the use (harvest) period in temporal species succession. After the species' high-yield period, it should be cut (and used as mulch) to allow for the emergent species to come to fruition subsequently (Götsch, 1995; Schulz et al., 1994). Neighbouring plant and crop species are arranged based on allelopathic effects, e.g. pest and disease control, nutrient and water demand. This enhances the environmental services including nutrient cycling, pest and disease control, pollination and habitat creation in order to make use of them and gradually increase diversity, resilience and productivity of the system (Götsch, 1995).

Syntropic agriculture can be considered process-based approach, instead of input-based conventional and organic agriculture (Andrade et al., 2020). Organic farming taking up agroecologic processes to increase sustainability (Rosati et al., 2020), as proposed by the CAP reform in the EU, is a step-wise or incremental procedure to enhance and make use of environmental services within the given agricultural production system. Case studies introducing syntropic principles to smallholder agroforestry systems in the Cerrado and the Atlantic Forest regions in Brazil report substantial yield increases of vegetables and fruits (1.6 to 8-times) (Andrade et al., 2020).

However, most of the agricultural management steps in syntropic production systems are performed manually. For the scale-up of syntropic agriculture, new technologies and machinery are currently under development with the label 'peace farming technology' (Andrade et al., 2020). The focus is on mechanisation of soil preparation, sowing and harvesting as well as cutting / pruning and mulching with minimal disturbance. The first machine developed is the 'Tree line preparer' (rhenusTek GmbH, Switzerland), a combination of rotary hoe and cultivator for sowing and planting with minimal disturbance of the soil horizons (Pasini, 2019).

For the transfer and adaptation of syntropic agriculture and its principles to temperate climates, some case study experience exists. According to Andrade et al. (2020), there are already about 5000 family farms that adopted syntropic principles. From there it spread across other Latin American countries, and more recently also to Europe with individual farms in Spain, Portugal, Italy, France and Germany (Andrade et al., 2020). Gosnell et al. (2019), who analysed the transition of conventional farming towards climate-smart, regenerative agriculture in Australia, concluded that this transition is much more than climate change induced adaptions of agricultural practices through innovation, education and supporting policies (Gosnell et al., 2019).

Several regenerative agricultural approaches exist (Newton et al., 2020), including syntropic agriculture (Andrade et al., 2020), permaculture (Mollison and Jeeves, 1988; Rosati et al., 2020) and agroecology (Altieri et al., 2012; Pretty and Bharucha, 2014) for supporting the SI of agricultural biomass production based on environmental services and nature-based solutions. These agricultural approaches promote a fundamental change in the human-nature perspective and the consumer-producer relationship (Andrade et al., 2020; Rosati et al., 2020), including non-material factors like culture, values, identity, emotion and ethics (Gosnell et al., 2019), while bridging the gap between agriculture and nature, which is required for the sustainability transition towards the bioeconomy.

5.3.4. Summary: Assessment and monetization of *environmental services in agricultural systems supports the sustainable biomass production in the growing bioeconomy*

The assessment and monetization of environmental services in agricultural systems is a key-solution for intensifying the sustainability of concurrent agricultural production systems:

- The value of nature can be expressed through the valorisation of environmental services in monetary units, which are basically understandable by every person worldwide (TEEB, 2010). This supports the human-nature relationship necessary for the sustainability transition (Andrade et al., 2020; Rosati et al., 2020).
- Sustainable intensification sets the premises and frames the goal of future agricultural development. Interdisciplinary collaboration of multiple sectors, including computational science and molecular biology (Cassman and Grassini, 2020), is required to explore, understand and utilise nature-based solutions and environmental services as integral part of the sustainable intensification of agricultural biomass production for the bioeconomy.
- The sustainability transition in agriculture requires a fundamental shift from input-based towards process-based agriculture that manages natural succession and enhances the productive use of environmental services (Andrade et al., 2020; Rosati et al., 2020).
- Agroecologic approaches have been developed over the past decades in countries of the South. There substantial productivity and energy efficiency increases have been achieved in

smallholder farming systems by enhancing and utilising environmental services instead of synthetic inputs (Altieri et al., 2012; LaCanne and Lundgren, 2018; Pretty et al., 2011). Substantial research is required for adapting these promising practices to temperate climates in countries of the North in order to provide robust information and know-how to the farmers.

- The new EU CAP intends to make agriculture in the EU sustainable (EC, 2020f). The new eco-scheme provides European farmers with a financial backup for exploring and adapting sustainable practices like e.g. agroecology and agroforestry (EC, 2020f). For the sustainability transition of European agriculture being effective, however, the eco-scheme of the new CAP requires a substantially higher share of the first pillars budget (least 30%) (Pe'er et al., 2020).
- Syntropic agriculture complements agroecology with the principles of energy concentration and optimal organisation and stratification of agricultural production systems. The syntropic principles show substantial productivity increases in multiple case studies in smallholder farming systems in countries of the South. Syntropy provides a natural law to guide and manage the sustainable intensification of agricultural biomass production for the growing bioeconomy (Andrade et al., 2020; Götsch, 1995; Schulz et al., 1994).

5.4. Integrated rural and urban agricultural production systems for the sustainability transition towards the bioeconomy

Agriculture has to re-focus on its social, environmental and economic multifunctionality to transform towards sustainability based on a holistic, cross-sectoral value chain perspective (McIntyre, 2009). The Sustainable agricultural production systems and a sustainable natural resource-use provide the backbone for the development of the bioeconomy, while contributing to solving the societal challenges of the 21st century (EC, 2018; Gawel et al., 2019).

Based on the interdisciplinary research of thesis, it can be concluded that 'integration' is central for the development of sustainable agricultural systems and the involvement of relevant stakeholders from the producer and consumer side in the growing bioeconomy. Therefore, a systemic bioeconomic concept (Fig. 4) is introduced in Chapter 5.4.1., comprising suitable agricultural production systems as well as producers and consumer along the rural-urban gradient. Finally, the main findings and conclusions of this thesis are summarized in Chapter 5.4.2 based on the Multi-Level Perspective for system innovation (Geels, 2005).

5.4.1. Integrated rural and urban agricultural systems

The systemic integration of agricultural production systems along the rural-urban gradient provides a pathway for the sustainable production of biomass for the 4F's, RE and environmental services for the society while at the same time connecting both producers and consumers as well as humans and nature. The following concept provides an example for an integrated rural and urban agricultural system (Fig. 4):

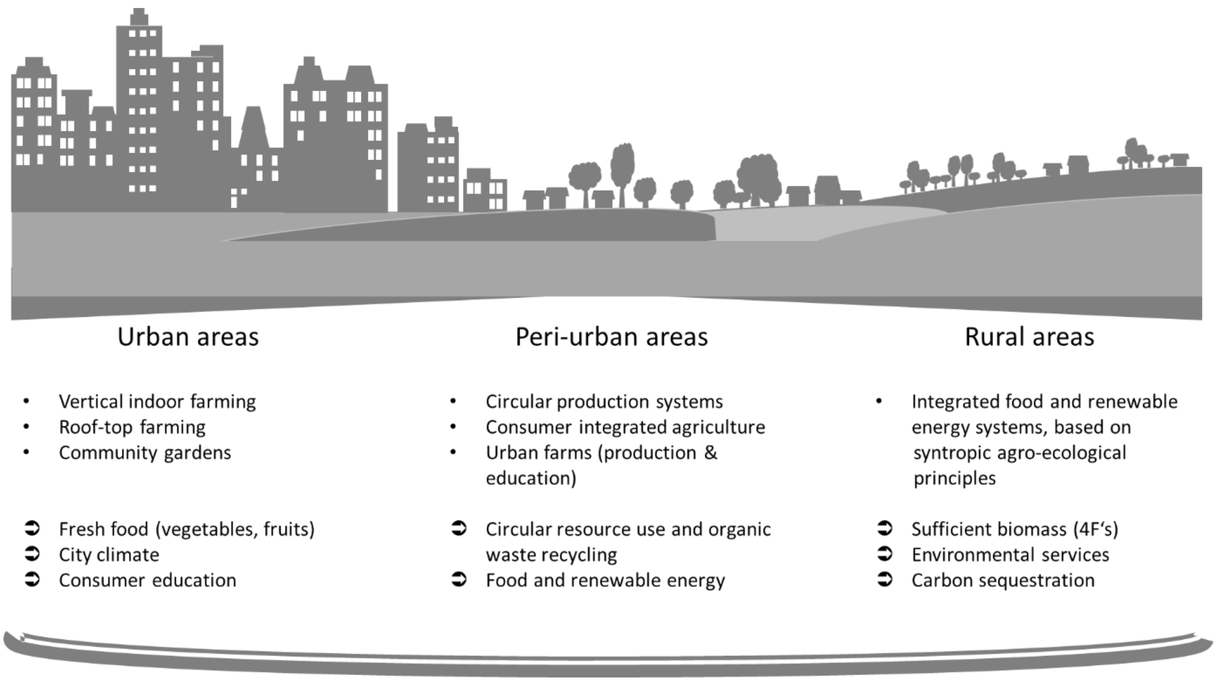

Figure 4: Integrated agricultural systems (•) and their functions (➲) in urban, peri-urban and rural areas for the decentralised and sustainable supply of biomass for food, feed, fibre and fuel and renewable energy

Rural areas: Integrated Food and Renewable Energy Systems (IFRES) allow for an efficient utilisation of land and natural resources for the combined production of sufficient biomass for the 4F's and RE (areas additionally include roofs of farm buildings) for the sustainable intensification on existing arable land.

The planning of IFRES has to take into account the local social, environmental, technical, institutional and economic factors in order to determine appropriate technologies, practices and management systems as well as relevant stakeholders along biobased and RE-based value chains. This allows for the creation of decentralised systems with a close consumer and producer relationship for matching demand and supply in terms of quantity and quality of biomass and RE, while recycling organic waste and residues within the system. Participatory, bottom-up approaches, like IREPA, are required that integrate stakeholder as well as expert knowledge in the planning and implementation process of locally appropriate sustainability solutions (Fischer et al., 2020; Köhler et al., 2019; Wittmayer and Schäpke, 2014; Zeweld et al., 2017).

For the sustainable supply of agricultural products, agroecologic practices and syntropic principles guide the organisation of different sub-production systems based on natural ecosystem cycles. Agroecologic practices have proven to substantially increase productivity in countries of the South, while substantially enhancing and efficiently utilising environmental services (Altieri et al., 2012; Pretty et al., 2011). In addition, large quantities of carbon can be sequestrated in the soil, with the highest sequestration rate (measured in Europe) under agroforestry systems (Aertsens et al., 2013). In countries of the South, access to modern and clean energy provides multiple benefits supporting the creation of sustainable rural livelihoods (FAO, 2014a; Kaygusuz, 2012; Mangoyana and Smith, 2011).

In countries of the North, however, little research exists about agroecology and agroforestry under temperate climatic conditions (Cossel et al., 2020; Rosati et al., 2020). Therefore, these regenerative agricultural systems (Newton et al., 2020) require more research to provide farmers with information and guidance in the selection and implementation of locally suitable practices and measures. In the EU, the new CAP provides (some) incentive for farmers to apply agroecologic practices and produce RE (EC, 2020f) for the development of IFRES that enhance and utilise environmental services.

Therefore, the assessment and valorisation of environmental services in agriculture is an important measure (i) to assess and include external costs into the accounting, (ii) make consumers aware about the multiple non-material outputs of agricultural systems for the society, (iii) incentivise payments for the public good provision to farmers (based on the amount of services provided) as well as make farmers accountable for avoidable negative environmental impacts, and (iv) to attract more farmers to apply agroecologic practices based on syntropic principles for the sustainable supply of biomass for the 4F's and RE in decentralised IFRES for the growing bioeconomy.

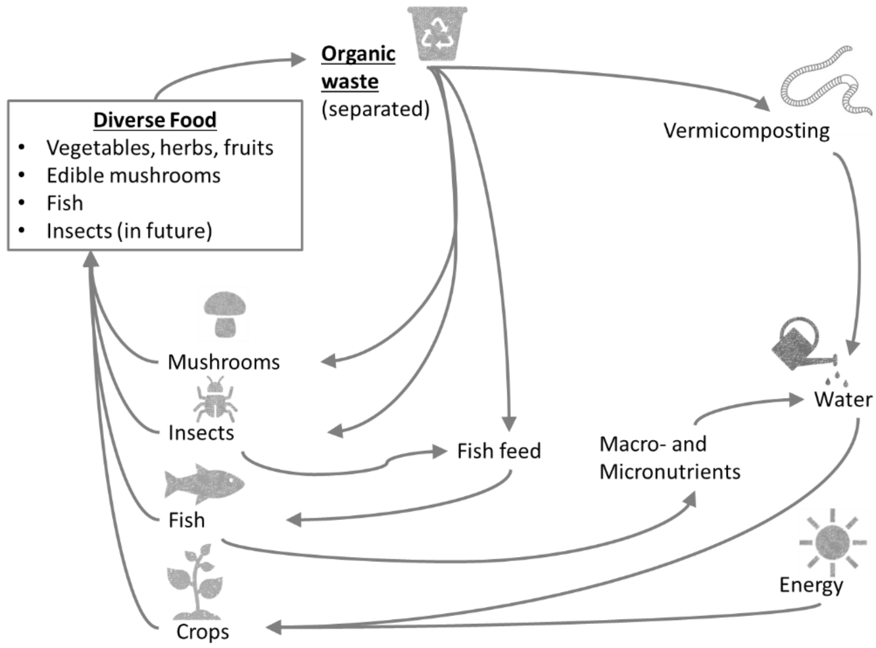

Figure 5: Concept for an integrated urban production system on the basis of organic waste including crop, mushroom, insect and fish as well as soar energy production (adapted from Cichocki et al. 2018))

Peri-urban areas: Circular production systems produce fresh and diverse food as well as RE embedded in decentralised production systems based on locally available resources. Circular production systems can rely entirely on organic household and municipal wastes (separated), using e.g. (vermi-)composting and biodigestion for its decomposition into nutrients and bioenergy (Al-Kodmany, 2018; Stoknes et al., 2016). Recovered nutrients can be applied in liquid forms to (semi-)soilless cultivation systems such as digeponics (Stoknes et al., 2016), terrabioponics (chapter 2.1 and 3), aquaponics (Goddek et al., 2019) and algae production (Al-Kodmany, 2018). Solid compost, digestate and other residues provide the cultivation substrate for vegetable (terrabioponics) and mushroom production (Stoknes et al., 2016). Circular production systems are capable of attaining the same or higher vegetable yield compared to conventional greenhouses, while minimizing the external inputs and environmental impacts (Stoknes et al., 2018; Stoknes et al., 2016).

As part of a student project (Humboldt reloaded) an integrated urban farming was conceptualised (Fig. 5). Based on initial experiments the integrated production system showed various options for synergistic resource use, e.g. by transferring biomass, nutrients, feed, water and various forms of energy between the systems (Cichocki et al., 2018).

Circular production systems in peri-urban areas provide fresh and diverse food directly to the consumers, while at the same time raising awareness about sustainable agricultural practices and a sustainable consumer behaviour. The benefits of circular production systems support green marketing strategies to attract local customers. In the peri-urban area farm shops (e.g. attached to the production system), local markets, delivery services (e.g. weekly vegetable box) as well as food cooperatives and community-supported models are suitable options for selling the produce directly to the consumers

(Sanyé-Mengual et al., 2019). Direct engagement of food producers and consumers increases social awareness of unsustainable food production (Artmann and Sartison, 2018). Therefore, circular production systems can familiarise the growing urban population, and in particular children, with sustainable agriculture and circular food production in order to promote a sustainable consumption behaviour for supporting the societal transition to the bioeconomy.

Urban areas: Urban agricultural activities provide and fulfil a wide variety of functions for sustainable city development. Substantial amounts of fresh food (especially vegetables, herbs, fruits, pharmaceutical plants) can be produced in vertical farms under controlled environmental conditions with very high area productivity. Vertical farms can potentially produce food for about 1000 people on 2000m² (Despommier, 2011; Zeidler et al., 2013), which is on global average currently the area needed to feed one person (Schutter and Lutter, 2016). With further technological development vertical farms may achieve financial viability within the next years (Al-Kodmany, 2018; Shamshiri et al., 2018).
Roof-top farming can utilise un-used flat roofs for food production and enhance the overall resource- and space-use efficiency of existing buildings (Sanyé-Mengual et al., 2015). Existing modern greenhouse technology can be applied for producing substantial amounts of fresh food, like in vertical farming, but at much lower investment costs (Sanyé-Mengual et al., 2015; Toledano, 2019).
Open roof-top agriculture as well as urban community gardens additionally enhance the provision of a wide variety of environmental services important for sustainable city development and climate change adaptation. Urban environmental services include air quality regulation, cooling effect (leaf transpiration and shading), water retention (important after heavy rains) and re-use, habitat for floral and faunal biodiversity, pest and disease control and pollination (Sanyé-Mengual et al., 2019). Currently, the value of environmental services from green areas in cities ranges from $88 to $164 billion globally (Clinton et al., 2018).
In addition to productivity-centred urban farming approaches and the reduction of food miles (Al-Kodmany, 2018; Sanyé-Mengual et al., 2019; Zeidler et al., 2013), urban gardening fulfils ample sustainability functions, including social communities and exchange across social classes, environmental service provision and the productive utilisation of unused spaces based on public-private partnerships (Chatterjee et al., 2020; Clerino and Fargue-Lelièvre, 2020; McEldowney, 2017). Urban gardening increases well-being of the inhabitants (Ambrose et al., 2020), which is a major driver for attracting further inhabitants to participate. Urban community gardens can be considered transformative social groups (Kropp and Müller, 2018) that foster pro-environmental behaviour by (unintentionally) applying several methodologies that are typically applied for fostering pro-environmental behaviours, including *education and awareness*, *social influence*, *nudges* and *outreach and relationship building* (Grilli and Curtis, 2021). Urban community gardening thus entails great

transformative potential towards more sustainable consumer behaviour in the growing urban and metropolitan areas. A sustainable consumer behaviour can considerably reduce consumer food waste, thus subtracting 25% (van den Verma et al., 2020) from the estimated 70% food demand increase until 2050 (FAO, 2009a). Urban gardening connects the consumer and the producer perspective and thus plays a crucial role for increasing agricultural sustainability.

Short food supply chains with short nutrient cycles allow for highly efficient resource use. This lowers the carbon footprint of urban and metropolitan food supply systems considerably (Al-Kodmany, 2018; Sanyé-Mengual et al., 2015), while at the same time increasing its resilience and security in case of external shocks.

For the interconnection and the management of the integrated agricultural system digital technologies are suitable for monitoring and managing product, resource and waste flows. IoT and sensor-based applications control the growing conditions in indoor farms, while smartphone apps and local online shops allow for direct producer and consumer relationships for matching demand and supply for an optimal resource-use efficiency and minimal waste.

Integrated rural and urban agricultural systems can strongly support the sustainability transition towards a the bioeconomy through multiple social, environmental and economic benefits and re-connecting producers and consumers.

5.4.2. The multi level perspective of the sustainability transition towards the bioeconomy

In the Multi-Level-Perspective (MLP) of system innovation (Fig. 6), individual socio-technical innovations emerging from (protected) niches are important driving forces of transitions (Geels, 2005). The three approaches investigated and developed further in this thesis can be considered such socio-technical innovations. Socio-technical innovations are being developed in protected niches (e.g. like here as part of scientific research) and may breakthrough when the window of opportunity, a co-existence of enabling processes on different socio-political levels (e.g. supportive societal trends), allows for the reinforcement of these enabling processes (Geels, 2005).

The subsequent transitions (referring here to the sustainability transition towards the bioeconomy) are conceptualised as a shift from one socio-technical system to another. A socio-technical system consists of several elements including technology, infrastructure, supply networks, markets, regulation, user-practices and cultural meaning. The complex interactions of these elements fulfil multiple social functions and thereby generate the current realities (considered as regimes) on local, national and international level (Geels, 2005). Transitions are "*the outcome of multi-dimensional interactions between radical niche-innovations, an incumbent regime and an external landscape*" (Verbong and Geels 2010, p. 1215).

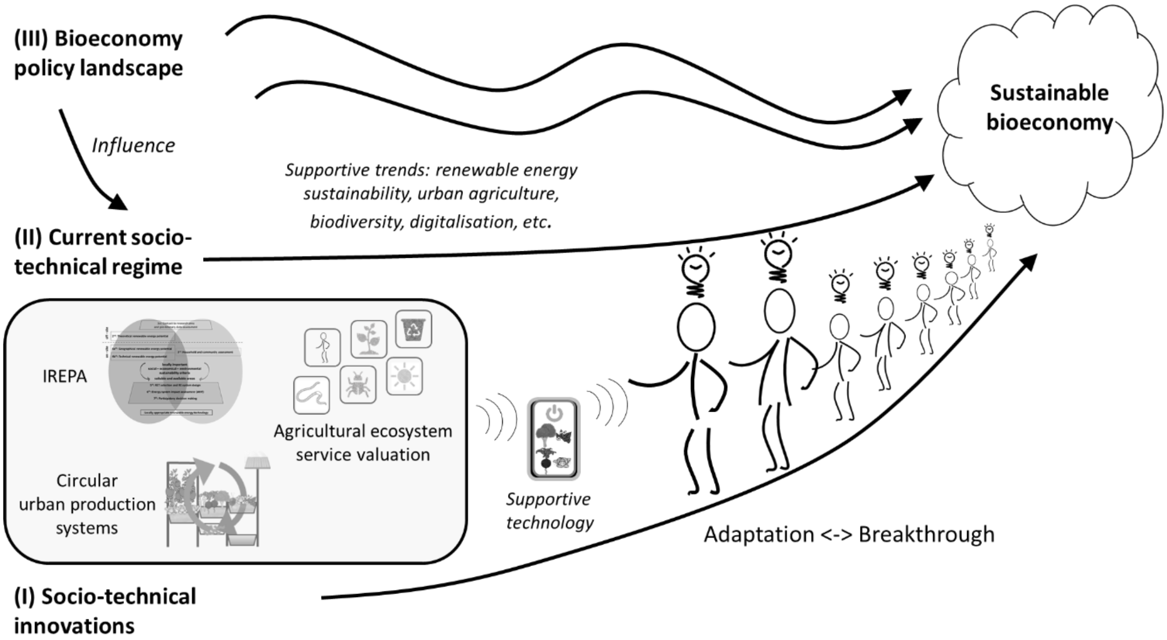

Figure 6: Socio-technical solutions elaborated in this thesis supporting system innovation towards a sustainable bioeconomy based on the dynamic Multi-Level Perspective (based on Geels 2005) (icons from pixabay.com; CCO)

The global bioeconomy developments provide very encouraging political conditions for innovation creation through research and development funds, aiming at rapid market deployment of innovative processes and biobased products (EC, 2018; Gawel et al., 2019). Recently, the foci of the German and the EU bioeconomy strategies were widened from technical innovations to the uptake of innovative processes and biobased products by society (BMBF & BMEL, 2020; EC, 2018). The uptake of socio-technical innovations can be fostered through supportive trends (Verbong and Geels, 2010). In this case the ongoing RE transition, the emerging sustainability transition, the urban gardening trend, the increased awareness in society about biodiversity losses and the ongoing digitalisation can be considered here as supportive trends for the uptake of socio-technical innovations investigated and developed further in this thesis (Fig. 6). A change in the current socio-technical regime, however, will only come about, if the socio-technical innovations, the current trends and (political) strategies reinforce at all three levels (Geels, 2005)

Currently, the political bioeconomy landscape is very conducive, while the ongoing trends can take up the three socio-technical innovations, leading to adaptation and finally the breakthrough for supporting the sustainable bioeconomy (Fig. 6):

IREPA has proven its methodological applicability in case study research with rural smallholders in South Africa and India:

- The case studies revealed the need of participatory, bottom-up approaches for the integration of local stakeholders in project planning and decision making, thus supporting sustainable rural livelihoods and an increase in agricultural production in smallholder farming systems for the growing bioeconomy.

- ➲ Local insights and stakeholder perspectives, obtained from participatory case study research, are crucial for the targeted formulation of agricultural development policies and the involvement of relevant stakeholders in the sustainability transition towards a bioeconomy.

Urban agriculture has multiple roles in sustainable city development and the sustainability transition:

- ➲ Vertical and rooftop farming are highly productive and allow for urban food production, however questionable sustainability and financial viability require further research and development, especially in case of vertical farming.
- ➲ Urban gardening provides multiple social, environmental and economic benefits for sustainable city development and fosters sustainable consumer behaviour, thus involving the growing urban population in the sustainability transition towards the bioeconomy.

The assessment and monetization makes the multiple environmental services provided by agricultural systems tangible and increases their recognition on farm, societal and political level:

- ➲ The assessment of environmental services in agricultural systems reveal the multifunctional roles of agriculture. Their monetization can incentivise payments to the farmers for the provision of public goods, supporting the enhancement of the environmental services in agriculture for societal and environmental benefit.
- ➲ The enhancement and intentional utilisation of environmental services can foster the sustainability transition in agriculture from input-based towards process-based production systems. Agroecologic practices and the syntropic principles of energy concentration, natural order and organisation provide a promising pathway for the sustainable intensification of agricultural production systems.

The three approaches investigated and developed further in this thesis address the societal challenges of the 21st century on social, environmental and economic level, based on an interdisciplinary, bottom-up and systemic perspective. Portraying these three socio-technical innovations in the Multi-Level Perspective (Geels, 2005), illustrates their potential for supporting the system innovation towards the sustainable bioeconomy.

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Nationality:	German

Professional Experience

Since 05/2019	Assistant of the scientific coordinators group of the 'European Bioeconomy University' (EBU)
Since 03/2016	Entrepreneur: *Geco-Gardens* – Circular urban garden systems
08/2014 – 07/2016	PhD scholarship of the Faculty of Agriculture, University of Hohenheim
08/2013 – 12/2014	Assistant of the Planning and Study Commission for the development of the M.Sc. programme *Bioeconomy*, University of Hohenheim
Since 01/2014	Doctoral student: Department of Biobased Resources in the Bioeconomy, University of Hohenheim Ph.D. Thesis: *Integrated rural and urban agricultural systems for the sustainability transformation towards the bioeconomy*
Since 08/2013	Research associate: Department of Biobased Resources in the Bioeconomy, University of Hohenheim
06/2013 - 07/2013	Research assistant: Department of Biobased Products and Energy crops, University of Hohenheim
05/2013 - 06/2013	Side job: Gardening, landscaping and demolition - Besir, Stuttgart
09/2011 - 06/2012	Research assistant: State Institute of Agricultural Engineering and Bioenergy, Hohenheim
05/2010 - 08/2012	Side job: Gardening and landscaping - Epple, Stuttgart
11/2009 - 04/2010	Internship: State Institute for Environment, Measurements and Nature Conservation Baden-Württemberg (LUBW, Karlsruhe) - Department: Soil and Residual Waste
10/2009 - 11/2009	Internship: demeter-farm, Weiler i.d.B. - Schwäbisch Gmünd
06/2009 - 07/2009	Research assistant: Institute for Plant Nutrition, University of Hohenheim
08.2005 - 04.2006	Civil Service: Technical Service, Evangelisches Stift Freiburg

Education

Studies: 2010 - 2013: Master Programme - Biobased Products and Bioenergy, University of Hohenheim

- Qualification: Master of Science / Grade: "Very Good"

04.07.2014: *NatureLife Sustainability Award 2014*
for the best M.Sc. Thesis in the area of "Sustainable land use systems as a bases for preserving biodiversity in the tropics and subtropics" (*NatureLife Foundation*)

2005 - 2010: Bachelor Programme - Agricultural Sciences, University of Hohenheim

- Area of specialization: Soil Science
- Qualification: Bachelor of Science / Grade: "Good"

School: 1996 – 2005: Primary School Todtnau
Secondary school Gymnasium Schönau im Schwarzwald
28.06.2005: Qualification - A levels

Stays abroad

12.2018	Case study research: Kapchorwa, Uganda / Teso South, Kenia Project: *Education and Training for Sustainable Agriculture and Nutrition in East Africa (EaTSANE)*
04.2016 - 05.2016	Case study research: Barro Alto, Goiás State, Brazil
01.2015 - 03.2015	Case study research: Ghoragachha and Baikunthapur, State of West Bengal, India
08.2012 - 12.2012	Case study research: *Monitoring and Evaluation of the Integrated Renewable Energy Potential Assessment - A case study in Mgwenyana, rural Eastern Cape, South Africa*
2009 - 2015	Travels to Peru, Ghana, South Africa (at least 6 weeks)

Voluntary Activities

Since 2015	2nd Board director: Grünfisch - Aquaponic e.V., Stuttgart
Since 2014	Parental initiative: Kinderhaus Birkach e.V., Stuttgart Facility Manager

Skills

Language:	German:	native
	English:	fluent
	Spanish, Portuguese, Latin:	basic

Computing:	Proficient:	MS Office (Word, Excel, PowerPoint),
	Basic:	Wordpress, GABI (Life Cycle Assessment), SigmaStat, AutoCAD, Sketch-Up, CropWat, PV-Sol

Conference contributions

10/2020

Poster: Humboldt reloaded conference, University of Hohenheim.
Fesani, S.; Günther, R.; Thormaehlen, M.; Angenendt, J.; Braunstein, I.; Cossel, M.; Cichocki, J.; Ludwig, H.; Winkler, B. 2020. Syntropic permaculture in temperate regions: Spatial and temporal diversification of crop communities.
Humboldt reloaded conference proceedings 2020, p. 19.

Poster: Humboldt reloaded conference, University of Hohenheim.
Ow-Wachendorf, F.; Erpenbach, F.; Cichocki, J.; Winkler, B. 2020. Plants-Water-Earthworms: Terrabioponic urban gardening.
Humboldt reloaded conference proceedings 2020, p. 20.

Poster: Humboldt reloaded conference, University of Hohenheim.
Kunle, M.; Bernhard, A.; Bihlmeier, M.; Cutura, D.; Buck, M-L,; Cichocki, J.; Winkler, B. 2020. Construction and cultivation: Innovative urban gardening systems and cultivation methods.
Humboldt reloaded conference proceedings 2020, p. 21.

10/2019

Poster: Humboldt reloaded conference, University of Hohenheim.
Kiefer, J., Gröner, J., Saltekin, J., Kraus, M., Winkler, B. 2019. Examination of the suitability of different hydroponic substrates.
Humboldt reloaded conference proceedings 2019, p. 27.

Poster: Humboldt reloaded conference, University of Hohenheim.
Cichocki, J., Teske, E., Winkler, B. 2019. Krasse Kresse – Einfluss unterschiedlicher LED-Lichtrezepte auf Wachstum und den Gehalt wertgebender Inhaltsstoffe bei Nutzpflanzen.
Humboldt reloaded conference proceedings 2019, p. 34.

10/2018

Poster & Oral presentation: Humboldt reloaded conference, University of Hohenheim. Cichocki, J., Selensky, F., Saumweber, B., Winkler, B. 2018. Integrated Urban Farming Systems.
Humboldt reloaded conference proceedings 2018, p. 49.

10/2017

Poster: Humboldt reloaded conference, University of Hohenheim
Stolz, T., Twiehaus, C-M., Winkler, B. 2017. Urban Gardening 2.0 – Terrabioponische Kleingartensysteme für Balkon und Terrasse.

Humboldt reloaded conference proceedings 2017, p.18.

02/2016 *Oral presentation:* BIOM-LAND Travelling Conference: Hanoi, Vietnam / Phitsanoluk, Thailand
Winkler, B. 2019. Integrated Renewable Energy Potential Assessment (IREPA) - Biomass for bioenergy potential assessment by a holistic and participatory approach.

09/2015 *Design thinking workshop:* Future Agricultural Systems
Federal Ministry of Education and Research (BMBF), Potsdam
- Invitation based on submitted vision: Winkler. B., 2015. FarmVille in real - Terrabioponic smart-garden-systems as a socio-technical innovation for the societal transition towards a bioeconomy

06/2015 *Poster:* European Biomass Conference and Exhibition (EUBCE), Vienna
Winkler, B., Lemke, S., Lewandowski, I. 2015. IREPA - Biomass for Bioenergy Potential Assessment by a Holistic and Participatory Approach.
European Biomass Conference and Exhibition Proceedings; S. 273 – 281.

10/2014 *Oral presentation*: 1. Bioeconomy Congress Baden-Württemberg, Stuttgart
Winkler, B. 2014. Integrated biomass potential assessment - a bottom-up approach.

Publications

Cossel, M.; Ludwig, H.; Cichocki, J.; Fesani, S.; Guenther, R.; Thormaehlen, M.; Angenendt, J.; Braunstein, I.; Buck, M.-L.; Kunle, M.; Bihlmeier, M.; Cutura, D.; Bernhard, A.; Ow-Wachendorf, F.; Erpenbach, F.; Melder, S.; Boob, M.; **Winkler, B. 2020**. Adapting Syntropic Permaculture for Renaturation of a Former Quarry Area in the Temperate Zone.
In: Agriculture 2020, 10, 603, doi: 10.3390/agriculture10120603.

Winkler, B.; Mangold, A.; Cossel, M. von; Clifton-Brown, J.; Pogrzeba, M.; Lewandowski, I.; Iqbal, Y.; Kiesel, A. **2020**. Implementing miscanthus into farming systems: A review of agronomic practices, capital and labour demand.
In: Renewable and Sustainable Energy Reviews 2020, 132, 110053, doi: 10.1016/j.rser.2020.110053.

Cossel, M. von; **Winkler, B.**; Mangold, A.; Lask, J.; Wagner, M.; Lewandowski, I.; Elbersen, B.;Eupen, M.; Mantel, S.; Kiesel, A. **2020**. Bridging the Gap between Biofuels and Biodiversity through Monetizing Environmental Services of Miscanthus Cultivation.
In: Earth's Future 2020, doi: 10.1029/2020ef001478.

Cossel, M.; Amarysti, C.; Wilhelm, H.; Priya, N.; **Winkler, B.**; Hoerner, L. **2020**. The replacement of maize (*Zea mays L.*) by cup plant (*Silphium perfoliatum L.*) as biogas substrate and its implications for the energy and material flows of a large biogas plant.
In: Biofuels, Bioproducts and Biorefining 14:152–179 2020; doi: 10.1002/bbb.2084

Cossel, M.; Wagner, M.; Lask, J.; Magenau, E.; Bauerle, A.; Warrach-Sagi, K.; Elbersen, B; Staritsky, I.; van Eupen, M.; Iqbal, J.; Jablonowski, N.D.; Happe, S.; Fernando, A.L.; Scordia, D.; Cosentino, S.L.; Wulfmeyer, V.; Lewandowski, I.; **Winkler, B. 2019**. Prospects of Bioenergy Cropping Systems for A More Social-Ecologically Sound Bioeconomy.
In: Agronomy 2019, 9, 605, DOI: 10.3390/agronomy9100605.

Winkler, B.; Maier, A.; Lewandowski, I. **2019**. Urban Gardening in Germany: Cultivating a Sustainable Lifestyle for the Societal Transition to a Bioeconomy.
In: Sustainability 2019, 11, 801; doi:10.3390/su11030801.

Winkler, B.; Lewandowski, I.; Voss, A.; Lemke, S. **2018**. Transition towards Renewable Energy Production? Potential in Smallholder Agricultural Systems in West Bengal, India.
In: Sustainability 2018, 10, 801; doi:10.3390/su10030801

Winkler, B.; Lemke, S.; Ritter, J.; Lewandowski, I. **2017**. Integrated assessment of renewable energy potential: Approach and application in rural South Africa.
In: Environmental Innovation and Societal Transitions 2017, 24, p. 17–31.

Hilger, T.; Lewandowski, I.; **Winkler, B.**; Ramsperger, B.; Kageyama, P.; Colombo, C. **2015**. Seeds of Change - Plant Genetic Resources and People’s Livelihoods.
In: Agroecology, Pilipavičius, V., IntechOpen, doi: 10.5772/59984.

Stuttgart, 15.02.2021

Bastian Winkler