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Ph.D. Thesis

Sara Shapiro-Bengtsen

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Preface

The work presented in this Ph.D. thesis has been carried out at the Technical University of Denmark (DTU) Department of Technology, Management and Economics in partial fulfillment of the requirements to acquiring a Ph.D. degree. The work has been supervised by main supervisor Professor Marie Münster (DTU) and co-supervisor Assistant Professor Rasmus Bramstoft (DTU).

The Ph.D. study has been funded by DTU and the Sino-Danish Collaboration (SDC) (https://sdc.university/). SDC is a partnership between all Danish universities and the Chinese Academy of Sciences (CAS) and the University of Chinese Academy of Sciences (UCAS). Part of this Ph.D. study has been conducted during an eight-month-long research stay at UCAS in Beijing under host supervisor Professor Wang Yi.

This thesis consists of two parts. The first part introduces the background and motivation, presents the research questions addressed in this thesis, introduces the methodology applied, and summarizes results and conclusions. The second part being the Paper Annex, which consists of the four papers included in this thesis. These are numbered I-IV and listed below:

Paper I: **Shapiro-Bengtsen S**, Andersen FM, Münster M, Zou L. 2020. Municipal solid waste available to the Chinese energy sector – Provincial projections to 2050. Waste Management;112:52–65. https://doi.org/10.1016/j.wasman.2020.05.014.

Paper II: Franz SM, Campion N, **Shapiro-Bengtsen S**, Bramstoft R, Keles D, Münster M. 2022. Requirements for a Maritime Transition in Line With the Paris Agreement. iScience. https://doi.org/10.2139/ssrn.4158005.

Paper III: **Shapiro-Bengtsen S**, Hamelin L, Bregnbæk L, Zou L, Münster M. 2022. Should residual biomass be used for fuels, power and heat, or materials? Assessing costs and environmental impacts for China in 2035. Energy & Environmental Science:1950–66. https://doi.org/10.1039/d1ee03816h.

Paper IV: **Shapiro-Bengtsen S**, Bramstoft R, Bregnbæk L, Münster M. 2023. Quantifying the Benefits of Refining Side Streams When Optimizing Use of Residual Biomass. Under review. Energy & Environmental Science.

In addition, the following publications are not included in the thesis, but were conducted during the Ph.D. study:

- Campion N, Franz S, **Shapiro-Bengtsen S**, Münster M. 2022. Quantification of costs and greenhouse gases emissions related to e-fuels production. Paper presented at 35th International Conference on Efficiency, Cost, Optimization, Simulation and Environmental Impact of Energy Systems, Copenhagen, Denmark.
- Franz S, **Shapiro-Bengtsen S**, Campion N, Backer M, Münster M. 2021. MarE-Fuel: ROADMAP for sustainable maritime fuels. Technical University of Denmark.
- Hevia-Koch P, Xu J, Sandholt K, Han X, Münster M, **Shapiro-Bengtsen S**. 2020. Energy scenarios and policies. In The SDC International Report 2020: Cooperating for Energy Transition, p. 24–32. https://doi.org/10.7146/aul.395.145.

Kongens Lyngby, April 2023

Sara Shapiro-Bengtsen

Summary

Addressing climate change requires a shift away from the use of fossil fuels. During and after this transition biomass will play an important role as a renewable source of carbon. Adding to climate change, there are additional threats to sustainable life on Earth. Regarding biomass use, these include biodiversity loss and eutrophication. A main motivation for limiting the resources studied in this thesis to residuals are concerns surrounding biodiversity, as this is primarily relevant when it comes to first generation biomass.

China holds a crucial role in the world in meeting global climate targets. While the Chinese energy system is still heavily dependent on fossil fuels, coal use has stabilized, and clean energy sources such as wind and solar have been heavily invested in to meet the increasing electricity demand. Additionally there is a strong national focus on reducing pollution and achieving the political goals of creating an Ecological Civilization and a Beautiful China.

This Ph.D. thesis contributes to the fields of resource assessments, environmental impacts, and use of residual biomass, where resource assessments and environmental impacts are integrated into energy system models. The main research question guiding this thesis is "What are economic and environmentally sustainable future uses of residual biomass in China?". Resource assessments are central, enabling long-term investments in resource management infrastructure, which must be of sufficient geographical detail to be relevant. This thesis contains a long-term projection of municipal solid waste for Chinese provinces. This projection is performed using an adapted version the econometric waste projection model FRIDA and developed scenarios illustrating different policy futures. The results indicate a risk of overinvesting in waste incineration capacity in several provinces. Additional resource assessments are based on statistics, scientific literature, and industry reports.

The global limitation of sustainable biomass is assessed and exemplified in a study on future shipping fuels. Here availabilities are assessed and a life cycle perspective on greenhouse gas emissions is employed, using the maritime fuel-use optimization model SEAMAPS. Indicators for climate change impact and the additional environmental impacts of ocean and freshwater eutrophication as well as air pollution indicators, are quantified for use of residual biomass in China in the bottom-up simulation model Bio3E. This model is soft linked to EDO, a partial equilibrium optimization model for the Chinese electricity and district heating sectors. The externalities mentioned above are further hard linked to EDO in the optimization through the OptiFlow network flow model for resource networks and allocation. The OptiFlow model is extended to model cross-sectoral use of residual biomass in non-energy sectors and the refining of side streams. It is important to consider various scenarios when evaluating the energy and environmental implications of competing uses for residual biomass. Incorporating counterfactual uses into these scenarios is critical in determining the significance of different utilization pathways and highlight the value of treating residual biomass to e.g. avoid eutrophication.

The results in this thesis provide insights into resource availability, quantified environmental impacts in energy system modeling, and use of residual biomass across sectors. The problematic nature of disregarding biogenic carbon emissions in energy system analysis is highlighted, as these have a decisive impact on the results. Adding to this, the expansion in terms of quantifying additional externalities in energy system modeling has proven substantial. The results demonstrate significant benefits of utilizing residual biomass for fuels and non-energy purposes as well as refining side streams in a Chinese context. This thesis offers insights to policymakers, researchers, and practitioners in the fields of energy system analysis and the bioeconomy, seeking to promote sustainable biomass utilization by incorporating both economic and environmental aspects. For residual biomass to be cost-efficiently and environmentally sustainably utilized in China, externalities should be priced and industrial symbiosis, or utilization of side streams across sectors, should be promoted.

Sammenfatning

For at afværge klimaforandringerne kræves et skifte væk fra brugen af fossile brændstoffer. Under og efter denne overgang vil biomasse spille en vigtig rolle som en vedvarende kilde til kulstof. Ud over klimaforandringerne er der yderligere trusler mod bæredygtigt liv på jorden. Med hensyn til biomasseanvendelse inkluderer disse biodiversitetstab og eutrofiering. Denne afhandling fokuserer på restbiomasse, da tab af biodiversitet primært vedrører brugen af første generations biomasse.

Kina spiller en helt afgørende rolle i indfrielsen af de globale klimaambitioner. Om end det kinesiske energisystem stadig i høj grad er afhængig af fossile brændsler, så ses der en stabilisering af kulforbruget, og der er blevet investeret kraftigt i rene energikilder, som vind og sol, for at imødekomme den stigende efterspørgsel. Derudover er der et stærkt nationalt fokus på at reducere forurening og nå de politiske mål om at skabe en "Ecological Civilization" og et "Beautiful China".

Denne Ph.D. afhandling bidrager til fagområderne ressourcekortlægning, miljøvurdering, og brug af restbiomasse, hvor ressourcekortlægning og miljøvurdering er integrerede i energisystemmodeller. Hovedspørgsmålet, der sætter rammen for denne afhandling, er "Hvad er økonomisk og miljømæssigt bæredygtige fremtidige anvendelser af restbiomasse i Kina?". Anvendelsen af ressourcekortlægning er central for at sikre et retvisende grundlag for langsigtede investeringer i infrastruktur til håndtering af restbiomasse, der skal etableres. Disse ressourcekortlægninger skal have tilstrækkelig geografisk detaljeringsgrad for at være relevant. Denne afhandling inkluderer en langsigtet fremskrivning af husholdningsaffald for de enkelte kinesiske provinser baseret på en tilpasset version af den økonometriske affaldsfremskrivningsmodel FRIDA samt scenarier, der illustrerer forskellige politiske tiltag. Resultaterne indikerer en risiko for overinvestering i affaldsforbrændingsanlæg i flere kinesiske provinser. Yderligere ressourcevurderinger er baseret på tilgængelig officiel statistik, videnskabelig litteratur og industrirapporter.

Hensynet til begrænsningerne i globalt tilgængelige biomasseressourcer inkluderes i afhandlingen gennem et globalt studie af mulige fremtidige brændsler til shipping-industrien, ved brug af optimeringsmodellen SEAMAPS. Dette inkluderer også et livscyklusperspektiv, der anvendes til at estimere drivhusgasemissioner i forbindelse med brændselsproduktion. Indikatorer for drivhusgasudledninger og yderligere miljøpåvirkninger på hav- og ferskvandseutrofiering samt luftforurening ved brug af restbiomasse i Kina kvantificeres i simuleringsmodellen Bio3E. Denne model er lænket til EDO, en delvis ligevægts-optimeringsmodel for de kinesiske elektricitets- og fjernvarmesektorer. De nævnte eksternaliteter er yderligere integreret med EDO i optimeringen gennem netværksmodellen OptiFlow for at muliggøre modellering af ressourcestrømme og allokering. OptiFlow modellen er udvidet til at modellere brug på tværs af sektorer udover energisektoren samt raffinering af biprodukter.

Resultaterne i denne afhandling giver indsigt i ressourcetilgængelighed, kvantificerede miljøpåvirkninger i energisystemmodellering og anvendelse af restbiomasse på tværs af sektorer. Det problematiske i ikke at inkludere biogene drivhusgasemissioner som en del af energisystemmodellering er belyst, da disse har en afgørende effekt på resultaterne. Herudover er det blevet tydeligt, at tilføjelsen af andre eksternaliteter i energisystemmodelleringen har betydelig effekt på resultaterne. Resultaterne demonstrerer betydelige fordele forbundet med at nyttiggøre restbiomasse til såvel brændselsproduktion som ikke energi-relaterede formål samt raffinering af biprodukter, i en kinesisk sammenhæng.

Det er vigtigt at overveje forskellige scenarier, når man evaluerer energi- og miljøkonsekvenserne af konkurrerende anvendelser af restbiomasse. Indarbejdelse af kontrafaktiske anvendelser i disse scenarier er afgørende for at fastlægge betydningen af forskellige anvendelsesveje og fremhæve værdien af at behandle restbiomasse for f.eks. at undgå eutrofiering. Denne afhandling tilbyder indsigt til politikere, forskere og fagfolk inden for energisystemanalyse og bioøkonomi, der søger at fremme bæredygtig biomasseudnyttelse ved at inkorporere både økonomiske og miljømæssige aspekter. For at restbiomasse kan udnyttes omkostningseffektivt og miljømæssigt bæredygtigt i Kina, bør eksternaliteter prissættes og industriel symbiose eller anvendelse af biprodukter på tværs af sektorer fremmes.

Acknowledgements

This Ph.D. has given me the opportunity to immerse myself in engaging topics and develop modeling and analytical skills. It has been a challenging and rigorous journey, but it has also been incredibly fulfilling, and I would like to express my gratitude to all those who provided me with support and assistance throughout the process.

Foremost, I am deeply grateful to my main supervisor Professor Marie Münster for her invaluable mentorship, guidance, and inspiration. Additionally, I would like to express my appreciation to my co-supervisor Assistant Professor Rasmus Bramstoft for always having a constructive approach and consistently providing support.

I am greatly appreciative to Lars Møllenbach Bregnbæk, who has been central for enabling me to get the opportunity to pursue this Ph.D. Thank you for your support and encouragement as well as the cooperation as co-author for two of the papers included in this thesis. I further would like to thank all my co-authors for your fruitful cooperation and generosity in sharing your knowledge and expertise.

Pursuing this Ph.D. has enriched me in many ways, not least through getting to know my colleagues. It has been a pleasure to work alongside people who are knowledgeable, supportive, and engaged. Special thanks to my office mates for creating a welcoming work environment, for the interesting discussions, and all the laughs in the office.

I would also like to express my gratitude to my friends and family for your understanding and words of encouragement. I am particularly grateful to my parents for consistently nurturing my inquisitiveness and persistence. Last, but certainly not least, I want to thank my husband and life partner Thomas for your extensive support and for cheering me on throughout this rollercoaster ride. Our family has grown by two adorable members during this Ph.D. journey. Thank you, Ruben and Inga, for filling our hearts with love and light and for reminding me to play and dance.

Abbriviations

AM	Animal manure
BSFT	Black soldier fly treatment
CH_4	Methane
CO_2	Carbon dioxide
CO_2e	Carbon dioxide equivalents
CR	Crop residues
DAC	Direct air capture
EJ	Exajoule = 10^{18} joules
eq.	Equivalents
FR	Forestry residues
FT	Fischer–Tropsch
FW	Food waste
GHG	Greenhouse gas
H_2	Hydrogen
HTL	Hydrothermal liquefaction
IAM	Integrated assessment model
LCA	Life cycle assessment
LBG	Liquefied biogas
MeOH	Methanol
Mt	Megatonne = one million metric tonnes = 1 Teragram
MRMB	Million Chinese yuan renminbi
MSW	Municipal solid waste
N	Nitrogen
N_2O	Nitrous oxide
NBS	National bureau of statistics
NH_3	Ammonia
P	Phosphorus
PJ	Petajoule = 10^{15} joules
PM2.5	Particulate matter ≤ 2.5 microns
PS	Point source
RMB	Chinese yuan renminbi
SNG	Synthetic natural gas
SS	Sewage sludge
t	Metric tonne = 1 Megagram = 10^6 grams
TG	Thermal gasification

Content

1. Introduction

1.1 Background

Reducing human-induced climate change is one of the most pressing challenges facing the world today [1]. To meet climate change mitigation targets, a drastic reduction in the use of fossil fuels is necessary. Combustion of fossil fuels account for 73% of global greenhouse gas (GHG) emissions and primarily stem from the energy sector [2]. Therefore, the energy sector plays a critical role in addressing global warming. Apart from climate change, there are additional threats to environmental sustainability which are receiving increased attention. The Planetary Boundary Framework defines critical global sustainability boundaries [3]. It includes nine interrelated boundaries that describe the Earth ecosystem framework, beyond which humanity's ability to function is compromised. Climate change is one of these boundaries, which is at risk of being surpassed. However, the risks of exceeding the established boundaries are even higher when it comes to nitrogen and phosphorus flows as well as biosphere integrity, also called biodiversity loss [4].

As the world moves towards sustainable energy sources and away from fossil fuels, biomass is becoming an increasingly valuable option due to its renewable nature and storage possibilities. Biomass is expected to become a more significant part of the energy sector in the coming decades, with a threefold increase in its use as bioenergy from 2020 to 2050 [5]. One industry, which might experience a surge in demand for bio-based fuels, is the shipping sector, as is moves away from use of fossil fuels [6]. Apart from the energy sector, there is an increasing demand for using biomass in other sectors [7]–[10]. Together, these trends, stress the high future demand for sustainably available biomass and a need to broaden the scope of environmental impacts.

While fossil CO_2 emissions make up the lion's share of greenhouse gas emissions from a fossil based system, in the transition away from use of fossil fuels it is important to expand this view and include other GHGs when assessing climate change impacts. The importance of reducing methane emissions was emphasized at COP26, which highlights this point. Another aspect of environmental impacts in the energy transition is the extensive need for new infrastructure. While the materials needs have been studied and confirmed to be sufficient, the environmental impacts from material production are determined to be limited, but not insignificant [11].

Use of biomass can result in several environmental impacts. One critical aspect is biodiversity loss from production of first generation biomass [12], [13]. Stemming from competition of arable land, there is an increasing focus on residual biomass [14]–[16]. This is the motivation for limiting this study to including residual biomass. The definition of residual biomass is not based on physical or chemical properties but rather on economic and market factors, leading to variations over time and location [17]. A product can be both a waste and a co-product, and can transition between the two. The term residual biomass is used to encompass the range of potential uses and values of the biomass studied in this thesis.

1.2 Green Transition in China

China is one of the largest and most populous countries in the world. It is a country experiencing massive growth. The extensive growth has lifted millions of people out of poverty, but also caused massive air, soil, and water pollution. While growth will continue, there is an extensive focus on reducing pollution. Air pollution has a specific focus, where the reduction of fine particulate matter ≤ 2.5 microns, PM2.5, is imperative [18]. Adding to this, soil and water pollution are also highly prioritized in order to reach the political goal of creating an Ecological Civilization and a Beautiful China [19], [20]. A tool used to realizing these visions include respecting established Ecological Redlines for ecological protection. The Ecological Redlines concept is a holistic approach used to assess ecosystem services, focusing on safeguarding local ecosystems [21]. Despite issues with implementation, this exhibits political will and there is a plan to establish a national Ecological Redlines system by 2030 [22].

For the world to reach the Paris Agreement, China is in a key position with a carbon neutrality goal for 2060 [23], [24]. Most carbon emissions stem from the energy sector. The Chinese energy mix has historically been, and is still, dominated by use of coal and other fossil fuels, currently making up 85% of annual energy consumption [25]. However, in recent years the use of coal has stabilized, and additional demand has to a large extent been covered by clean energy sources. In recent years, China has invested heavily in wind and solar capacity [25]. While much more is needed to transition away from the current fossil reliant energy system, there are great opportunities for China to continue vast investments in renewable energy and phasing out fossil fuels [25].

China consists of 34 provincial level administrative divisions, of which 23 provinces, five autonomous regions, four municipalities, and two special administrative regions; Hong Kong and Macao, as well as Taiwan. In this thesis Hong Kong, Macao, and Taiwan are excluded from the analysis due to lack of data in main data sources, and all provincial level administrative divisions are referred to as provinces. The 31 provinces included are sometimes referred to as mainland China, hereafter China.

1.3 Biomass Availability and Environmental Impacts in Energy System Analysis

The purpose of energy system analysis is insight and understanding of the interactions between resources, conversion technologies and other infrastructure, and demand. Different models are used to illustrate these interactions. As the complexity of energy systems extend, there is an increasing need for expanding energy models to represent these complexities and enable modelers to explore possible future scenarios [26]. Using models can create insights to ensure that the energy system is developing in a clean, reliable, and cost-efficient direction. The needed transition away from use of fossil fuels in the energy sector exposes a range of challenges to be addressed [26]. One source of increased complexity in energy systems stems from the increasing use of variable electricity sources, i.e. wind and solar power. This requires increased coupling of sectors, e.g. between the electricity and transport sectors with smart charging of electric vehicles [27]. By integrating several sectors the system costs, need for transmission, and greenhouse gases can be reduced [28]. In an energy system based on renewable energy, bioenergy can be an important source of transport fuel [29].

Models are operated in energy system analysis to simulate and optimize both present and future energy systems. This practice provides decision-makers with valuable insights. By using a systems approach, energy systems can be represented in great detail, allowing for an assessment of the energy that is avoided and replaced in various scenarios. This approach also enables the integration of different sectors and the capture of co-benefits, such as demonstrating how the value of a resource is dependent on the energy system in which it is utilized [30]. As a result, cost-optimal resource allocation can be assessed through energy system analysis.

Quantification of environmental indicators is typically limited to fossil CO_2 emissions in energy system analysis [31]. The comprehensive greenhouse gas accounting, which is required in life cycle assessments**,** is generally lacking in energy system analysis. This is despite of that one of the primary purposes of energy system analysis is to investigate how climate change impact can be reduced in future energy systems. This limited view on greenhouse gas emissions in energy system analysis is partly due to the notion of biomass used for energy being treated as inherently climate neutral [32]. However, even if the biomass can be considered climate neutral, as in the case for residual biomass [32], the CH_4 and N_2O emissions associated with various conversion processes are typically disregarded. Studies often focus on the CO_2 emissions from fuel use for energy purposes [33], [34], meaning that process emissions are overlooked. Adding to this, the emissions from producing materials needed for infrastructure are typically disregarded. This is exemplified in this thesis with a study on future maritime fuels. Due to the extensive fuel demand from the shipping sector, and the prospect for using infrastructure intense electrofuels, the study includes considerations on both biomass limitations as well as quantification of upstream GHG emissions from constructing electrofuel infrastructure.

There are studies which include a more comprehensive view of impacts from biomass utilization with CH_4 emissions from biogas production and carbon sequestration of digestate when assessing use of residual biomass [35]. However, there does not include N_2O emissions from application of digestate to soils [36], nor the nutrient losses to water, which can cause eutrophication. Apart from climate change indicators, other environmental indicators are rarely included in energy system analysis [37]. Regarding use of residual biomass, this is often assumed to be carbon neutral and process emissions are typically not included. Additionally there is typically no assessment of other environmental impacts from use of residual biomass. This in spite of the link between waste management and nutrient losses to water [38]–[41]. This is most relevant in terms of treatment of wet fractions of residual biomass, animal manure and sewage sludge in particular. The biogeochemical N and P cycles is a planetary boundary at risk of being exceeded, making monitoring N and P flows pertinent. This thesis assesses potential climate change impact by including the three main GHG emissions; CO_2, CH_4, and N_2O. Additionally N and P flows are represented by including indicators for eutrophication, and direct PM2.5 emissions are included as an indicator for air pollution. These externalities are not only accounted for, but also monetized.

In energy system analysis biomass is typically used as exogenous input to the model. In some energy system analysis studies there are implemented constraints to use municipal solid waste (MSW)[42]. Municipal solid waste quantities depend on economic activity and hence econometric modelling can be used to project MSW quantities [43]–[45]. Projections of MSW in China have formerly been done on a national level [46]–[48]. For these projections to be valuable input to energy system models they should have higher spatial detail, particularly due to the significant differences in waste collection between provinces [49]. Additionally, policy development has been identified as a key parameter [47], and should be included. The present thesis addresses this gap by performing a provincial level long-term projection of MSW including policy scenarios.

Biomass availability is typically assessed using statistical analysis, geographic information system analysis, or a combination [50], [51]. When used as input in energy system modeling these resources are typically associated with a price or a price curve to represent scarcity. Uncertainty can be represented with different scenarios [52]. Imports of biomass to use in various systems are typically not associated with any quantity constraints, but price curves can be used to reflect supply and demand [53]. Biomass is limited and availability to the energy sector depend on competing demand for alternative uses [52]. A previous study including cross-sectoral uses for biomass is included in energy system modeling, provides extensive insight on use of biomass [54], but has a limited view of environmental impacts and essentially consider residual biomass a commodity where either the model will use the available resources or not. It is used if it is beneficial to solving the model and what would otherwise happen to the residual biomass is not included in the considerations. However, as these residuals are byproducts from production of primary products, these residuals will be produced regardless of where they will end up. It is therefore unlikely that the theoretical availability of residual biomass responds to changes in demand, resulting in an upper limit of available resources. Demand changes can however affect the share of economically viable collectible quantities [55]. Considering the nature of residual biomass, the waste management of these resources should be included in assessments to represent the value of utilizing the resources. Assessments which include alternative uses for residual biomass are limited. This thesis addresses the gap of managing residual biomass by including alternative pathways for utilization as well as representing residual biomass for energy use in the energy system modeling.

With these considerations, this thesis contributes to three aspects; biomass resource assessments focusing on the energy sector, environmental impacts in energy system analysis, and residual biomass resource allocation, where the first two serve as prerequisites for the third.

1.4 Thesis Structure

The current chapter serves as an overall introduction to the motivation and structure of the thesis. The following papers make up the core of the Ph.D. thesis. They will be referred to as Paper I-IV and are included in the Paper Annex:

- Paper I: **Shapiro-Bengtsen S**, Andersen FM, Münster M, Zou L. Municipal solid waste available to the Chinese energy sector – Provincial projections to 2050. Waste Manag 2020;112:52–65. https://doi.org/10.1016/j.wasman.2020.05.014.
- Paper II: Franz SM, Campion N, **Shapiro-Bengtsen S**, Bramstoft R, Keles D, Münster M. Requirements for a Maritime Transition in Line With the Paris Agreement. IScience 2022. https://doi.org/10.2139/ssrn.4158005.

- Paper III: **Shapiro-Bengtsen S**, Hamelin L, Bregnbæk L, Zou L, Münster M. Should residual biomass be used for fuels, power and heat, or materials? Assessing costs and environmental impacts for China in 2035. Energy Environ Sci 2022:1950–66. https://doi.org/10.1039/d1ee03816h.
- Paper IV: **Shapiro-Bengtsen S**, Bramstoft R, Bregnbæk L, Münster M. Quantifying the Benefits of Refining Side Streams When Optimizing Use of Residual Biomass. Manuscript submitted to Energy & Environmental Science.

Subsequent to this **Introduction** chapter the **Methods** chapter presents an overview of methods used and how these have been developed. Following this, a **Results and Discussion** chapter showcases implications of the scientific contribution of the work in this thesis. Lastly, a **Conclusions and Perspectives** chapter both summarizes answers to the posed research questions and looks ahead to outline future perspectives.

1.4.1 Research Questions

The objective of this thesis is to contribute with advancements regarding assessment of resource availability for the energy sector as well as broadening the representation of environmental impacts in energy system analysis. These resource and environmental impacts are integrated in the system analysis performed in this thesis. Here scenarios are formulated and modelled to investigate plausible futures and inform policy decisions. This thesis is guided by the overarching research question "What are economic and environmentally sustainable future uses of residual biomass in China?". To help answering this question sub-research questions RQ 1 - RQ 4 are formulated to study inherent elements of the overarching question. Table 1 and Figure 1 presents the sub-research questions and in which papers these are addressed. Paper I deals with projections of municipal solid waste for the energy sector including scenarios for sorting of food waste, showing the value of resource availability projections for capacity planning. Paper II includes both resource availability assessments and climate impacts from shipping fuel production. Paper III performs a China-wide assessment of residual biomass resources, and investigates uses for these. Here key environmental impacts are quantified and dynamic energy system modelling is used to assess impacts to the energy sector. This work leads up to Paper IV, where cross-sectoral use of residual biomass and the value of side streams is in focus. Here configurations of residual biomass use are studied.

What are economic and environmentally sustainable future uses of residual biomass in China?					
		Paper			
		I	II	III	IV
RQ 1	Which residual biomass resources will be available to the energy sector and how should these be assessed?	X	X	X	X
RQ 2	How does including residual biomass related environmental impacts affect results in energy system analysis?		X	X	X
RQ 3	What is the impact of applying marginal energy mixes when assessing environmental impacts of residual biomass utilization scenarios?			X	
RQ 4	How does cross-sectoral use and integrated use of side streams affect environmental and economic aspects?				X

Table 1: Overview of research questions and in which papers they are addressed.

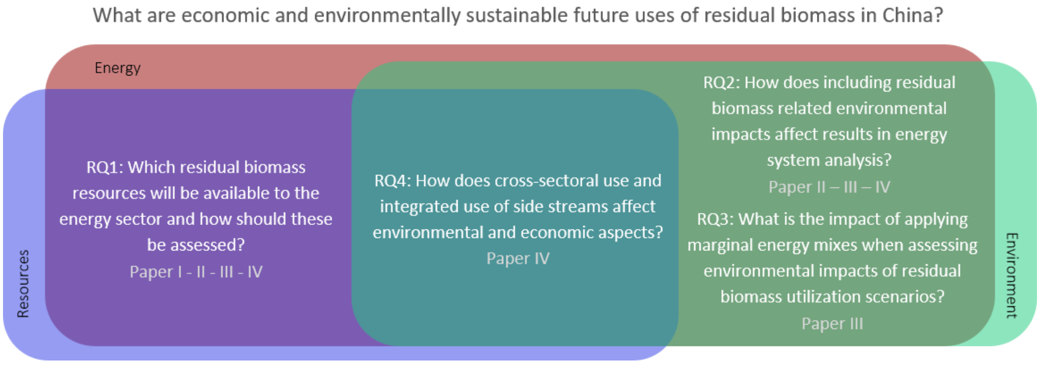


Figure 1: Overview of research questions and in which papers they are addressed, organized by the three main themes energy, resources, and environment.

1.4.2 Research Framework

The work in this thesis serves to improve input to and advance energy system modeling for a better representation of biomass in these models. The purpose is to create a stronger foundation for policy recommendations based on model results. Figure 2 shows an overview of the energy system model structure, where energy supply, conversion, and demand parameters are defined exogenously and results from the model include system costs, investment and operations, fuel use, and environmental externalities. The results are then validated or verified and inputs calibrated in an iterative process. The work in this thesis covers use of scenarios, expansion of techno-economic parameters, as well as sector demand input. However, the main contribution of this thesis lies within resource availability and environmental impacts input.

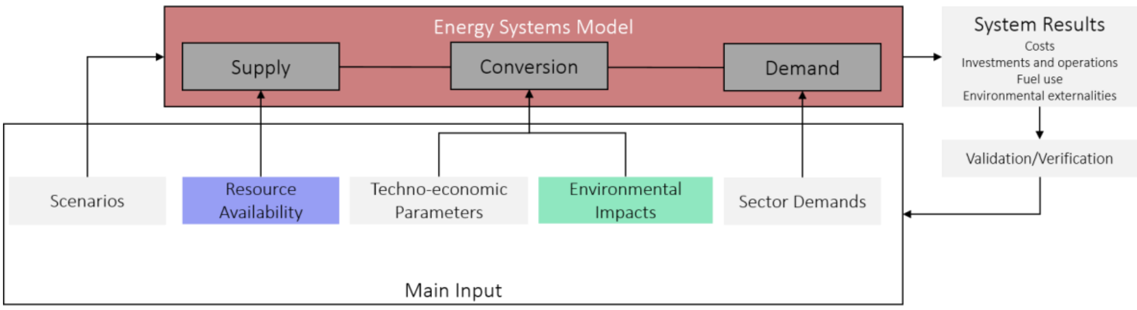


Figure 2: Overview of research framework for energy system modelling used in the thesis.

2. Methods

The methodology used in this thesis revolves around energy system modeling and integration with environmental impacts; in addition, resource assessments play a central part. This chapter starts by introducing the tools used in this thesis. This is followed by a more detailed presentation of resource availability methods in sub-chapter 2.2, methods for assessing environmental impacts in sub-chapter 2.3, and the last sub-chapter 2.4 covers the integration of these aspects in energy system models. Data will not be detailed here, but is all specified in the supplementary information to the papers.

2.1 Introduction to Tools

Five models are employed to answer the research questions for this PhD thesis. These models encompass one or several of the three areas: energy, resources, and environment as illustrated in Figure 3. The FRIDA model is an econometric model for waste projections, used in Paper I. These projections provide insights which can be used as input to energy system models, which is the case in Paper III and Paper IV. SEAMAPS is a marine fuel-use optimization model used in Paper II to project future fueling pathways for the shipping sector. The partial equilibrium optimization model, EDO, used in Paper III and Paper IV, provides a detailed representation of the Chinese electricity and district heating sectors. Bio3E, a bottom-up simulation model, is used in Paper III to manage environmental impacts as well as input to and output from EDO. The network-model OptiFlow has a detailed representation of resource networks, enabling allocation of resources for one or several applications. In Paper IV, OptiFlow is linked to EDO and used to model use of residual biomass.

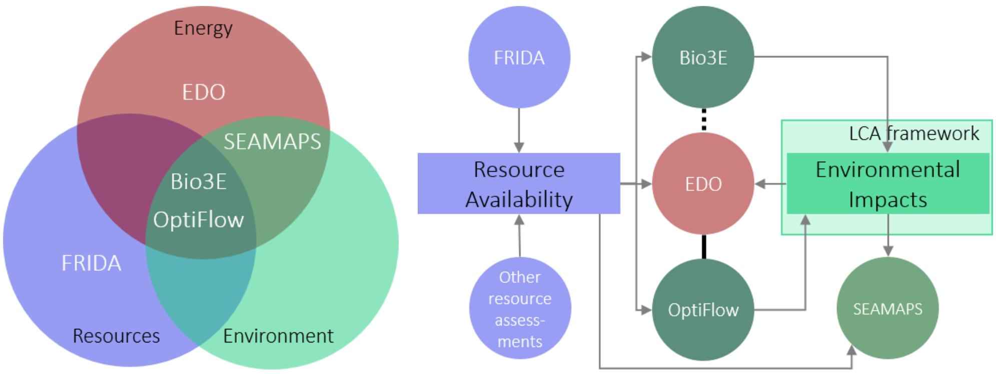


Figure 3: Overview of models used and their detailed representation of three areas; resources, energy, and environment (left). Links between models, resource availability and environmental impacts (right).

2.2 Resource Availability

2.2.1 Projection of Municipal Solid Waste

In Paper I, collected MSW quantities are projected by Chinese province using the FRIDA econometric waste projection model. The FRIDA model was developed in 2012 [45] and has later been revised and used by the Danish Environmental Agency to project Danish waste generation and treatment [56]. In Paper I, an adapted FRIDA model projects collected quantities of municipal solid waste in China to year 2050. The adaption consists of a simplification of the model due to limited data points, essentially going from projections of specific individual waste streams in the Danish case to projections of collected mixed municipal solid waste in Chinese provinces. Here I identified and collected data for the analysis. Econometric analysis of historical data found disposable household income and urban population to be relevant factors to include when projecting future MSW quantities in Chinese provinces. The model uses the least squares method to estimate coefficients for each Chinese province to 2050. See Equation 1 in Paper I for the general model equation.

I included sorting efficiencies and developed scenarios for the projections. I based the scenarios to assess future MSW quantities on policy targets and political narratives for sorting of food waste from MSW and minimizing mixed MSW. For details, please see Paper I where Table 1 presents an overview of scenarios and Section 3 presents data and sources. Sorted food waste is estimated as a share of total MSW combined with sorting efficiency in the different scenarios. This results in two projected fractions, mixed MSW and sorted food waste from 2020 to 2050 by province and scenario.

2.2.2 Other Resource Assessments

Bio3E is a spreadsheet model I developed for Paper III with detailed representation of resource availability as well as utilization scenarios for residuals. Crop and forestry residues, animal manure, and sewage sludge is assessed and projected using data found in literature and the methodology implemented in Bio3E is described in this section.

Available biomass resources can be specified by type of availability, as in Batidzirai [55], illustrated in Figure 4. The ecologically sustainable potential does not necessarily overlap with the economic potential, but it does consider technical collection limitations. The ecologically sustainable potential exceeds the implementation potential, which also includes considerations regarding sociopolitical framework conditions. For the resource assessments used in this thesis, the assessed quantities are the ecologically sustainable potentials.

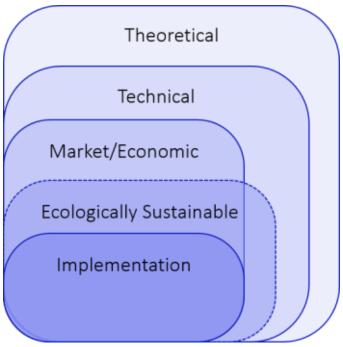


Figure 4: Illustration of different types of biomass potentials adapted from Batidzirai [55]

Crop Residues

Crop residues, CR, are inherently linked to cereal and other food production and have been assessed by region, r, using Equation 1, adapted from Kang et al. [57], where $P_{i,r}$ denotes the produced crop i in region r. The residue to product ratio, RPR, specifies how much crop residue is left after harvesting. C is the collection coefficient which specifies how much can be collected subject to technical limitations. ES denotes the remaining availability share after residues retained for soil improvement, used for feed or in industrial purposes, e.g. paper production, are subtracted. Lastly, LHV denotes the mass to joules conversion factor for energy content of crop residues.

Equation 1

$$CR_r = \sum_{i=1}^{n} P_{i,r} \cdot RPR_{i,r} \cdot C_i \cdot ES_i \cdot LHV_i$$

The assessed crop residues are projected on national level to year 2050, using scenarios for crop yield development from the Food and Agriculture Organization [58], and the regional distribution for crop production is kept the same.

Forestry Residues

Forestry residues (FR) are naturally linked to forestry activities and are assessed starting with forestry output and are specified by region using Equation 2, adapted from Kang et al. [57], where A_i is the forestry output for forestry type i in area A and Y denotes the yield, C the collection coefficient and LHV_{FR} the lower heating value of forestry residues.

Equation 2

$$FR_r = \sum_{i=1}^{n} A_i \cdot Y_i \cdot C_i \cdot LHV_{FR}$$

Only forestry residues from forestry activities which can be categorized as production forests are included in this thesis, all forestry categories with a collection coefficient below 0.5 are excluded. The forestry residues are not assumed to change over time, and hence the same annual levels are assumed in 2050.

Animal Manure

For animal manure (AM), which is the major wet residual biomass stream included in this thesis, Equation 3 is used to assess provincial quantities. Here $N_{r,i}$ denotes number of heads of livestock in region r for species i, E is the daily excretion coefficient, B the breading cycle in days, and C is the collection coefficient.

Equation 3

$$AM_r = \sum_{i=1}^{n} N_{r,i} \cdot E_i \cdot B_i \cdot C_i$$

Quantities follow animal husbandry, and projected scenarios on national livestock development [58] are used to project quantities. Historical data on distribution of livestock by province is used to regionalize livestock populations.

Sewage Sludge

Sewage sludge quantities are assessed using historical data from Wei et al. [59] and projected using the indexed urban projection development described in Paper I, to account for interprovincial migration.

2.2.3 Biomass availability for shipping fuels

The SEAMAPS model, introduced in Paper II, was developed to answer questions regarding future fuel use in the shipping sector. The model uses least-cost optimization of fuel consumption and is subject to a number of constraints. I contributed with biomass resource assessments and calculated the availability of bio-based fuels, which is included as exogenous constraints.

The global biomass availability for producing shipping fuels included in Paper II has been assessed using data in literature with the perspective of limiting availability to residual biomass and serving competing sectors first. Competing demand for electricity production, petrochemicals, aviation fuels, and road fuels is considered. This was assessed using projections found in literature, illustrated in Figure 5, adapted from Franz et al. [60].

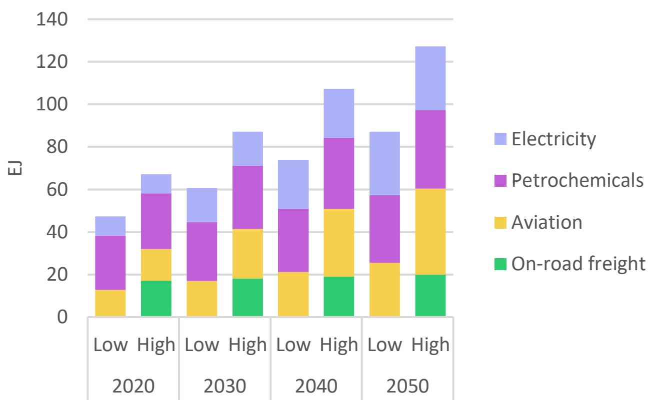


Figure 5: Overview of competing demands for bio-based fuels and chemicals. Figure generated using data from Franz et al. [60] **(Figure 13 and Figure 15).**

The biomass availability considered for methanol or pyrolysis oil production are crop residues [7], forestry residues [61], and black liquor [62]. First, the competing demand for the power sector [5] is subtracted and the exhaust from this power production is used as basis to calculate the availability for CO_2 for point source methanol, using carbon content [63] and converting this to point source methanol potential.

After demand for other sectors is covered, the rest is left for shipping. This is described in Equation 4. The bio-fuel availability from solid biomass for the shipping sector S_f , which denotes shipping fuel availability S by fuel f, is assessed by the total available biomass resources for methanol B. This is done after subtracting demand for power production D_{el} , of which some of the carbon is sequestrated, B_{CSS}, but the remainder is used as a carbon source for point source methanol availability, using the conversion factor $C_{MeOH_{PS}}$. Hereafter demand from the remaining competing sectors, petrochemicals, aviation, and road fuels D_{cf} are subtracted and the remainder is converted to bio-e-methanol or pyrolysis oil using the fuel specific conversion ratio C_f.

Equation 4

$$S_f = ((B - D_{el} + \left((D_{el} - B_{ccs}) \cdot C_{MeOH\,PS}\right) - D_{cf}) \cdot C_f$$

For liquefied biogas, availability is assessed using Equation 5, where the resources animal manure, AM, and food as well as garden waste, FGW, [64] is considered. These are converted to liquefied biogas availability S_{LBG} by using the potential methane yield $_{MY}$, subtracting biogas used in the power sector, BG_{el} and converting to LBG using a conversion factor, C_{LBG} which considers methane losses [65].

Equation 5

$$S_{LBG} = (AM \cdot AM_{MY} + FGW \cdot FGW_{MY} - BG_{el}) \cdot C_{LBG}$$

2.3 Environmental Impacts

2.3.1 Life cycle perspective

In general terms, life cycle assessments (LCA) can be divided into attributional and consequential studies. While Paper III does not involve a full LCA study, it employs a LCA approach using a consequential perspective. Paper IV builds on this work and continues this consequential LCA approach, using a different methodology. The consequential approach has been found relevant and it harmonizes with my view on residual biomass and assessing systemic changes. Regarding residual biomass, a consequential approach avoids allocation of burden by expanding the system to include impacts from residuals, while focusing on the differences in the analyzed systems [66]. Conversely, in attributional LCA, the residuals should be allocated part of the burden, and there are different practices regarding this [17]. Another reason for using a consequential LCA approach is because it is found suitable for assessing impacts from different scenarios in energy system modeling. These scenarios illustrate future systems and the objective of consequential LCA is to gain insight into the consequences of systemic changes. This is contrasted to attributing the impacts to e.g. part of an energy system, which is the case with attributional LCA. The life cycle perspective take into account emissions occurring during the upstream and downstream processes, as well as emissions avoided resulting from services displaced with final products, and net changes in emissions resulting from use of co-products or side streams.

2.3.2 Global Upstream Emissions for Fuel Production

My input regarding fossil and biogenic main GHGs make up the environmental impact part of the optimization of fuel use and thus integrates a representation climate impacts in the SEAMAPS model. This input is divided into so-called upstream emissions, which cover the infrastructure needed for e-fuel production, well-to-tank emissions for conventional fuels, as well as tank-to-wake emissions, which cover the on-board exhaust emissions. This enables using different scopes when assessing climate change impact of shipping fuel use, as illustrated in Figure 6.

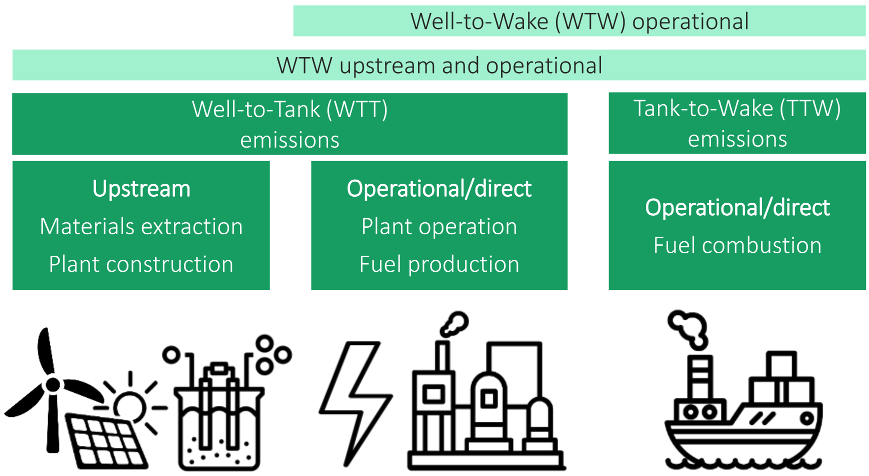


Figure 6: Overview of greenhouse gas emission accounting scopes used in Paper II.

In Paper II the so-called upstream GHG emissions are quantified and included in the modeling. These emissions represent the environmental burden in terms of GHG emissions from the infrastructure needed to produce shipping fuels. When these emissions are disregarded there are several fueling options associated with zero emissions, e.g. green ammonia. However, these should be considered for a comprehensive overview and to enable an assessment of different fuels. In Paper II a life-cycle perspective is used for assessing the GHG emissions. Here the infrastructure needed for production of shipping fuels is associated with GHG emissions factors. The background data used for this assessment primarily stems for the Ecoinvent database [67]. I gathered the data used to calculate impact for infrastructure, it can be found in Tables 10 and 11 of Franz et al. [60]. This includes onshore and offshore wind turbines, solar PV, electrolyzers, batteries, hydrogen storage, methanol plants, air separation units, carbon capture, and gasifies. The data on GHG emissions is normalized using the assumed lifetime and production output for each part of the required infrastructure. An additional inventory has been performed to enable comparison to using power from the electricity grid. This approach enables comparison of e-fuel production using specific electriricy mixes, where the power produced is off-grid, as in the analysis presented in Paper II, or using a mix of power from the grid and producer-owned wind and solar power as in Campion et al. [68].

2.3.3 Impacts from Cross-Sectoral use of Residual Biomass in China

Apart from GHG emissions, indicators for eutrophication and air pollution are included in Paper III and Paper IV. The indicators for marine and freshwater eutrophication are N and P lost to water, and air pollution is included in terms of direct PM2.5 emissions. The environmental impacts considered in this study are crucial aspects of energy systems [69]. Air pollution is especially significant due to the harmful particles that result from incomplete combustion of biomass [70], while eutrophication is recognized as a major issue linked to the management of organic waste, particularly manure [71]. Emissions from conversion processes are based on published life cycle inventories and associated estimation methods. The methods are outlined below and further described in section 2 of the Supplementary Information for Paper III and Supplementary Information 9 for Paper IV.

Climate change

To quantify impacts on climate change the three main GHG substances CO_2, CH_4, and N_2O are considered. These are aggregated to CO_2e using a 100 year time-frame for global warming potential. The residual biomass included in this thesis is considered to be carbon natural, meaning that the carbon uptake during growth and CO_2 emissions from degradation are not taken into account. The CO_2e emissions, $GHGF_{b,a}$, is assessed for each residual biomass resource b and pathway a using Equation 6, from the supplementary information for Paper III.

Equation 6

$$GHGF_{b,a} = -CC_b \cdot SC_{b,a} + (CH_{4_{b,a}} \cdot GWP_{CH4}) + (N_2O_{b,a} \cdot GWP_{N2O}) - AC_{b,a}$$

Here, the methane, CH_4, and nitrous oxide, N_2O, emissions are included and converted to CO2e using specific global warming potential factors, GWP. The carbon content CC and share of sequestered carbon, SC is considered. In Paper III, the avoided CO_2e emissions from replaced products, AC, is also included. This also covers the avoided CO_2e emissions from indirect land use change [72] for replaced conventional feed production. In Paper IV, the pathways for bio-based production are competing with the conventional production to fulfil the same demand. Emissions associated with conventional production are associated with these conventional products. For this reason the avoided emissions, AC, are not deducted in Paper IV when calculating the CO_2e emissions associated with conversion of residual biomass. Apart from this exception, the methodology presented in Equation 6 is also used in Paper IV.

When crop and forestry residues are used for construction materials, the carbon is assumed to be sequestered for the lifetime of the material, without considering degradation of the material. The fate of the materials after their end-of-life is not considered in the calculation, but delaying carbon emissions can be beneficial for climate change mitigation. It is also likely that carbon storage and utilization technology will advance over time.

Eutrophication

Eutrophication is a central issue of the biogeochemical flows of nitrogen and phosphorus, which is one of the planetary boundaries, underscoring the importance of examining this impact. While there are additional contributors to eutrophication, N and P losses are used as indicators for marine and freshwater eutrophication, respectively. It is expressed as N and P equivalents using the Environmental Footprint Life Cycle Impact Assessment method [73]. As the impact largely depends on local soil conditions, these assessments are associated with high degrees of uncertainty.

Air pollution

A key motivation to quantify PM2.5 emissions is to illustrate the burden of e.g. open burning of crop and forestry residues. This is because burning residual biomass contributes to the already extensive health issues caused by air pollution [74]. While there are intricate relationships leading to air pollution, which are not accounted for in this thesis, direct PM2.5 emissions are considered in conversion where relevant.

Reference use

For impacts from the unutilized residual biomass, Reference scenario in Paper III and reference use in Paper IV, the IPCC guidelines [75], [76] and data from literature are used to calculate impacts. The terms Reference scenario in Paper III and reference use in Paper IV cover the same counterfactual use of residual biomass illustrated in Figure 7. This is an approximation of assessed counterfactual use of residual biomass in China, i.e. what likely happens to these resources when they are not separately collected and utilized as input in e.g. energy production. Two options are included for each resource stream, with a set ratio, based on scientific literature, statistics, and discussions with industry experts. For crop residues this is calculated using data from Fang et al. [77], forestry residues are assumed to be burned or abandoned with a 50/50 ratio, for animal manure data from Sommer et al. [78] is used, for food waste data from MoHURD [49] is used, and for sewage sludge the counterfactual use is calculated using data from Qu et al. [79].

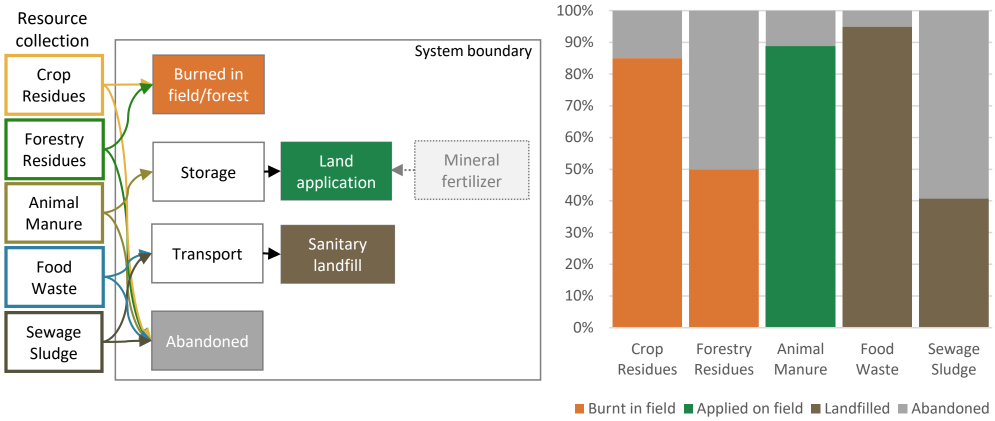


Figure 7: Overview of the system boundary of the Reference scenario in Paper III (left). Figure adapted from Paper III Figure S1. The shares for counterfactual use of residual biomass in Reference scenario in Paper III and Reference use in Paper IV (right).

2.3.4 Monetization of environmental impacts

Monetization of environmental impacts is a crucial aspect of this thesis. In Paper II, externalities are represented by a carbon price, which is an exogenous input to the model. Combined with fuel savings, the interactions of these parameters are tested resulting in a full range of possible fuel pathway configurations. In Paper III and Paper IV externality costs are key parameters and values are found in literature. To address sensitivity to this parameter, different sources with varying levels of externality costs are tested in both Paper III and Paper IV.

2.4 Integration with Energy System Models

In order to model future scenario for the Chinese energy system and answer questions about e.g. electricity generation and costs, the selected model must fulfil a number of criteria. The district heating network in the northern regions of China is the largest in the world [80], making it relevant to include a well representation of the integration between power and heating. The extensive and expanding integration of variable renewable energy in China requires a model which allows for sufficient temporal resolution. The applied model must also be able to represent the energy system on provincial level, including transmission bottlenecks for interprovincial transmission. The EDO model has been chosen as it fulfils these criteria and is flexible in terms of linking with e.g. the OptiFlow model, which provides the opportunity to model various cross-sectoral uses of residual biomass and to include options for side stream refining. Models can used separately or integrated to varying extent. In a soft link information is shared between models and in hard linking code is shared between two models [81]. This sub-chapter presents the soft link between EDO and Bio3E and the hard link between EDO and OptiFlow.

2.4.1 EDO

EDO is a Chinese adaptation of the open source energy system model Balmorel, which was first released in 2001 and has been developed and used for many analyses since [82]. It is a bottom-up partial equilibrium model with a specific focus on the electricity and district heating sectors and their integration. The EDO model was built by the China National Renewable Energy Centre in 2012 and has been used for several studies on the Chinese energy system [83]. The EDO model is an optimization model and the objective function minimizes total system costs subject to a range of constraints. The EDO model has a detailed representation of the Chinese electricity and district heating sectors. The Chinese grid regions are modeled as countries in the Balmorel terminology and the provinces are as regions. In each province the areas represent urban, suburban, rural, and industrial areas. Resource input is provided exogenously and quantification of environmental factors are limited to fossil CO_2 emissions. These can be restricted with a cap and or a price, which thus includes CO_2 emissions in the optimization.

2.4.2 Bio3E

I developed Bio3E to model production of fuels and materials while accounting for environmental impacts. The model can be soft linked to an optimization model, such as EDO in Paper III. This link is illustrated with the information flows shown in Figure 8.

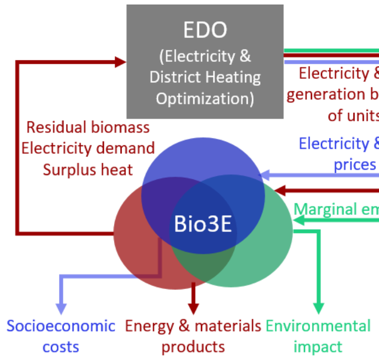


Figure 8: Illustration of the soft link between Bio3E and EDO. Figure from Paper III (Figure 2).

The information from Bio3E provided to EDO consists of residual biomass availability, electricity demand and surplus heat availability. In Bio3E residual biomass is converted to biogas as well as crop and forestry residues fuel input for EDO to produce electricity and/or heat. The biogas input is the methane yield from anaerobic digestion calculated using the volatile solids content of the available resources. This resulting methane yield, after subtracted methane slips, is the biogas output, which is made available as a fuel input to EDO for combustion. Crop and forestry residues available as fuel input to EDO is also calculated in Bio3E, using the methodology described in 2.2.2. As the sorted food waste affects mixed

MSW quantities and energy content, the sorted food waste is subtracted and new MSW input data for EDO is calculated in Bio3E. Hydrogen is needed for the methanation of CO_2 in biogas to synthetic natural gas and methanol synthesis of pyrolysis gas to produce bio-e-jet. For technological parameters, data on costs, and efficiencies, see Table S1 in supplementary information for Paper III. The required hydrogen is generated through alkaline water electrolysis and calculated in Bio3E. Here the electrolysis production and hydrogen storage capacity is calculated. The required power demand, primarily for electrolysis, and the excess heat from methanol synthesis and methanation processes is provided as input for EDO. The electricity demand for electrolysis is implemented as a flexible demand, where the flexibility is up to 12 hours per day, following the scale of the hydrogen storage. After the scenarios are run in EDO, the resulting electricity and district heating generation and prices as well as CO_2 emissions are transferred to Bio3E. Subsequently the results are combined in Bio3E to enable an overview of results from the scenarios.

2.4.3 OptiFlow

The OptiFlow network flow model was originally developed under the name OptiWaste to model optimal use or waste [84] and has been developed further and used to model use of gas and liquid fuels [85]. It is a generalized network flow optimization model which can be integrated with EDO, the link between the two models is illustrated in Figure 9.

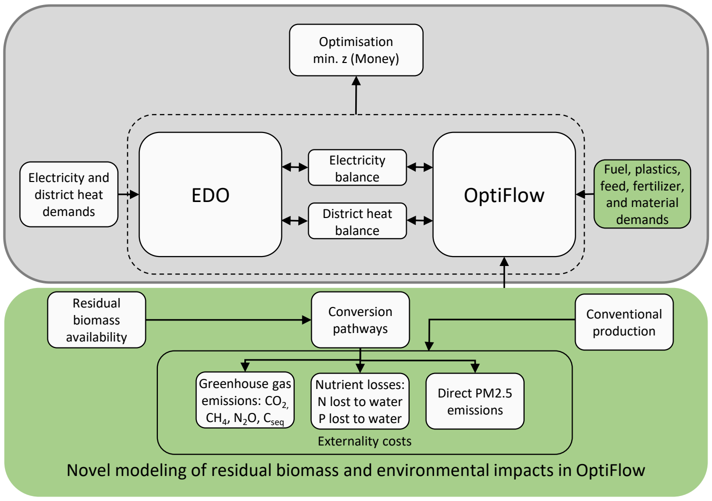


Figure 9: Illustration of the hard link between the EDO and OptiFlow models used in Paper IV. Figure from Paper IV (Figure 1).

In Paper IV I have extended the representation of GHG emissions in OptiFlow by including CH_4 and N_2O emissions as well as carbon sequestration for a more comprehensive GHG accounting. Each GHG species is modeled individually and thus global warming potential (GWP) factors can be varied. Adding to this, I have included N and P losses to water to quantify eutrophication impact as well as fine particulate matter, by quantifying direct PM2.5 emissions. This has been done by including additional processes and flows to represent the additional externalities. The externalities have then been associated with costs on a national level. This enables implementing varying externality costs to test sensitivities to this parameter. The model used in Paper IV builds on previous work to model renewable fuels [85] and electrofuels [86]. Apart from introducing a representation of the externalities described above, I further extended the network to cover cross-sectoral use as well as refining of side-streams. This model development is illustrated in Figure 12. This is a simplification providing an overview. To further clarify the model development, Figure 10 provides an example of side stream refining, and Figure 11 a description of the plastics refining processes, to illustrate the level of detail included.

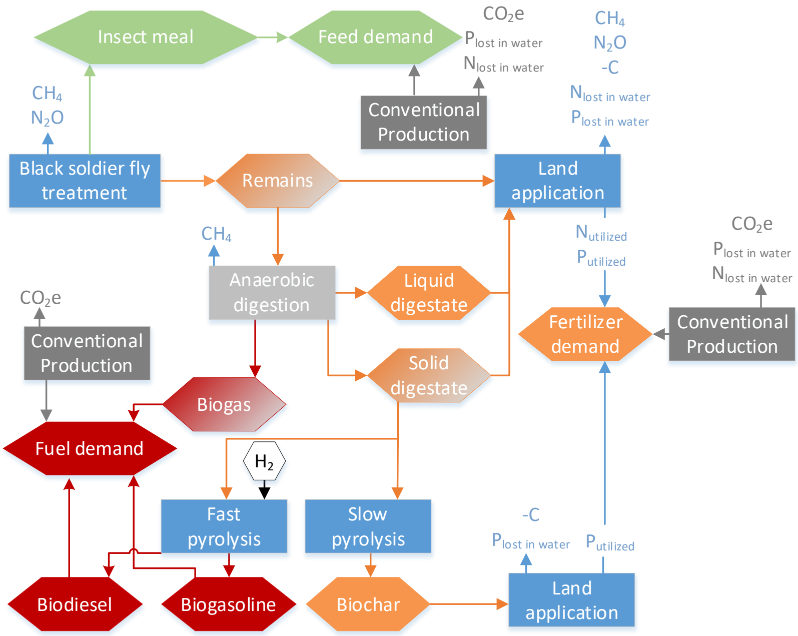


Figure 10: Example of side stream refining. Figure from Paper IV (Figure 3).

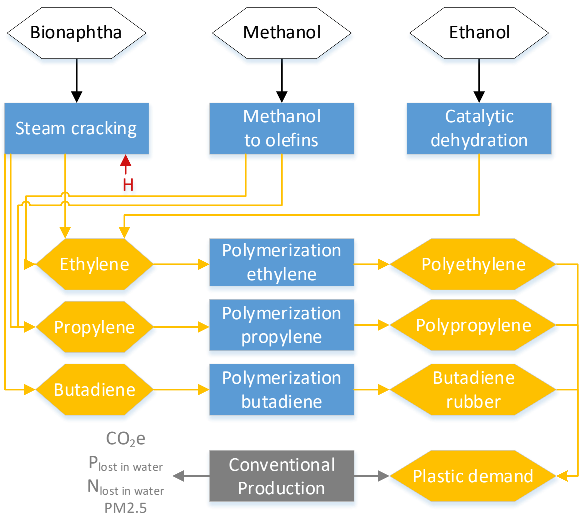


Figure 11: Overview of plastics refining (right) using data from Paper IV.

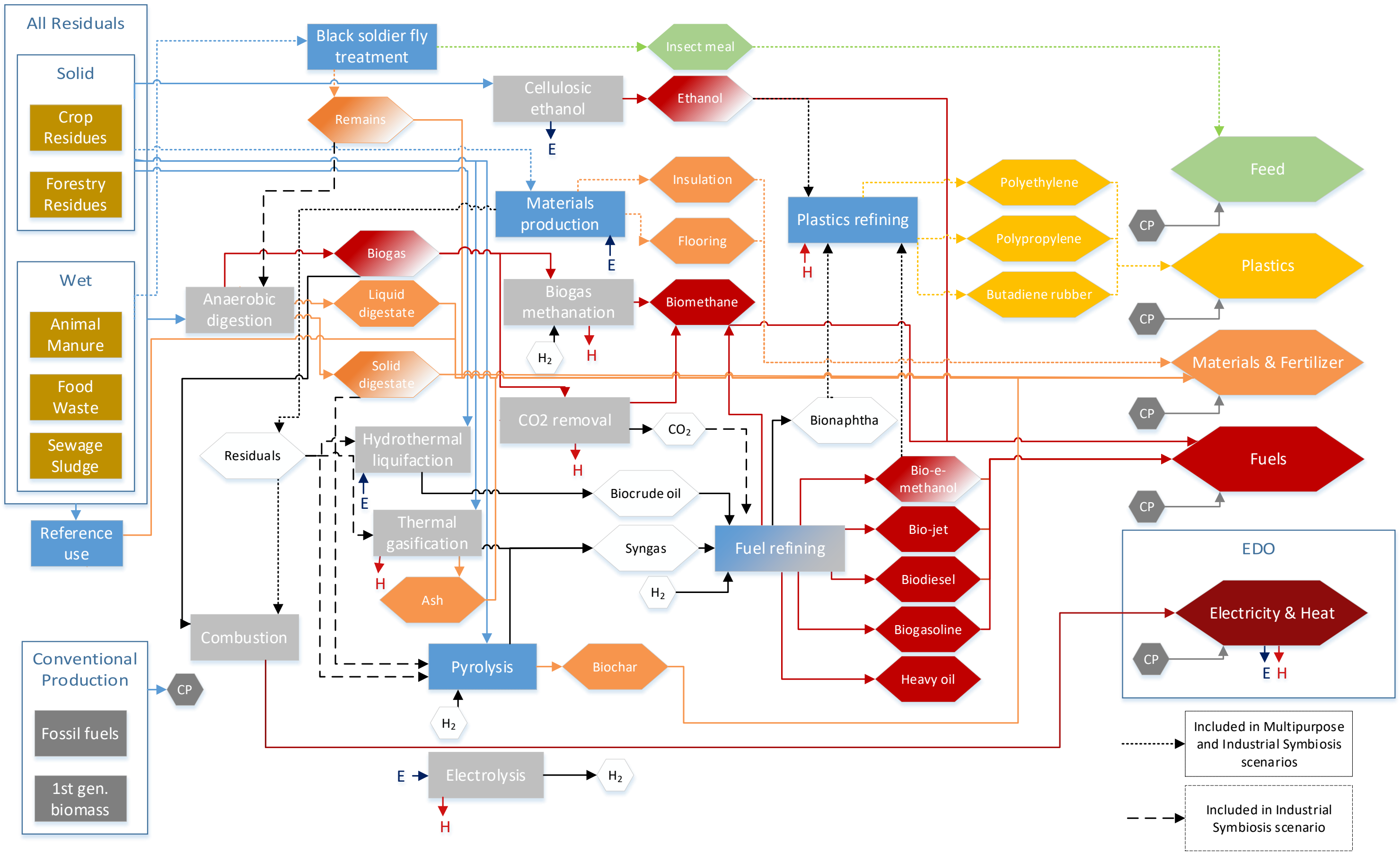


Figure 12: Overview of the network modeled in Paper IV with processes previously included in light gray and the new included processes in blue. Fuel refining has both colors as it represents several processes, some of which are new. Processes with electricity input or output are labeled with E, and similarly H for heat. The gradually white hexagons can also be used as intermediaries, as inputs for other processes. Figure adapted from Paper IV (Figure 2)

3. Results and Discussion

This chapter serves to present and discuss results from the papers included in this thesis to illustrate the impact of the contribution of this thesis. The chapter is organized in three themes: resource assessments, environmental impacts, and residual biomass utilization.

3.1 Resource Assessments

How to assess residual biomass availability for the energy sector is a theme primarily covered in Paper I, where MSW and sorted food waste is projected. In Paper II, global biomass available to produce shipping fuels is assessed and used as input. For Chinese residual biomass apart from sorted food waste, resource assessments are included in Paper III and Paper IV as input, which is why results from all four papers are included in this sub-chapter, but with emphasis on, and starting with, results from Paper I.

3.1.1 Municipal solid waste projections

In Paper I, Chinese MSW quantities were projected on provincial level. The results are shown on national level in Figure 13, adapted from Paper I. The different scenarios are based on policy analysis and illustrate implementation of different policies.

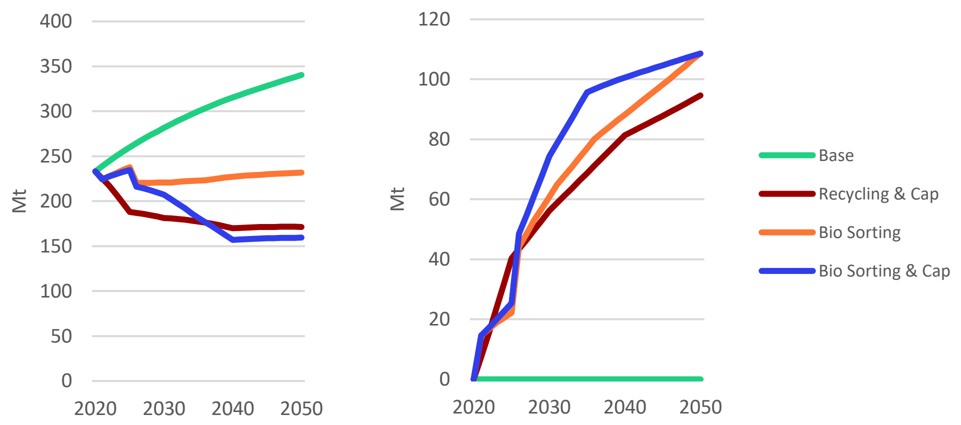


Figure 13: Projected mixed MSW (left) and sorted food waste (right) aggregated national values for different scenarios. Adapted from Paper 1 (Figure 6).

The projected quantities in different scenarios can be used as input to energy system models. Often several different scenarios are explored in energy system modeling, this could be guided by different policy futures. Here it is relevant to use a projection scenario for MSW and food waste projections that harmonizes with the overall assumptions for the particular scenario. A comparison of the projected quantities with new updated data since the publication of Paper I, in Figure 14, shows that the results from the Base scenario in Paper I are close to the recent data points. Here the results from Paper I, where projected disposable household income and urban population are factors used in the projection model, are compared to using the single coefficient generated waste per urban capita, or a linear trend of collected MSW quantities using the same historical data. More recent papers, both published in 2022, project provincial MSW [87] and food waste [88] in China under different scenarios, both using the shared socioeconomic pathways (SSPs). For mixed MSW projected by Zhang et al. [87], the resulting quantities by 2050, around 450 – 600 Mt, are considerably higher than the results from Paper I. There is a benefit of utilizing the established SSP framework for developing scenarios, as these are predefined pathways which are widely applied. The results can be used as input for resource utilization modeling also using the SSP framework. Zhang et al. [87] use machine learning techniques which generally are applicable to a wide range of complex situations, but their performance is heavily dependent on the selection of data and the availability of substantial historical datasets. For food waste, the results from Ogunmoroti et al. [88] aggregate to 101 – 140 Mt food waste by 2040. However, this does not consider sorting efficiencies, so the corresponding value from Paper I is higher, at 176 Mt of food waste by 2040.

On a provincial level, the projected quantities in Paper I are compared to reported data for year 2020, show in Figure 15. It should be highlighted that the latest available data year for the modeling done in Paper I was 2017. Year 2020 is used in Figure 15 because it is the year for political targets set in the 13th five year plan, which was referenced in Paper I. The projected levels in Paper I lie between 72% and 128% of reported quantities in 2020, with a median of 96%. One of the results pointed out in Paper I is the risk of overcapacity investments in the provinces Tianjin, Zhejiang, and Anhui. When comparing the realized incineration investments with the actual MSW quantities in Figure 15, it appears that there is an MSW incineration overcapacity in the highlighted provinces. Adding to this, the installed MSW incineration capacity also surpasses MSW quantities in Jiangsu and Guizhou, as incineration investments in these two provinces exceeded planned capacity.

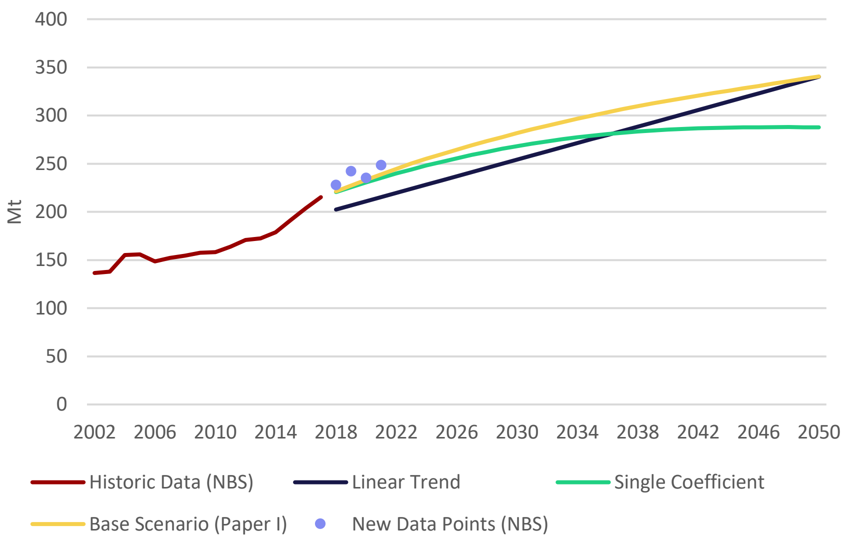


Figure 14: Methodological comparison of MSW projections. Historic Data shows the collected MSW quantities and New Data Points the latest data on collected MSW quantities [89] **since the publication of Paper I. Single Coefficient is using urban population data available in Paper I to project quantities and linear Trend is a linear projection of Historic Data on collected waste quantities.**

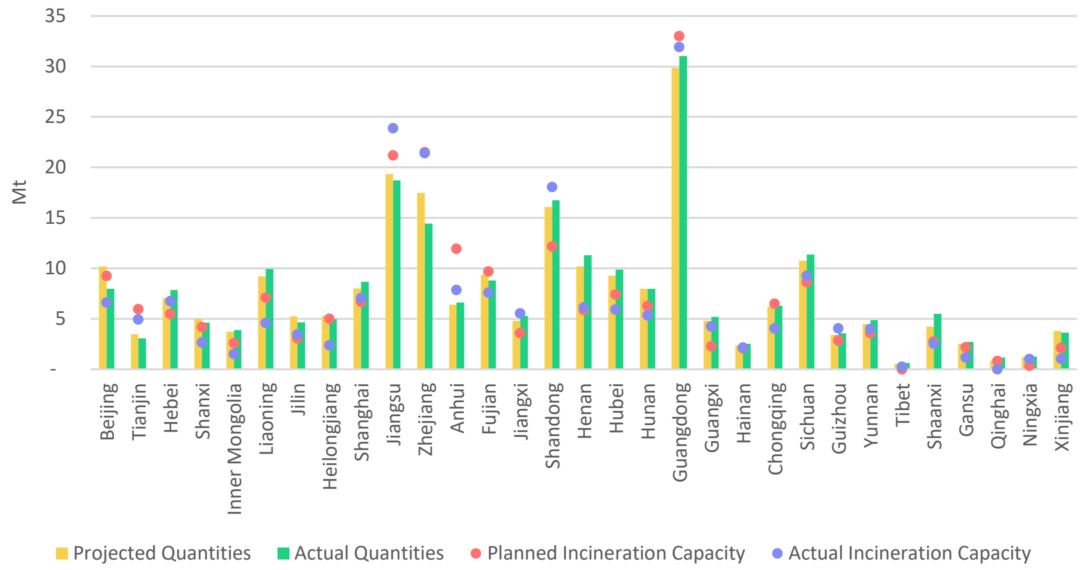


Figure 15: Municipal solid waste (MSW) by province for 2020. Projection results from Paper I compared to statistical data [89] **and planned incineration capacity** [90] **compared to realized incineration capacity** [89]**.**

Sorting of food waste differs in the scenarios included in Paper I, which include waste sorting policies and waste minimization. Paper I does not cover any considerations regarding use of MSW or sorted food waste, but in Paper III and Paper IV the projected MSW quantities and sorted food waste in Paper I is included in the resource input.

3.1.2 Residual Biomass Assessments for China

Food waste is projected to have the highest increase of the included residual biomass resources, increasing by 46% from 2020 to 2050. However, when compared to the other residual biomass fractions considered in this thesis, food waste only contributes to 3-4% of national residual biomass availability, see Figure 16, which is adapted from Paper III. The increase primarily stems from increased crop residues. The map in Figure 16 shows the aggregated data on provincial availability for year 2050 and it indicates the vast regional differences across China. The same resource availability assessment is used as input in Paper IV. Figure 17, from Paper IV, shows the provincial availability by resource fraction for year 2050. This shows the link between urban population and food waste and sewage sludge, for example, in the populous provinces Guangdong and Zhejiang. For crop residues, the provinces Henan, Heilongjiang, and Shandong stand out. Most of Chinese wheat is produced in Henan, and second most in Shandong. Heilongjiang has the largest corn and second largest rice production in China. Adding to this, the neighboring provinces Henan and Shandong also have a considerable animal husbandry, with most chickens in Shandong, and Henan with second to largest population of cow, pigs, and chickens. The overall animal manure availability is largest in Sichuan, as this is the province with the largest cow and pig populations while also having considerable sheep and chicken production. For forestry residues, the largest availability is in the neighboring provinces Yunnan in the south and Sichuan in the central region of China.

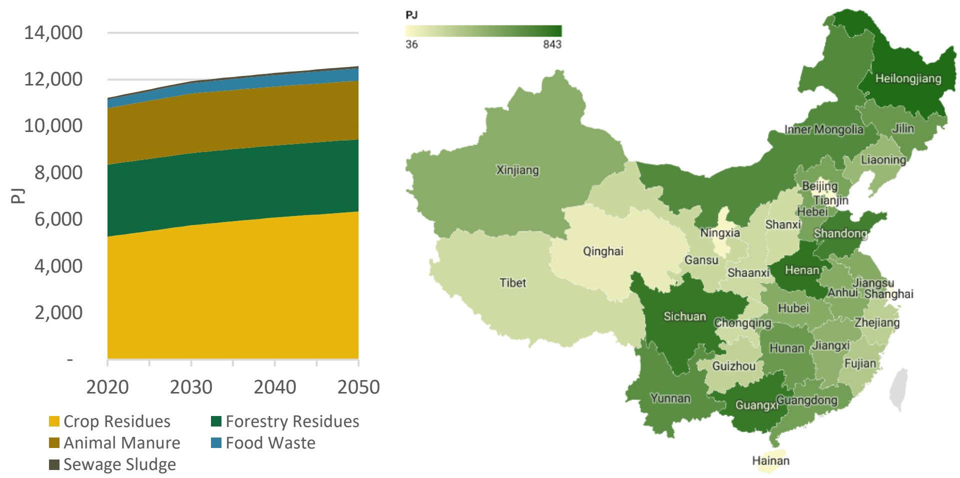


Figure 16: Projected national residual biomass availability (left) adapted from Paper III (Figure 4). For wet biomass (animal manure, food waste, and sewage sludge) biomass potentials are converted to energy content using methane potential from volatile solids in the assessed quantities. The same data is shown by province in PJ for year 2050 (right).

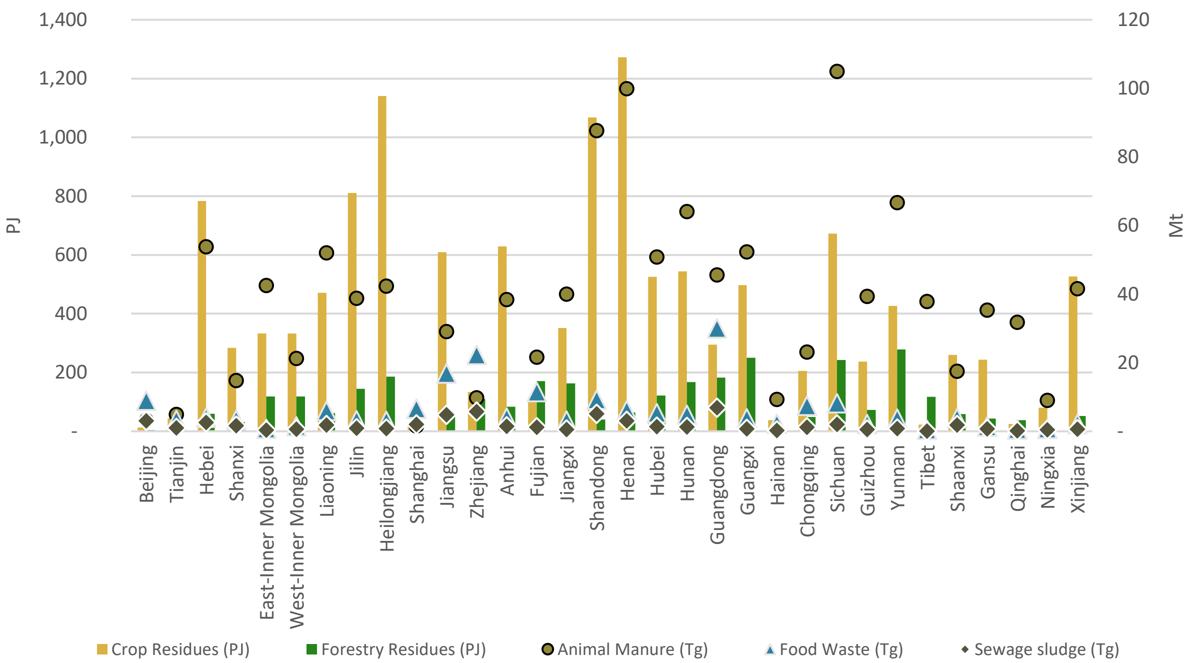


Figure 17: Overview of assessed residual biomass availability by province in 2050. Crop and forestry residues shown in bars in PJ on the left axis and animal manure, food waste, and sewage sludge shown on the right axis in Mt. Figure from Paper IV (Figure 4).

3.1.3 Global Biomass Available for Shipping Fuels

While still being a wide range, there is a general consensus that there is a global annual residual biomass availability of around 100-300 EJ [7]. In Paper II, global availability of biomass for production of shipping fuels are assessed. The production of biofuels for the shipping industry should rely on sustainable and low-cost resources, which is why only residual biomass obtained from waste streams in the agricultural and forestry sectors is considered. The limited biomass available for shipping fuel production was converted to biofuel and bio-e-fuel potentials, shown in Figure 18. This was part of the established framework conditions required to model shipping fuel pathways in Paper II. The potential for these resources is calculated with consideration for ecological sustainability, but it does not include projections over time. The assessment of crop residues is for year 2050 [7] and forestry residues for year 2100 [61], due to limited data for year 2050. For black liquor the assessment is from 2007 [62] and for manure and organic waste from 2020 [64], both without any projection for future availabilities. Additionally the potential impact of a change in global diets on the availability of these resources has not been taken into account. For the assessment in Paper II, the competing demand is limited to electricity generation, aviation and road freight, and plastics. Other competing demands, such as those from the construction sector, have not been considered.

The availability projection shows that in the medium availability scenario, which is used in the base scenarios for Paper II, there will be biomass available to produce bio-e-methanol or pyrolysis oil in the short to medium term to 2035. The input shown in Figure 18 shows the conversion to bio-e-methanol, which were included as input in Paper II. The costs for pyrolysis oil were too uncertain for pyrolysis oil to be included in the Paper II analysis. For liquefied biogas, there is availability throughout the time period, although it is decreasing slightly over time. For biogenic CO_2, which could be used to synthesize e-methanol, the availability in the medium scenario is increasing and then declining after 2035 due to competing demands. In the high biomass availability, this is increasing over time and with low biomass availability, there is only a very limited availability of biogenic CO_2 in the first couple of years. The graphs in Figure 18 show the low, medium, and high availability scenarios used as input for the biomass availability sensitivity scenarios in Paper II.

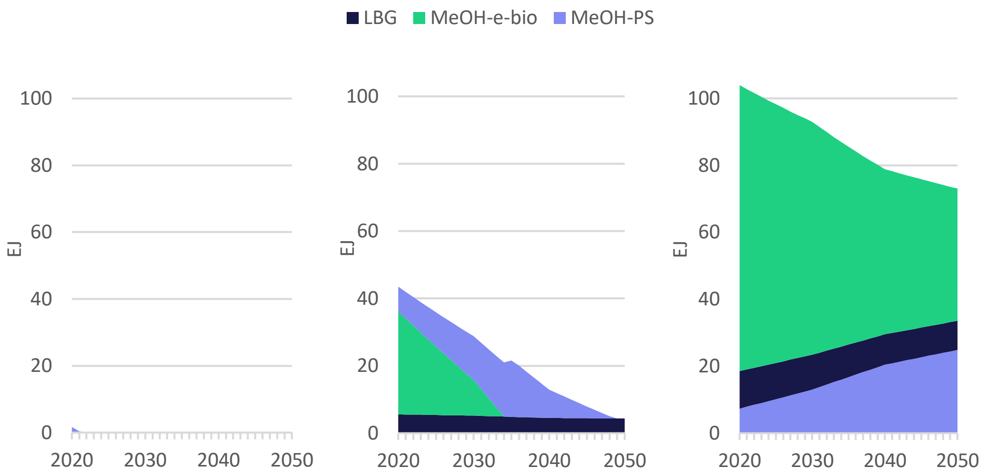


Figure 18: Showing liquefied biogas (LBG) methanol, from gasification and additional hydrogen input (MeOH-e-bio) and methanol from using point source CO_2 (MeOH-PS) shipping fuel availability in the low (left) medium (middle) and high (right) scenarios used as input for Paper II.

3.1.4 Resource Assessments Overview and Discussion

The results on resource availability presented in this section cover Chinese MSW projections, assessment of other residual biomass resources in China, and global availability of biomass for shipping fuels. Regarding global biomass available for shipping, the competing demand is a crucial factor to include in assessments. The short-term projected MSW quantities in Paper I has a strong correlation to recent data. More recent studies have exemplified interesting approaches, implementing SSPs narratives for scenario projections. For residual biomass, these are closely related to population and socio-economic development. While the projections used in the framework presented in this thesis include projections for population and food production, it would be relevant to link this to the SSP narratives.

Using other methodologies, for example geographical information system analysis, could provide a more geographically detailed assessment. This would be relevant for regional or local feasibility assessments. On a global scale, integrated assessment models (IAMs) can be used to investigate biomass availability scenarios. These models take into account socio-economic factors, such as population, growth, and trade-flows and combining them with detailed information on biophysical factors and impacts on land-use. Assessing Chinese residual biomass availability using IAM projections is associated with challenges, as these projections typically aggregate results into five regions worldwide [91].

When looking at the IAM outputs for the traditional use of biomass for all of Asia in 1.5˚ C scenarios with low overshoot, availability covers a wide span, from zero to 16 EJ by 2050, with an average of 8 EJ [91]. The results for use of modern biomass also display a considerable degree of variation with values ranging from 8 EJ to 93 EJ by 2050, averaging at 36 EJ [91]. The results presented in this thesis for China lie within these wide ranges. This can be seen as a very rough validation of the bottom-up-modeling framework. However, comparing these results is difficult due to the limitations of the IAMs modeling framework, which lacks geospatial resolution. The modeling framework presented in this thesis was designed to answer a specific research question about the availability of residual biomass in Chinese provinces. The results show significant variations in the availability of residual biomass across provinces. Thus, the presented modeling framework could potentially serve as input for more spatially detailed IAM modeling.

3.2 Environmental Impacts

This sub-chapter covers the theme of using environmental impacts in energy system modeling, which is covered in Paper II and a central theme in Paper III and Paper IV. The sub-chapter starts with illustrating how dynamic energy modeling affects assessment of environmental impacts, which is covered in Paper III.

3.2.1 Comparing Impact of Marginal Energy Mixes

Paper III has illustrated the importance of combining energy system modelling with LCA to generate case specific marginal energy mixes, as these have significant impacts on results. This is demonstrated by a sensitivity analysis, and the results are shown in Figure 19. In the Base scenarios the GHG emissions are specified for each plant type used by the EDO model, and this is the data used in the main scenarios of Paper III. In the EDO mix sensitivities the output from the EDO model defines the marginal power and heat mixes for avoided and additional heat and power production. As opposed to using plant specific data, as in the Base scenarios, here the power and heat marginal mixes are quantified data from the Ecoinvent database [67]. The processes are specified in the Supplementary Information of Paper III, Table S7. This data has a wider scope as it includes upstream and downstream emissions. It is more general than the outcome from EDO which is used in the base scenarios, but it is fuel specific and spatially specific when data has been available. In the Base and EDO mix scenarios, the additional heat and power is covered by a different mix than the avoided heat and power production. In the Static mix sensitivities, the best-practice among LCA practitioners is deployed, using spatial and temporal marginal electricity mixes. These are, at best, country-wide and the temporal resolution is in this case specified for a ten year interval [92]. For China, the consequential marginal mixes used in the Ecoinvent 3.4 database are based on the International Energy Agency Current Policies scenario in the 2016 World Energy Outlook [92]. For heat, a common assumption in consequential LCAs is that marginal heat is from use of natural gas, which is assumed in the Static mix scenarios presented in Figure 19. In the Static mix scenarios the same marginal mix is applied for avoided and additional heat and power.

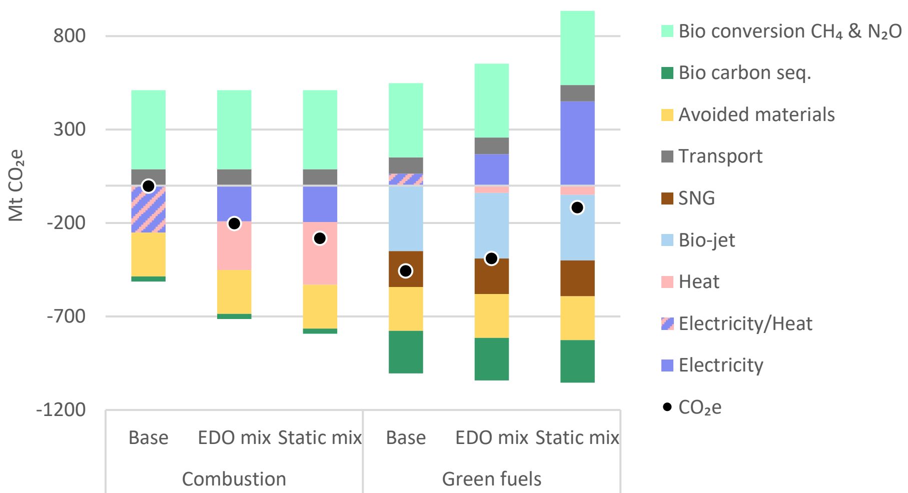


Figure 19: Sensitivity on GHG emissions comparing marginal energy mixes from Paper III. Adapted to show the differences between fossil fuel emissions combining in the sensitivity scenarios by Figure 11 and Figure S5 from Paper III.

While there is a considerable difference between the assessed emissions in the Base and EDO mix, the order of the two scenarios remains the same, with lower emissions in the Green Fuels scenario compared to the Combustion scenario. In the Static mix sensitivity, this is not the case, here the Combustion scenario is favorable when it comes to GHG emissions. This is primarily due to two reasons. The first being that the avoided heat is assumed to be stemming from natural gas, while the results from the EDO modeling shows that there is a considerable share of heat pumps in the avoided mix, this results in an exaggerated benefit in terms of GHG reductions in the Combustion scenario. The second reason being that the additional power required in the Green Fuels scenario primarily stems from wind and solar power in the main results, and the marginal mix used in the Static mix sensitivity has a higher use of fossil fuels. For the Green Fuels scenario, the additional electricity is primarily used to produce hydrogen through electrolysis for bio-e-fuel production. In Paper II the upstream emissions for producing e-fuels are assessed.

3.2.2 Upstream Emissions in e-fuels Production

One of the conclusions from Paper II is that the fuel infrastructure for producing e-fuels, i.e. electrolyzer capacity, is a main bottleneck for scaling up green fuel production. This limitation is a decisive constraint for the resulting fuel mix and transition of shipping fuels. The quantified upstream emissions delays the investments in e-fuel production, as the upstream emissions from infrastructure are projected to reduce over time. While this improves representation of GHG emissions it adds another aspect to the challenges to reach climate targets. It is likely to assume that the emissions will reduce over time, following a global net-zero energy system by 2050 [5], but trying to assess the specific reduction curves has not been a focus in Paper II. The upstream emissions are reduced linearly to zero by 2050, as shown in Figure 20.

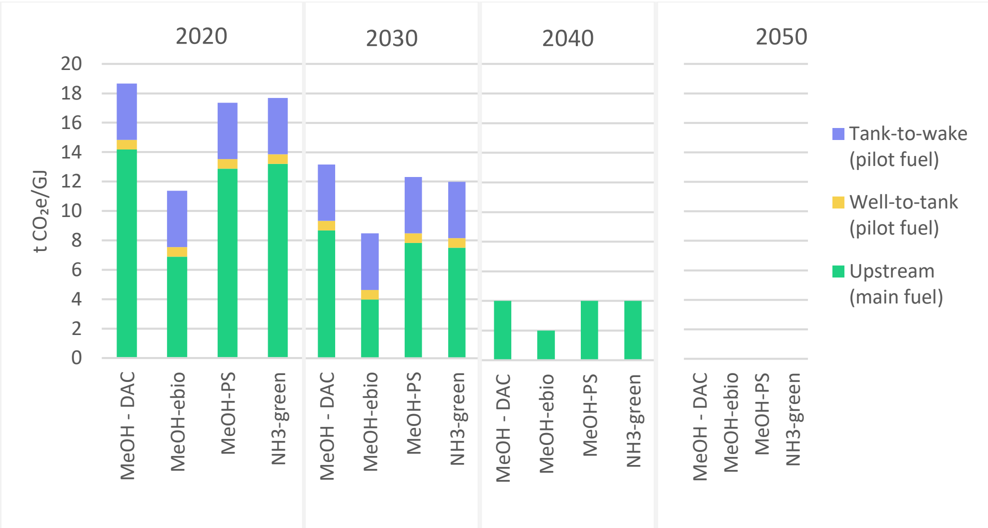


Figure 20: Fuel emissions for green fuels including 5% pilot fuel (very low sulphur oil until 2035 and dimethyl ether thereafter) adapted from Paper II (Figure 3).

3.2.3 Extended Quantification of Environmental Impacts

In Paper III the quantification of several GHGs is decisive for results. As presented in Paper III and shown in Figure 21, limiting the quantification to fossil CO_2 would drastically change the results. The Materials scenario would go from one of the best preforming scenarios in terms of GHG emissions when all are considered, to the worst when limited to fossil CO_2 emissions. The negative impacts for the Reference scenario are also vastly underrepresented with a limited scope only assessing fossil CO_2 emissions.

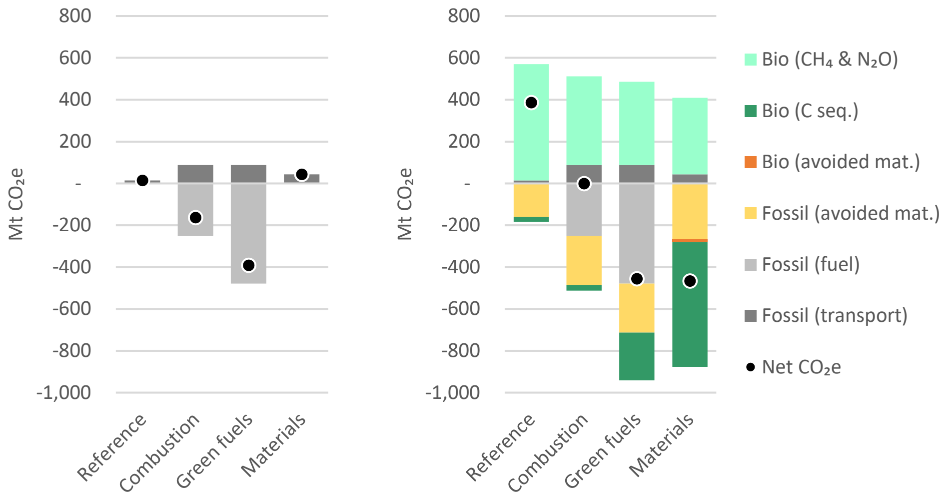


Figure 21: Fossil GHG emissions (left) and the comprehensive GHG emissions (right) for the different scenarios modelled in Paper III. Adapted from Paper III (Figure 5).

In Paper III, stylized scenarios for residual biomass utilization are modeled and analyzed. The results show that there is a clear environmental benefit of utilizing residual biomass and that the scenario where residual biomass is used for materials, followed by the one where it is used for fuels, are associated with the lowest costs, as seen in Figure 22.

In Paper III, the Combustion scenario, used to model use of residual biomass for power and heat, is the least favorable of the three scenarios modeling utilization of these resources. However, it vastly outperforms the Reference scenario, where residual biomass is treated as waste with little to no proper waste management. The results show that externalities need to be sufficiently priced for there to be an economic benefit of utilizing residual biomass. These hyperbolic scenarios serve to explore extremes. Additionally, it should be noted that while the Materials scenario is associated with the lowest costs it is also associated with high degrees of uncertainty.

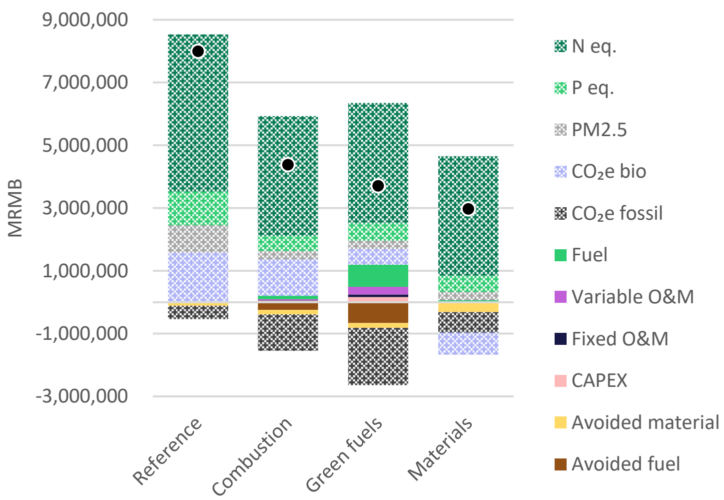


Figure 22: System costs for the scenarios modelled in Paper III. Figure from Paper III (Figure 9).

Monetization of the eutrophication indicators, N and P lost to water, are contributing with a significant share of the system costs. These are also associated with a high degree of uncertainty. However, disregarding these impacts would not lead to a change regarding how the three utilization scenarios, Combustion, Green Fuels, and Materials, are ranked in terms of costs. Even with a low or no cost for these impacts. This is due to the similarity of the assessed N and P losses to water across these scenarios, as shown in Figure 23, as these impacts primarily stem from the unutilized resources, which are the same in the three utilization scenarios. The N lost to water from the utilized resources are made up by spreading of digestate from anaerobic digestion in the Combustion and Green Fuels scenarios and efficient land application of animal manure and sewage sludge in the Materials scenario. For P, the differences in the three utilization scenarios primarily stem from animal manure management. The difference between the Combustion and Green Fuels scenario stems from the avoided electricity generation in the Combustion scenario and the additional electricity generated in the Green Fuels scenario.

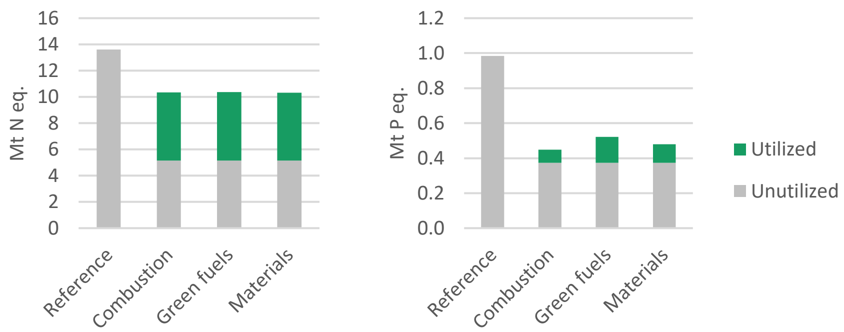


Figure 23: Overview of N and P equivalents lost to water in the scenarios in Paper III divided by utilized and unutilized resources. Figure adapted from Paper III (Figure 6).

3.2.4 Externalities Pricing Levels and Cross-Sectoral use

In Paper IV, externality costs are part of the optimization. Here, the pricing level has a critical impact on results, as is shown in Figure 24. With low externality costs large shares of residual biomass are not utilized to fulfil demands for end-use products. As externality costs increase, so does the value of the residual biomass and more of these resources are used to fulfil demands. Going from left to right in Figure 24, in the first column residual biomass is limited to be used to essentially fulfil fuel demands, in the Energy scenario. In the middle column residual biomass is made available to fulfil cross-sectoral demands in the Multipurpose scenario. Lastly, in the third column cross-sectoral use and refining of side streams is enabled in the Industrial Symbiosis scenario. On the other axis the externality costs go from the lowest studied levels in the bottom, are increased in the middle row, and the highest in the top row of Figure 24. The scenario shown in the top right corner, the Industrial Symbiosis scenario with the highest externality costs, has the lowest share of residual biomass ending up in reference use, with all resources but 11% of food waste being utilized.

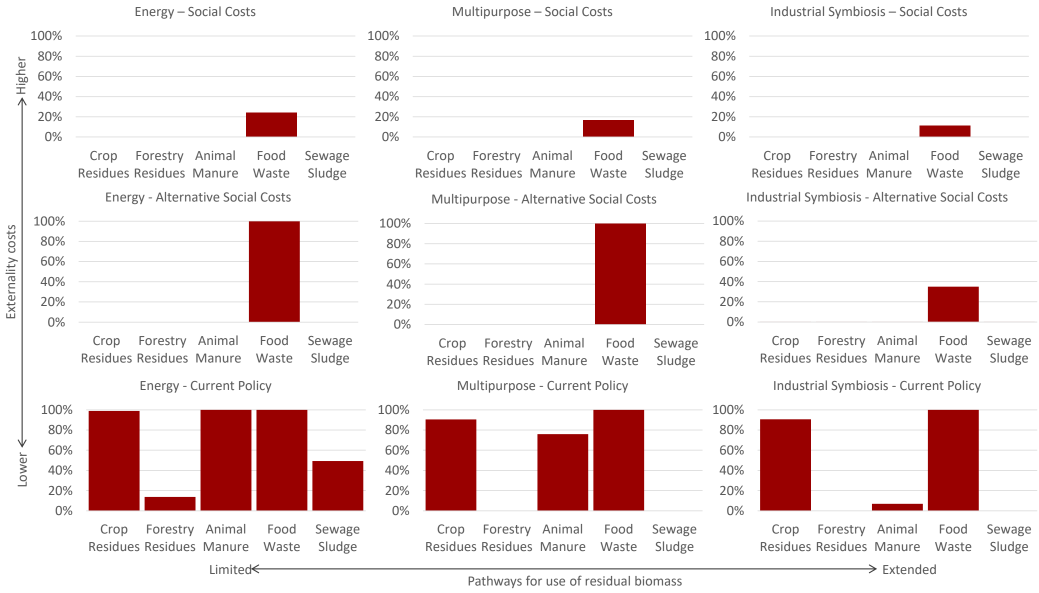
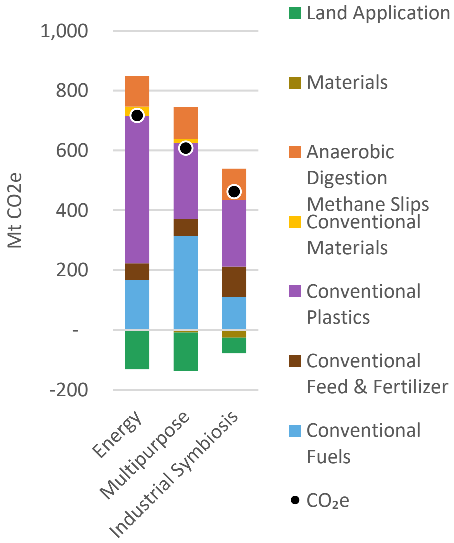


Figure 24: Overview of results for shares of unutilized residual biomass resources in scenarios with lower and higher externality costs and limited to extended utilization pathways. Figure from Paper IV (Figure 13).

The main scenarios studied in Paper IV are the three with social externality cost, shown in the top row of Figure 24. When comparing the externalities in these main scenarios, there is a clear reduction for all pollutants as opportunities for biomass utilization expand, as shown in Figure 25. Going from the Energy scenario to the Multipurpose scenario means a reduction of GHGs by 15% and an additional reduction of 24% comparing the Multipurpose scenario with the Industrial Symbiosis scenario. When comparing the Industrial Symbiosis scenario to the Energy scenario the reduction is 76% and 67% for N and P lost to water, respectively. For PM2.5 there is a 55% reduction.



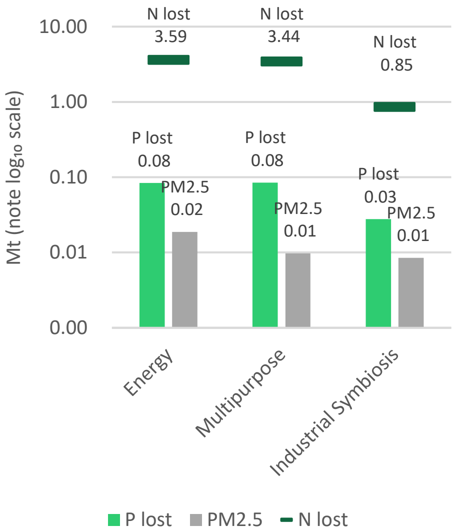


Figure 25: Overview of GHG emissions (left) and other environmental impacts on a logarithmic scale (right) from Paper IV. Figures from Paper IV (Figures 10 and 11).

This trend stays the same when studying environmental indicators across the tested levels of externality costs and utilization options. Figure 26 shows the difference in emissions relative to the Energy scenario with the lowest externality costs. Here, it is interesting to point out N and P losses, shown in dark and light green, which are drastically reduced, even with low externality costs, when side streams can be refined in the Industrial Symbiosis scenario with low externality costs. With low externality costs, shown on the bottom row, there is a reduction of 88% N and 92% P lost to water when comparing the Energy scenario to the Industrial Symbiosis scenario. This shows that, while pricing of externalities has extensive impact, ensuring cross-sectoral integration and collaboration is another important parameter.

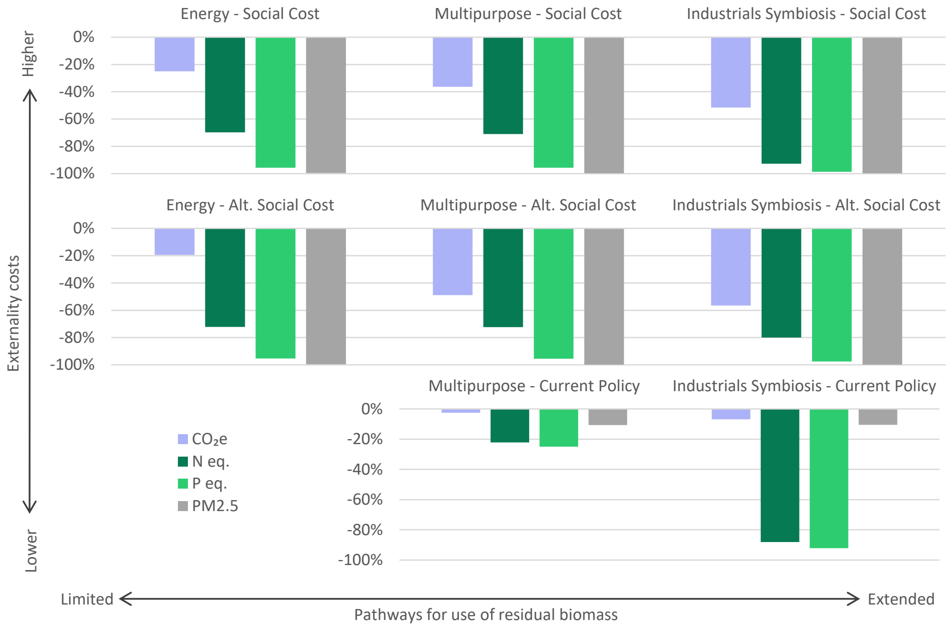


Figure 26: Relative reduction of pollutants compared to the Energy scenario with Current Policy externality costs, as described in Paper IV. Figure showing results from Paper IV.

When comparing the system costs of the main scenarios from Paper IV, there is a reduction of 27% when comparing the Industrial Symbiosis scenario to the Energy scenario. This significant reduction is a consequence of the high externality costs. The same trend is evident with lower externality costs, but the difference is a reduction of 3% when comparing the Industrial Symbiosis scenario to the Energy scenario using alternative social costs, and a reduction of 1% when comparing the same scenarios with current policy externality costs.

3.2.5 Environmental Impacts Overview and Discussion

Marginal energy mixes are often determining parameters in environmental impact assessments. The presented results show the importance of specifying these marginal mixes, as this can drastically change the interpretation of results. When upstream emissions for e-fuel production are accounted for, there are no zero emission fuels today. These are likely to reduce over time, but the rate in which this reduction will take place requires further studies. The environmental burden of not utilizing residual biomass is not represented when GHGs are limited to fossil CO_2. Including eutrophication and air pollution indicators highlights the benefits of utilizing residual biomass. Apart from monetizing externalities, reducing pollutants can be achieved by including cross-sectoral uses and refining of side streams.

Biodiversity is an important aspect, specifically for first generation biomass, but can also be highly relevant when assessing use of forestry residues. It is therefore relevant for further research to support the quantification of biodiversity and find methods to include this parameter. As the framework assessing environmental impacts in this thesis is guided by planetary boundaries and a life cycle approach, it would be relevant to use absolute environmental sustainability assessment methodology [93]. However, this requires detailed data on specific regionalized and quantified boundaries for environmental pollution, e.g. carbon budgets [94]. This could be integrated as a cap in the least-cost energy system optimization models used in this thesis, and thereby avoiding the question of how to monetize externalities.

3.3 Residual Biomass Utilization

Use of residual biomass is a theme covered in Paper III and Paper IV as well as, to a limited extent, in Paper II. While Paper III explores stylized scenarios, where the resource allocation is predefined by the scenario design, utilization pathways are optimized in Paper IV to explore cross-sectoral utilization. The sub-chapter starts with a focus on food waste, as this is projected in Paper I and used in Paper III and Paper IV.

3.3.1 Utilization of Food Waste

In Paper III, sorted food waste is used for production of biogas through anaerobic digestion or for production of insect meal for feed through black soldier fly treatment. In Paper IV, the same options for sorted food waste are modeled, but here in combination. The option to not sort food waste are modelled in both Paper III and Paper IV, called reference use where unsorted food waste is landfilled. In Paper IV, where these options are all in play in all scenarios, sorted food waste is primarily used for biogas. It is also used in black soldier fly treatment, if the side stream from this process is refined. One of the conclusions in Paper IV is that food waste is the last of the studied residual biomass fractions to be utilized. Sorting and utilizing food waste requires high externality costs to be of value to society, due to high costs of sorting and collecting and even in the scenario with the most extensive options for side stream utilization and highest externality costs, not all food waste is utilized. The value of sorting food waste could potentially be increased if the N and P leaching from landfills are differentiated. There are regional variations on leaching from landfills and leaching is often underestimated [95]. Adding to this there are a range of aspects regarding food waste in the different stages of the production and consumption chain, which have not been included in this thesis, but would provide a more comprehensive picture [96]. Another benefit of sorting food waste, that is not considered, is that sorting of food waste facilitates recycling of dry MSW fractions as it reduces contamination from food matter [97], [98].

3.3.2 Integrated Residual Biomass Utilization Scenarios

In Paper III, the results show the high value of utilizing residual biomass and that specifically using it for materials or fuels are promising. In Paper IV, these options are expanded and studied in combination. One of the purposes of Paper IV is to further explore the options of utilizing residual biomass, using another methodology which enables an integrated approach to study cross-sectoral uses. This is an independent study that builds on Paper III. The main scenarios in Paper IV are designed to illustrate the possible benefits of cross-sectoral use of residual biomass and impact of refining side streams for various processes. The demands covered in Paper IV are demands for fuels, plastics, feed, flooring and insulation, as well as N and P fertilizer. These demands can be covered by residual-bio-based production, which are by converting residual biomass resources, or by conventional production.

There is a clear trend in the results, showing that higher shares of demand are covered by residual-bio-based production as pathway options expand and as externality costs increase, as show in Figure 27. Here the residual biomass goes from being available to cover fuel demands in the Energy scenario, to a cross-sectoral approach in the Multipurpose scenario, and lastly to include refining of side streams from these processes in the Industrial Symbiosis scenario. On the vertical axis are different cost levels for externalities. In all cases where it is an option, residual biomass is used to cover the shares of plastic and fertilizer demand. Plastic demand covered by use of residual biomass goes from 14% with low externality costs to 48-63% with higher externality costs. For fuel demands, the methanol and heavy fuel oil demand is covered by bio-based production in all scenarios. It should be noted that the projected demand for methanol and heavy fuel oil combined makes up less than 1% of total fuel demand. The most significant fuel demand is for natural gas, making up 65% of projected fuel demands. This is covered by varying shares of bio-based production. With low externality costs there is 5% of natural gas demand covered by SNG from use of residual biomass in the industrial symbiosis scenario. As externality costs increase, the share covered by bio-based production is determined by the competition for residual biomass resources. When residual biomass only is available to fulfil fuel demands in the Energy scenario, a larger share of natural gas demand is covered by SNG from conversion of residual biomass compared to cross-sectoral uses. This is because the resources are diverted to produce plastics and materials in the Multipurpose and Industrial Symbiosis scenarios.

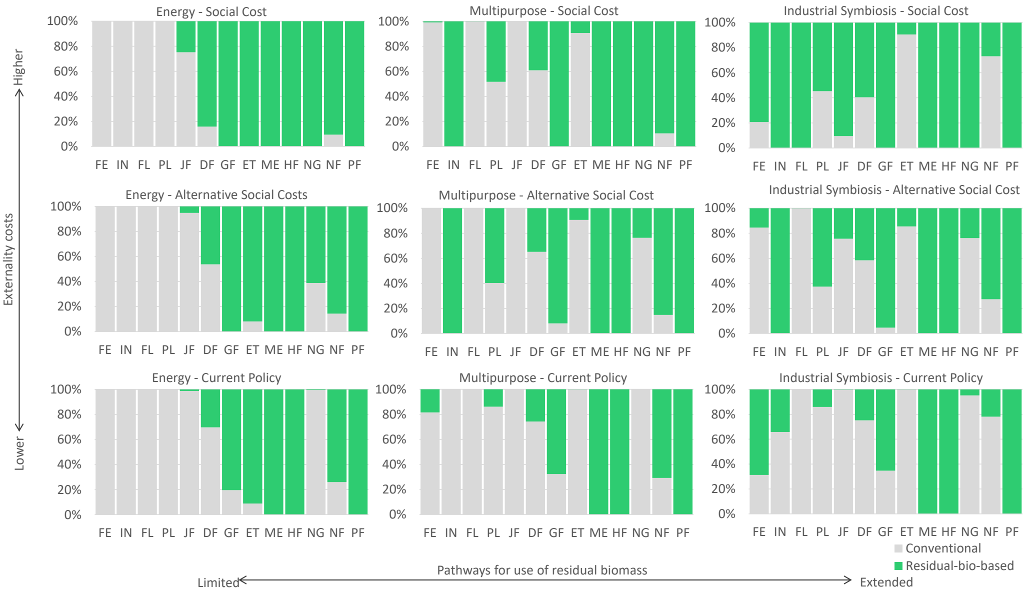


Figure 27: Overview of shares of demands met by residual-bio-based and conventional production. FE: Feed, IN: Insulation, FL: Flooring, PL: Plastics, JF: Jet Fuel, DF: Diesel, GF: Gasoline, ET: Ethanol, ME: Methanol, HF: Heavy fuel oil, NG: Natural gas, NF: N fertilizer, PF: P fertilizer. Figure from Paper IV (Figure 12).

The Industrial Symbiosis scenario, with the highest externality costs, is the scenario with the largest shares of demand covered by conversion of residual biomass. For this scenario, Figure 28 shows the conversion of residual biomass used to fulfill demands. Looking at the demands towards the right of the diagram, going from top to bottom, most feed is covered by use of residual biomass through black soldier fly conversion to insect meal. The remains from this process are used in anaerobic digestion. For flooring and insulation, these demands are covered by use of crop and forestry residues. The material residues from these processes are used in thermal gasification, hydrothermal liquefaction, and fast pyrolysis, which also treats the solid digestate fraction from anaerobic digestion. About half of plastics demands are covered by use of residual biomass in this scenario. This is primarily by processing bio-methanol from thermal gasification of crop and forestry residues to propylene and ethylene which are polymerized. In this scenario, another method of producing plastics involves the steam cracking of naphtha derived from the Fischer-Tropsch process, which utilizes point source biogenic carbon obtained from upgrading of biogas, in the CO_2-to-fuel process. The main output from the CO_2-to-fuel process is bio-e-jet which covers most of the jet fuel demand. A minor share of bio-e-jet stems from hydrotreatment of biocrude oil from hydrothermal liquefaction. Gasoline demand is fully covered by bio-e-gasoline from fast pyrolysis, which also covers a significant share of diesel demand. This is also partly covered by bio-e-diesel from the CO_2-to-fuel process. One tenth of ethanol demand is covered by cellulosic ethanol from a mixture of forestry residues and residuals from material production. The produced bio-methanol from thermal gasification, primarily used for plastics, also covers methanol demand. Demand for heavy-fuel-oil is covered by biocrude oil from hydrothermal liquefaction. Natural gas demand is fully covered by SNG from upgraded biogas. Surplus heat from thermal gasification, upgrading of biogas, and the CO_2-to-fuel process, is made available for use in district heating. Not all food waste is utilized, so 21 Mt still ends up in reference use. The hydrogen used for the production of bio-e-fuels is produced through electrolysis. The electricity required for electrolysis, together with the direct electricity demand primarily required for the biogas upgrading and material conversion processes, is an input from the EDO model. The results show that this is covered by renewable electricity generation with 8% from solar PV and 91% from wind power.

Results in Paper IV show a high value to society when using, particularly, forestry residues, sewage sludge, and animal manure for energy and non-energy products. Or rather a high value of not wasting these resources. The vast benefits of utilizing forestry residues might be challenged if the forestry residues are specified in more detailed assessments. This is due to the benefits from extracting forestry residues partly depending on the type of forestry residues, i.e. their decomposition rates [100], [101]. Another important aspect is the lack of including an indicator for biodiversity loss regarding use of forestry residues. There are some studies highlighting the biodiversity benefits of leaving forestry residues in forests to increase biodiversity [102], so this could be interesting to include in further research. In Paper III and Paper IV, biofuels are assumed to replace fossil counterparts 1:1. This does however not take possible rebound effects into account. Previously studied rebound effects [103] occur from increased availability of biofuels reducing fossil oil prices and thus increasing demand. In this study, fossil prices were assumed to be static and unaffected by the availability of green fuels.

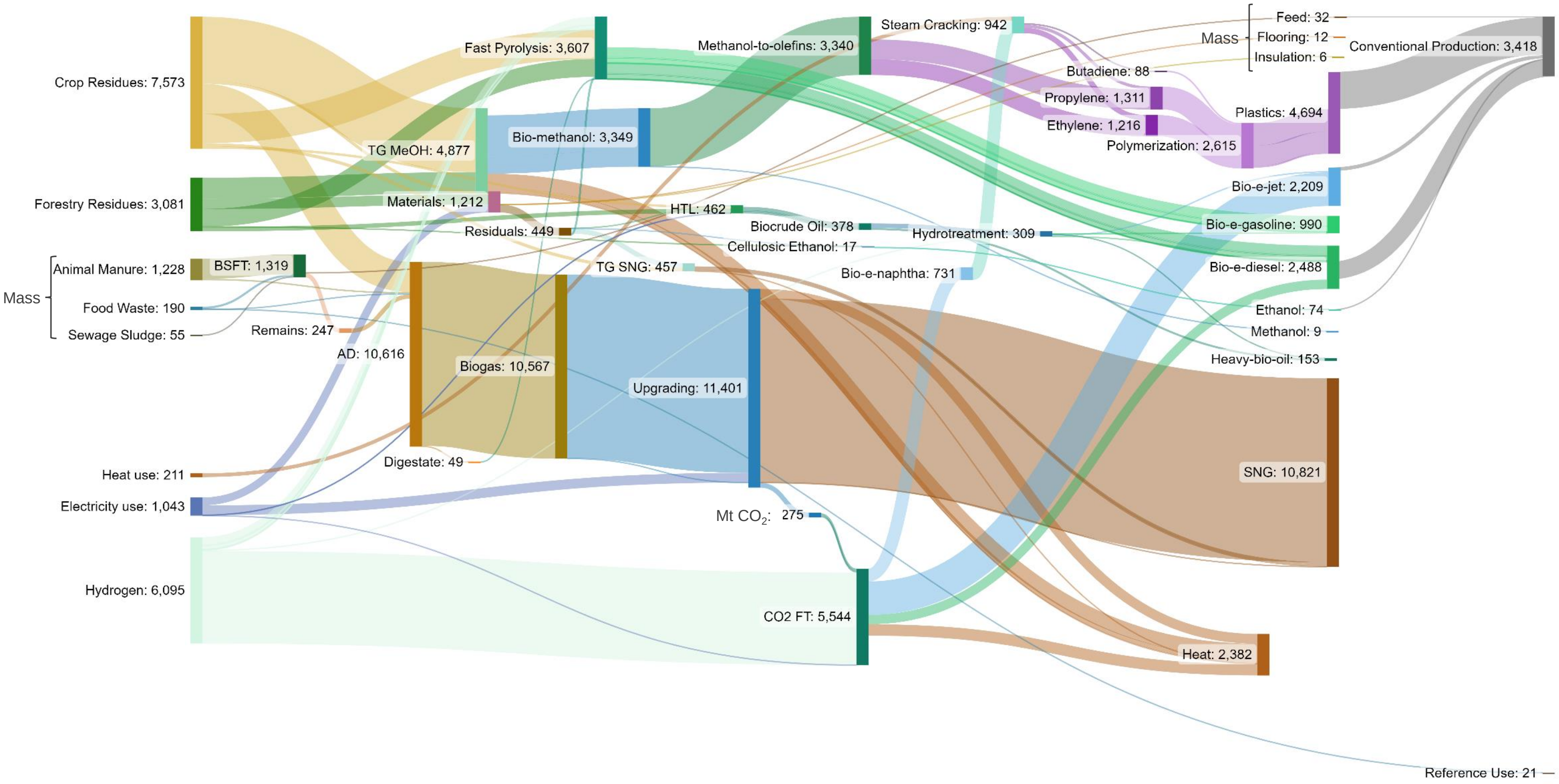


Figure 28: Energy flows in PJ and Mt (when specified as mass) for the Industrial Symbiosis scenario with the highest externality costs in Paper IV. Black soldier fly treatment (BSFT), thermal gasification (TG), methanol (MeOH), synthetic natural gas (SNG), hydrothermal liquefaction (HTL). Figure from Paper IV (Figure 9).

3.3.3 Residual Biomass for Shipping Fuel

The assessed biomass availability used in Paper II is conservative compared to other studies, as it is limited to residual biomass as opposed to including for example energy crops, for which potential assessments have a very high variability [7], [104]. A sensitivity analysis on biomass availability was performed in Paper II using the different biomass availability inputs seen in Figure 18. The resulting fuel mixes presented in Figure 21 shows that with medium biomass availability, a maximum of 1% of fuel demand is covered by bio-e-MeOH while there is some availability of this fuel. In the long-term, with no solid biomass availability, 5% of demand is covered by e-methanol from use of biogenic point source CO_2. With high biomass availability bio-e-MeOH is used for 4-14% of fuel demand from 2035 to 2040 and up to 17% of shipping fuel to 2050. This is as the cost of green ammonia reduce over time, making this the least cost green option by 2038. The limited use of e-methanol is not due to implemented availability constraints, but rather the costs for producing methanol from point source carbon emissions. For liquefied biogas prices are assumed to increase, which is why it is not utilized.

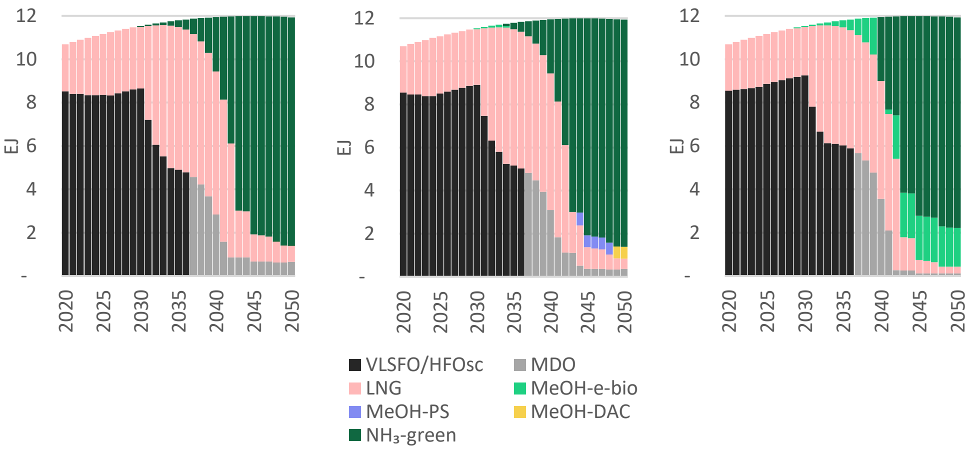


Figure 29: Fuel mixes for global shipping fuels using a carbon price of 200€/tCO2e and 30% fuel savings with varying biomass availability. Sensitivity analysis scenarios presented in Paper II (Figure 6). VLSFO: Very low sulphur fuel oil, HFOsc: Heavy fuel oil on ships with scrubbers, LNG: Liquefied natural gas, MeOH-PS: methanol from point source biogenic carbon and hydrogen from water electrolysis, NH_3-green: green ammonia, MDO: Marine diesel oil, MeOH-e-bio: methanol from gasification and hydrogen from water electrolysis. MeOH-DAC: methanol from direct air capture carbon and hydrogen from water electrolysis.

3.3.4 Residual Biomass Utilization Overview and Discussion

In the conceptual framework for the bio-economy, resources should be used for high-value products and cascaded into lower value products after end-of-life [105]. Here products are listed, ranging from e.g. high-value feed and plastics to lower value fuels and energy recovery [105]. Part of this concept has been tested in this thesis by allowing residual biomass to flow to processes where the value to society is the highest. The results showing use of residual biomass for feed and plastics in line with the conceptual conclusions that resources could be used for high-value products in the bio-economy. Not all feed and plastics demands are covered by use of residuals, but the results show that using residual biomass for plastics is beneficial. However, here the conventional route is production of virgin plastics, as opposed to recycling of plastic fractions, which are relevant to compare [106]. For feed there is a full range of options not studied regarding possible feed conversion pathways for residual biomass [107]. This would be relevant for further research. Due to the proven link between marginal energy mixes and GHG benefits of using e.g. crop residues for feed production [107], it is relevant to employ a comprehensive bio-use system modeling methodology, as presented in this thesis, for such an analysis. Of the fuel routes studies, thermal gasification as well as fast pyrolysis of crop and forestry residues is utilized in all scenarios. There is no considerations regarding cost curves, or any representation of how i.e. the first strain of straw is less costly to collect than the last in this thesis. This limitation risks creating a skewed picture of the profitability of different pathways.

4. Conclusion and Perspectives

The conclusion in this final chapter serves to answer the research questions, which have guided this thesis. The sub-research questions are answered first, leading up to the main research question, all presented in section 1.4.1. This conclusion is followed by a sub-chapter, which outlines recommendations and reflects on further research perspectives.

4.1 Conclusion

With the world in a crucial move away from using fossil fuels, biomass is gaining increasing importance, and the energy sector plays a critical role in facilitating this transition. However, the demand for biomass is expanding across multiple sectors, while the availability of sustainable biomass is limited. Thus, there is a need to use these resources efficiently and avoid major environmental impacts. To address this, this thesis combines resource assessments, energy system analysis, and a life cycle approach to environmental impacts. This is used to evaluate the available quantities, environmental impacts, and system benefits associated with utilizing residual biomass.

RQ 1	Which residual biomass resources will be available to the energy sector and how should these be assessed?

The efficient utilization of residual biomass relies on accurate projections of resource availability, permitting planning of utilization capacity. Residual biomass is limited and the share available to the energy sector depends partly on demand from competing sectors. The demand for residual biomass from non-energy sectors is increasing and should be assessed and included in the availability assessments when specifying availability for energy use.

Assessing scenarios for cross-sectoral use of residual biomass show that regardless of the level of externality costs employed, there is some use of residual biomass for plastics. This shows that it is relevant to include the specific demands for plastic products. When adding an increased integration of different sectors in an industrial symbiosis, where side streams from processes can be refined, results show fewer residuals being available to cover fuel demands. Here residual biomass is used for feed, insulation, and, depending on the externality costs level used, for flooring. This indicates that as the system becomes more integrated, the resources available for the energy sector diminish.

RQ 2	How does including residual biomass related environmental impacts affect results in energy system analysis?

Using a more comprehensive GHG accounting approach, including CH_4 and N_2O emissions as well as biogenic CO_2, into energy system analysis enables more representative results. This will serve as a more informative basis for decision makers. Adding to this, indicators for eutrophication and direct particulate emissions have been included in this thesis. To include eutrophication indicators have proven specifically relevant when assessing pathways for animal manure management. The air pollution indicator, direct PM2.5 emissions, is relevant to show the value of collecting and utilizing crop and forestry residues. Including upstream emissions for e-fuel production for shipping has proven impactful, but not decisive for the results.

For use of residual biomass, going from quantifying fossil CO_2 emissions to including the three main GHGs with a life cycle approach puts a, in many cases new, burden on biomass conversion. This is due to the CH_4 and N_2O emissions stemming from biomass conversion processes and subsequent use of co products or side streams. When using this approach it is necessary to include a counterfactual scenario, to assess impacts from not utilizing the resources. If a counterfactual scenario is not considered, there is a great risk that the benefits of using and thereby treating these resources are not apparent.

RQ 3	What is the impact of applying marginal energy mixes when assessing environmental impacts of residual biomass utilization scenarios?

In environmental impact assessments, for example LCAs, the assumptions regarding the energy supply is a critical parameter. This thesis has exemplified an integration of LCAs and energy system analysis, enabling a case specific assessment of energy mixes which has a significant impact on results. The findings in Paper III show that using specific marginal energy mixes and emissions can provide a more accurate picture of the results, diverging from those obtained through static values commonly employed in LCAs. In the case illustrated in Paper III, the impact changes the conclusion regarding which scenario performs better regarding GHG emissions. This shows not only that it is impactful, but has a decisive impact.

RQ 4	How does cross-sectoral use and integrated use of side streams affect environmental and economic aspects?

Results presented in this thesis quantify benefits associated with using residual biomass for non-energy uses as well as for production of biofuels and bio-e-fuels. There is a significant reduction of system costs as cross-sectoral use and refining of side streams are included. There is a clear trend, that an increased share non-energy demands are covered by use of residual biomass when options to refine side streams are included.

For plastic production, several different pathways have been tested and a significant share of plastic demand is covered by use of residual biomass in all studied scenarios where the option is available. Other non-energy uses have also shown relevance, although only a limited number of applications have been studied; for example using crop and forestry residues to produce construction materials, which shows promising results. For wet fractions, conversion to insect meal for feed purposes, shows great potential. These pathways are not widely deployed and thus associated with high degrees of uncertainty.

Regarding environmental pollution, the increased system integration is highly relevant, as the results show significant reduction of environmental impact indicators as the options to include use of residual biomass expand from the energy sector to cross-sectoral use, and to include side stream refining.

How can residual biomass be cost-efficiently and environmentally sustainably utilized in China?

To promote cost-efficient and environmentally sustainable utilization of residual biomass in China, resources should be properly assessed, externalities should be priced, and cooperation for utilization of side streams across sectors should be encouraged.

Proper utilization of residual biomass depends on projections of resource availability, which can enable planning of utilization capacity. When utilization options are assessed with a sectoral approach, the demand from competing sectors should be considered to reduce the risk of exaggerating availability. However, assessing competing demands depends on the assumptions made for development trends and possibilities in these sectors. Therefore, including cross-sectoral demands, when assessing resource utilization, is beneficial. This can improve resource efficiency, minimize waste streams, and improve feasibility of conversion plants. Resource efficiency can be increased as resources flow to the sectors and specific conversion processes where they create value. Waste streams can be minimized as uses across sectors can be valorized and highlighted. Here, a side stream from one process can be used as valuable input in another process. As this often requires close collaboration, the value of cross-sectoral collaboration and industrial clusters can be shown and promoted when including cross-sectoral demands in assessments of residual biomass use.

It is important to monetize the externalities associated with residual biomass utilization, as this enables a comparison of the environmental burden. In the least-cost optimization models used in this thesis, an economic value of externalities must be included for it to affect the optimization. Furthermore, using a single scale when including several environmental impacts makes conclusions easier to convey. This is important in order to make advice actionable and can help incentivize the development of cleaner and more sustainable technologies and practices.

4.1.1 Recommendations

This thesis shows a need for a better representation of the energy system in e.g. LCAs. Here the use of rough assessments on marginal energy mixes risk leading to suboptimal recommendations. For energy system modeling and analysis, going beyond the quantification of fossil CO_2 is crucial when it comes to assessing use of biomass. As shown in this thesis, the comprehensive conversion GHG emissions should be taken into account. Adding to this, the expansion of environmental indicators is highly relevant. Energy system modeling has been used as a starting point, due to the role of energy systems as key in the transition. This is a relevant place to start, but the results in this thesis shows that it needs to be extended and include representation of cross-sectoral use and refining of side streams to quantify the benefits of utilizing residual biomass.

4.2 Perspectives

The methodology presented in this thesis could be applied to other geographical regions, resource streams, or extended with additional environmental indicators. One group of residual biomass resource streams that could be relevant to include are industrial residuals from for example food processing, additional residues from the forest products industry, or post-consumer wood products. When looking at life cycle assessment indicators, there are a full range of additional impacts which could be included. However, including additional indicators is not necessarily strictly a benefit as this could result in conclusions being lost in details and lead to inaction. In the least-cost optimization methodology used in this thesis, it is fundamental that additional indicators are monetized, or associated with a cap, when included.

Costs of externalities has proven to be a decisive parameter. Here different externalities are priced and the levels have been varied for all at once. Further studies could assess the inter-connectivity of pricing different externalities. Such a study could for example include a comparison of the outcomes from pricing single externalities and different combinations. Further work could also include studying the effects of caps on environmental pollutants as opposed to using costs.

Indicators for eutrophication are included when assessing use of residual biomass in this thesis through N and P lost to water. Another aspect of these biogeochemical flows is the depletion of phosphate reserves. This combined with the projected increased demand for P fertilizer highlights the importance of efficient use of P. The aspect of increased scarcity of P fertilizer could be expanded further. Biodiversity, or biosphere integrity, is a planetary boundary which is not specifically studied in this thesis, but acknowledged as being relevant when it comes to use of forestry residues. If, in future modeling, steps are taken to include specifically use of first generation biomass, finding a way to include this aspect is highly relevant.

One of the conclusions of this thesis is that producing plastics from residual biomass is promising. However, this is without any consideration regarding the planetary boundary of novel entities, or new materials. Here it is relevant to consider, in further research, which services it is reasonable for these materials to provide and how they are treated after end-of-life. The aspect of end-of-life treatment would be an interesting topic to explore in general. Including the aspect of time and modeling options for end-of-life use would enable studying cascading effects, and analyze under which conditions it is beneficial for materials to be repurposed, recycled, or used as input to other processes.

While Chinese residual biomass resources are assessed on provincial level in this thesis, the results are generally analyzed on a national level. A relevant further analysis could be to analyze regional differences and, for example, compare the use of residual biomass in a province with abundant biomass resources to a region with limited biomass resources. Such an analysis could provide general advice regarding use of these resources in areas with plentiful resources and areas with scarce resource availability. Using resources locally to limit transportation is particularly relevant for use of voluminous residual biomass. This aspect could also be included with for example varying acceptable transport distances depending on the resource fraction.

The research presented in this thesis has broadened the implementation of environmental indicators in energy system analysis. This has proven impactful for results, pointing to the need for an improved representation of environmental impacts from the use of biomass in energy system modeling. This could be through an improved integration between energy system modeling and LCAs. This would also be beneficial for LCAs, as marginal energy mixes often are decisive factors in LCAs. Performing a full LCA study is extensive, but the methodology presented in this thesis is a step towards including relevant factors. This thesis has presented a framework for assessing and comparing use of residual biomass, which is of increasing importance as the scarcity of sustainable resources increase.

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Paper Annex

This Paper Annex constitutes the second part of the Ph.D. thesis Economic and Environmentally Sustainable Use of Residual Biomass in China.

The papers included in this thesis are the following:

Paper I: **Shapiro-Bengtsen S**, Andersen FM, Münster M, Zou L. 2020. Municipal solid waste available to the Chinese energy sector – Provincial projections to 2050. Waste Management;112:52–65. https://doi.org/10.1016/j.wasman.2020.05.014.

Paper II: Franz SM, Campion N, **Shapiro-Bengtsen S**, Bramstoft R, Keles D, Münster M. 2022. Requirements for a Maritime Transition in Line With the Paris Agreement. iScience. https://doi.org/10.2139/ssrn.4158005.

Paper III: **Shapiro-Bengtsen S**, Hamelin L, Bregnbæk L, Zou L, Münster M. 2022. Should residual biomass be used for fuels, power and heat, or materials? Assessing costs and environmental impacts for China in 2035. Energy & Environmental Science:1950–66. https://doi.org/10.1039/d1ee03816h.

Paper IV: **Shapiro-Bengtsen S**, Bramstoft R, Bregnbæk L, Münster M. 2023. Quantifying the Benefits of Refining Side Streams When Optimizing Use of Residual Biomass. Under review. Energy & Environmental Science.

Paper I

Municipal solid waste available to the Chinese energy sector – Provincial projections to 2050

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Municipal solid waste available to the Chinese energy sector – Provincial projections to 2050

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ABSTRACT

A shift is underway in China, from perceiving municipal solid waste (MSW) as a strictly environmental concern to identifying MSW as a resource. China exhibits a growing focus on using MSW in the energy sector while putting more emphasis on waste sorting and recycling in general and sorting food waste in particular. Timely planning of MSW treatment capacity requires reliable forecasts of future MSW quantities and their characteristics. This article uses econometric analysis to perform regional specific projections for collected MSW. Four scenarios are presented, three of which include sorting of food waste from the mixed MSW stream and/or capping mixed MSW generation. In the different scenarios, aggregated on a national level, mixed MSW ranges from 159 million metric tons (MMT) to 340 MMT and sorted food waste from MSW from zero to 109 MMT in 2050. Conclusions show that sorting of food waste will create stable levels of mixed MSW in many provinces and that there is a risk of overinvestments in MSW incineration capacity in most provinces.

1. Introduction

China is the most populous country in the world; with rapid increase in urbanization rates and economic growth municipal resulting in surging solid waste (MSW) quantities. MSW is a heterogeneous mixture of resources managed by the municipal government, generated by households, the service sector, and in public areas (IPCC, 2006). Households generate 80% of Chinese MSW (Gu et al., 2015). The unofficial waste sector collects between 17% and 38% of MSW for recycling (Linzner and Salhofer, 2014), this is not covered by the official statistics on collected and treated urban MSW. In the official MSW management, there has been great progress in terms of treating collected MSW from Chinese cities, from treating just over half of collected MSW in the early 2000′s to 98% of the 215 MMT collected in 2017. This has been possible due to extensive investments in treatment capacity, especially in incineration plants. In 2017 there were 286 incineration plants and 654 landfills in China, 40% of treated MSW was incinerated and 57% landfilled (NBS, 2020). High moisture content (48%) and a limited lower heating value of 5.4 GJ/ton characterize Chinese MSW (Zhou et al., 2014).

MSW management options include thermal gasification, anaerobic digestion, incineration, black soldier fly treatment[1], composting, and landfill. Leaching from landfills causes extensive soil and groundwater pollution (Han et al., 2016). Other issues include loss of precious materials and unacceptable use of limited land resources (Mian et al., 2017). Landfilling MSW in China is also almost twice as greenhouse gas (GHG) intensive as incineration (NDRC, 2018). Shifting to a more sustainable use of MSW resources is high on the political agenda, including boosting recycling rates, recovering energy from incineration of non-recyclable waste, and separate treatment of food waste (NDRC and MoHURD, 2016a; UNEP, 2016). MSW sorting schemes are being rolled out (MoHURD, 2019a); in 2019 Shanghai started sorting MSW into four categories; recyclables, hazardous, perishable biomass, and other (Zhou et al., 2019). The 13th Five-Year Plan on urban waste management from the Chinese central government stipulates the share of incineration capacity to at least 54% of MSW treatment capacity by 2020 and for most of the remaining treatment to be landfill (NDRC and MoHURD, 2016a). Targets are also set for treatment capacity by province. Nationally it adds up to incineration capacity of 216 million metric tons (MMT) by 2020. Investments in waste management infrastructure today shape waste management systems of the future. A realistic and geographically

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[1] Using larvae to process organic waste and produce feed and/or biofuels, and fertilizer (Čičková et al., 2015). The black soldier fly is a common species used for these purposes (Mertenat et al., 2019).

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detailed projection of available MSW quantities and characteristics enables effective planning, timely investments, and prevents lock-in in unsustainable waste management systems.

In general, economic activities generate waste and different activities generate different quantities and types of waste. Looking at detailed economic activities in the short term, an assumption of constant waste coefficients seems reasonable, that is, assuming a constant amount of waste per economic activity. Bruvoll and Ibenholt (1997) applied this assumption linking detailed Norwegian waste streams to detailed economic activities. Analyzing aggregated waste streams and economic activities in 27 European countries, Andersen et al. (2007) generally reject the assumption of constant waste coefficients and model the generation of waste allowing the waste coefficients to change over time. Analyzing MSW in the EU, Mazzanti and Montini (2009) and Mazzanti and Zoboli (2009) generally show a relative decoupling of MSW from economic activities. A considerable extension of the European waste model is found in Gibbs et al. (2014) analyzing MSW generation, handling, and policies in individual EU countries. Analyzing very detailed waste streams in Denmark, Andersen and Larsen (2012) model aggregated waste streams, such as MSW, creating the FRIDA model. For large waste streams FRIDA allows waste coefficients to change over time while for small and very specific waste streams the model assumes constant waste coefficients. The FRIDA model is regularly updated and used by the Danish Environmental Protection Agency, it may be downloaded from their website (Miljøstyrelsen, 2019). The Danish and European MSW models using econometric analyses of historical links between the amount of waste and economic indicators allowing waste coefficients to change over time form the basis for the model presented in this article projecting MSW in China.

In recent years, the growth of modelling based on artificial intelligence and machine learning has also been applied for projection of MSW. Abbasi and Hanandeh (2016) analyze the techniques ANN, ANFIS, SVM and k-nearest neighbor (kNN) forecasting monthly MSW generation in Logan city, Australia, and conclude that these methods give a good prediction performance. However, the techniques require large historical datasets and can be difficult to generalize. Artificial intelligence and machine learning models are adaptable to many and complex cases/new situations, but are very sensitive to data selection (Intharathirat et al., 2015). Combining several models may reduce uncertainty, see Xu et al. (2013). However, due to limited data availability, in this article we apply econometric modelling linking MSW generation to economic indicators.

Previous studies of China developed projections for waste generation and collection. Most recently, the World Bank published a study projecting MSW quantities of 295 MMT by 2030 and 335 MMT by 2050 (Kaza et al., 2018). Chhay et al. (2018) applied and analyzed various methods, all based on historical data, concluding that China is expected to reach 247 MMT of MSW in 2030. Chhay et al. identified policy as an important parameter, yet did not included it in the analysis. Wei et al. (2013) developed a multilinear regression model for projecting MSW on a national level and found the main factors influencing MSW development to be GDP, urban population, and household consumption, projecting Chinese MSW levels to reach 500 MMT by 2030. All of these studies have projected MSW on a national level and have not had a specific focus on the use of MSW in the energy sector nor included the sorting of food waste. China is highly diversified with collected MSW ranging from 0.46 to 1.35 kg/capita/day in different provinces and a national mean of 0.72 kg/capita/day (MoHURD, 2019b). Increased focus on energy recovery from MSW motivates an analysis of MSW available to the energy sector as mixed MSW and sorted food waste.

MSW generation is a consequence of daily activities, which depend on social, cultural, seasonal, and geographical conditions (Oribe-Garcia et al., 2015); hence, regionalizing forecasts permit a more detailed representation of MSW development. Furthermore, as policy targets are often set per province, it is relevant to divide analysis in this manner in order to track progress, implementation, and to provide policy recommendations. This article applies econometric analysis at provincial level combined with policy scenarios, not previously utilized in a Chinese context, to project mixed MSW and sorted food waste and to assess required incineration and biological treatment capacities.

Estimating current and future waste quantities and their characteristics, including regional differences, creates a more precise basis when determining the role MSW can play in the energy system. The projections in this article cover collected MSW from Chinese urban areas, using the Ministry of Housing, Urban, and Rural Development (MoHURD) urban statistical yearbook as a primary data source.

2. Methodology

Statistics and literature review provide regionally available MSW quantities and characteristics. Policy analysis and forecasts for societal development are used to appraise tendencies and factors affecting MSW development. This analysis uses a spreadsheet model that combines econometric analysis with politically based explorative scenarios for development, drawing upon international experiences and targets set in international cases, see Fig. 1. This model projects future MSW quantities available to the energy sector until 2050. MSW currently sorted for recycling is not included in the projection.

2.1. Projection methodology

2.1.1. Municipal solid waste projection

Socio-economic and demographic conditions relate to the generation of MSW. Therefore, modeling the generation of MSW in Chinese regions requires analysis of links between changes in waste generation and the economic and demographic development in Chinese provinces; the model[2] provides a Base Scenario for MSW in Chinese provinces. Based on previous studies (Wei et al., 2013) explanatory variables are the urban population and real disposable household income. The National Bureau of Statistics (NBS) and the MoHURD yearbooks provided historical province-level data for these factors from 2003 to 2017. Econometric analysis establishes the urban population and the real disposable household income as factors influencing the development of MSW. The general model equation is specified as:

$$\log\left(w_t^r\right) = \alpha_0^r + \alpha_1^r \cdot \log\left(Y_t^r\right) + \alpha_2^r \cdot \log\left(U_t^r\right) + \alpha_3^r \cdot T_t + \delta_i^r \cdot D_t^r \qquad (1)$$

where log is the natural logarithm, w_t^r is the metric tons of MSW in region r in year t, Y_t^r is the real disposable urban household income in fixed 2002 CNY the region and year, U_t^r is the urban population in the region and year, T_t is time, and D_t^r is a number of 0–1 variables (dummy-variables) used to correct for data-shifts and outliers in the time-series. Finally, model parameters $\alpha_0^r, \alpha_1^r, \alpha_2^r, \alpha_3^r$ *and* δ_i^r are estimated on historical time-series.

The interpretation of Eq. (1) is that if the real household income in a region increases 1%, the amount of MSW is increased α_1^r% and if the population increases 1% the amount of waste increases α_2^r%.

Eq. (1) is general and reduces to a number of special cases if the parameters are restricted:

[2] The model can be described as a simplified version of the FRIDA model linking economic activities and waste streams in Denmark (Andersen and Larsen, 2012).

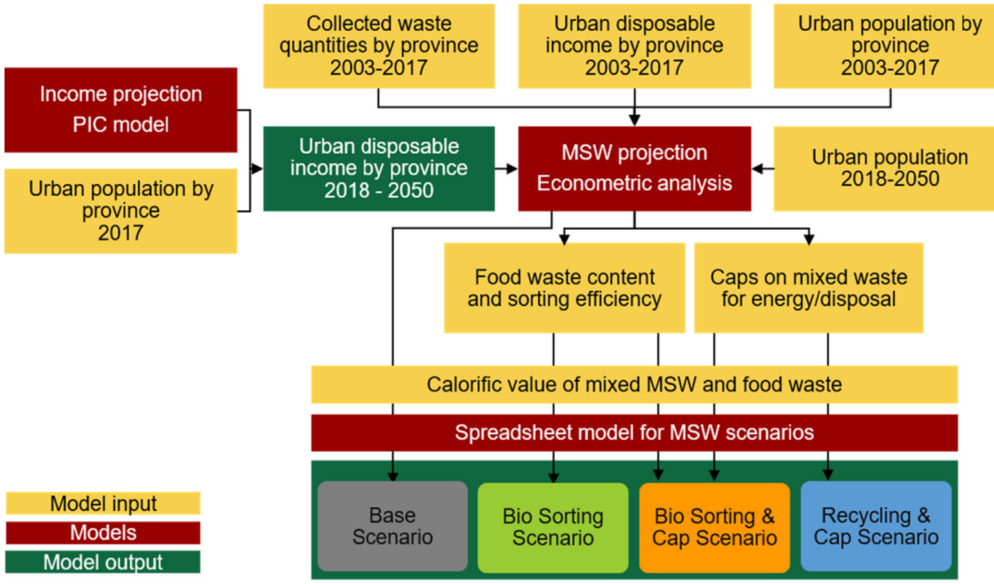

Fig. 1. Overview of methodology.

If $\alpha_1^r = 1$ and $\alpha_2^r = 0$ the equation reduces to a constant waste-coefficient. That is, the amount of MSW changes proportionally to changes in the real household income.

If $\alpha_1^r = 0$ and $\alpha_2^r = 1$ the equation reduces to constant amount of MSW per capita.

If $\alpha_2^r = (1 - \alpha_1^r)$ the equation reflects a relation between MSW per capita and the real household income per capita. That is, if (Y_t^r/U_t^r) changes 1%, (w_t^r/U_t^r) changes α_1^r%.

Thirty-one areas regionalize the waste projection. These are Chinese provinces, autonomous regions, and the four province-level municipalities. In the following all referred to as provinces. Due to the scope of key data sources Hong Kong, Macao, and Taiwan are not included in this research.

2.1.2. Disposable urban household income projection

The National Bureau of Statistics publishes data on disposable urban household income in annual yearbooks, which are the source for historical data. Private consumption has accounted for about 66% of disposable urban household income since 2013,[3] and consumption varies with the disposal income. The Institute of Science and Development, Chinese Academy of Sciences (CASISD) has estimated future private consumption at provincial level up to 2050. Assuming constant propensity to consume, this is used to establish provincial development of disposable urban household income. Here private consumption is projected with the PIC model developed by CASISD (Zou et al., 2018). In this model, private consumption depends on real disposable income, the price effect, the income effect, while the price effect is a key factor to calculate disposal income.

The PIC model divides household consumption goods into 10 categories: food; clothing; residence; household facilities, articles and services; health care and personal articles; transportation and communications; recreation, education and culture articles; financial service; insurance service; others. In the PIC model, consumption of a good (j) in a province (r) are impacted by age composition, major region, regional income, regional relative price, regional population and nationwide consumption level.

[3] Since 2013, the National Bureau of Statistics has adopted a new statistical standard.

$$C_{j,t}^r = AG_j^r \cdot CR_j^r \cdot YR_t^r \cdot PR_{j,t}^r \cdot UR_t^r \cdot C_{j,\ t} \tag{2}$$

where AG is the age composition effect, CR is regional consumption effect, YR is the regional income effect, PR is the regional price effect, UR is the population effect and C is the national private consumption in fixed 2007 CNY. r is a region, j is a consumer good, t is time and $C_{j,t}^r$ is the consumption of good j in region r in year t in fixed 2007 CNY.

2.1.2.1. Age composition effect. The age composition effect is determined as:

$$AG_j^r = \sum_{i=1}^{20}\left(\%AG_i^r * PC_{i,j}\right) / \sum_{i=1}^{20}\left(\%AG_i * PC_{i,j}\right) \tag{3}$$

where i indicates an age group with a five years interval, consistent with the Chinese national statistic yearbook. $\%AG_i^r$ is the percentage of each age group i in the total regional population, and $PC_{i,j}$ is the national average propensity of age-group i to consume good j.

2.1.2.2. Major regional effect. The major regional effect is determined as:

$$CR_j^r = \frac{C_{j,2012}^r}{C_{j,2012}} / AG_j^r \tag{4}$$

where $C_{j,2012}^r$ is the base year (2012) consumption of good j in region r and $C_{j,2012}$ is the national consumption of the good.

The major regional effect is the difference of consumption patterns between regions after adjusting for age composition. The age composition adjustment helps to predict changes in consumption as a result of demographic changes.

2.1.2.3. Regional income and price effect. The regional income and price effects are determined by the income and price elasticities β_j and γ_j. The income effect reflects the consumption change introduced by changes in the real disposable income per capita (Y_t^r/U_t^r), and the price effect reflects the consumption change caused by changes in the price of good j (Pj). Both income and price effects are normalized to base year T to show the relative change of the projective year. YR_r^t is the regional income effect in year t in region r. $PR_{j,t}^r$ is the regional price effect in region r for good j in year t.

$$YR_r^t = \left[\left(\frac{Y_t^r/U_t^r}{Y_t/U_t}\right)/\left(\frac{Y_T^r/U_T^r}{Y_T/U_T}\right)\right]^{\beta_j} \quad (5)$$

$$PR_{j,t}^r = \left[\left(\frac{P_{j,t}^r/P_t^r}{P_{j,t}/P_t}\right)/\left(\frac{P_{j,T}^r/P_T^r}{P_{j,T}/P_T}\right)\right]^{\gamma_j} \quad (6)$$

2.1.2.4. Regional population effect and national consumption. The regional population effect is the proportion of regional population in the national population. UR_t^r is the population effect in region r in year t.

$$UR_t^r = U_t^r/U_t \quad (7)$$

The national consumption level is determined by the population, disposable income and price in the base year. The projection of the total household consumption in China until 2050 is shown in Fig. S1.

For a detailed description and calculation of the consumption projection, please refer to Treyz (1995).

2.1.3. Urban population projection

A central component in waste projection is the development of urban populations. Data for base year 2017 is from the NBS (NBS, 2018); the annual growth from the United Nations population and urbanization projections (UN, 2019, 2018). Sun et al., (2017) projected urban population by province to 2030. This provincial share of urban population is used for 2050 and interpolated linearly from the base year, 2017. The large increase of urban citizens in Guangdong seen in Fig. S2 primarily stems from interprovincial migration.

2.2. Scenarios

Waste generation and its composition depend on multiple factors associated with high degrees of uncertainty. Three scenarios: Recycling & Cap, Bio Sorting, and Bio Sorting & Cap are presented based on policy analysis to accommodate for some of this uncertainty; they illustrate possible developments deviating from the Base Scenario from 2020, see Table 1. In the scenarios that include a cap, dry MSW fractions are avoided and/or recycled to a larger degree. In scenarios focusing on sorting of food waste, the food waste fraction is diverted from the mixed MSW stream to be treated separately, for example in a biogas plant.

3. Data

The model uses the national average for all provinces where provincial data is unreliable or unavailable. For setting a cap on mixed MSW and defining possible sorting efficiency of food waste, international cases are used.

3.1. Collected MSW

MoHURD, the ministry responsible for collecting and treating MSW in China publishes annual statistical yearbooks, the most recent comprises 2017 (MoHURD, 2019b). These include data on collected and treated MSW but does not describe waste composition or estimates of generated waste quantities.

3.2. Energy content

A compilation of 34 studies from 1992 to 2009 across China shows great variety in lower heating value (LHV) ranging from 2.86 to 9.44 GJ/ton with a mean of 5.34 GJ/ton (Zhou et al., 2014). More recent studies use a LHV of 4.5 GJ/ton (Guo et al., 2018) and 4.9 GJ/ton (Liu et al., 2017). Due to the lack of comprehensive regional data, a simple average of the above-mentioned three studies, 4.9 GJ/ton, is used for all of China, giving more weight to more recent studies.

Chinese MSW has a higher share of food waste and a higher moisture content than waste in European countries (Li et al., 2017; Yang et al., 2012; Zhou et al., 2014). This article uses the LHV 1.9 GJ/ton for Chinese food waste (Liu et al., 2017). This LHV is used to calculate development of LHV for mixed MSW when food waste is separated from mixed MSW.

3.2.1. Waste composition

MSW composition is case specific and varies across different cities as well as over time and by season (Wang and Nie, 2001). Looking at data from 91 cases collected between 1990 and 2011, there is no clear trend in the development of share of food waste in Chinese MSW (Li et al., 2017; Wei et al., 2017; Zhou et al., 2014). The national average from these studies, 56 wt% food waste in Chinese MSW, is used.

3.2.2. Sorting efficiency

Some food waste will be unavoidable, stuck to other materials or not sorted due to inattentiveness. This affects the sorting efficiency, the share of food waste segregated at source for separate recovery. This article assumes that maximum 57% of the food waste can be segregated (Cimpan et al., 2015). The 13th Five-Year Plan on urban waste management stipulates that 46 key cities should be ambitious and quickly implement food waste sorting (NDRC and MoHURD, 2016b). The 46 key cities include all provincial capitals and province level municipalities. This article assumes that efforts for source sorting are in place in key cities by 2020 and in 2025 in other areas, and for China to reach a sorting efficiency of 25% in key cities by 2021 and by 2026 in other areas.

3.2.3. Cap on mixed MSW

There are no quantitative targets set in China for waste prevention, although it is stated as a priority (NDRC and MoHURD, 2016a). Targets set in specific EU countries correspond to 0.49 and 0.43 kg/capita/day mixed MSW for energy recovery or landfilling (European Environment Agency, 2015; European Parliament, 2018). These targets are used as cap values for mixed MSW for energy recovery or landfill.

4. Results

4.1. Econometric analysis

For the Chinese provinces, Table 2 shows estimation results[4] for Eq. (1). The figures in the columns for $\alpha_0^r, \alpha_1^r, \alpha_2^r,$ *and* δ_i^r are the estimated coefficients in Eq. (1) (with t-values in parentheses). R^2 is a measure of how much of the historical variation in waste that the equation explains, and DW is the Durbin-Watson statistic measuring if the error has a systematic serial variation (the R^2-value varies between zero and one, where higher values represent a closer fit. The DW-statistics vary between zero and four, with the central value (two) indicating no serial variation in the error).

As seen in Table 2 for many provinces the restriction: $\alpha_2^r = (1 - \alpha_1^r)$ is imposed. That is, the amount of waste per capita is due to the real disposable household income per capita, and in general, the estimated coefficient is quite significant (t-values

[4] Coefficients are estimated using TSP (Time Series Processor) software and LSQ (least squares) method (Hall and Cummins, 2009). The projections are central values and a forecast confidence interval is not calculated. It is assumed that the largest uncertainty relate to the income and population projections that are external assumptions to the waste projection, for which sensitivity analysis have been conducted.

Table 1
Overview of MSW forecast scenarios.

	Base Scenario	Bio Sorting Scenario	Bio Sorting & Cap Scenario	Recycling & Cap Scenario
Maximum level of mixed waste suitable for energy recovery/landfill (kg/capita/day)[a]	None	None	0.43 in 2040	0.55 in 2025 0.49 in 2030 0.43 in 2040
Food waste successfully sorted[b]	None	Starting in 2020 reaching full potential (57%) in 2050 in all areas	Starting in 2020 reaching full potential (57%) in 2030 in key cities and 2035 in all areas	Intrinsic part of the cap
Lower heating value (GJ/ton)[c]	4.9 throughout the whole period	Increases as food waste is sorted, reaching 6.4 in 2050	Increases as food waste is sorted, reaching 6.4 in 2035	4.9 throughout the whole period

[a] See Section 3.2.3 for assumptions and sources.
[b] See Section 3.2.2 for assumptions and sources.
[c] See Section 3.2 for assumptions and sources.

above 2.5). For a few regions, the coefficient for the real disposable income is restricted to zero implying that the amount of waste increases along with the population. Another observation is, that for almost all regions the time-series show significant outliers and shifts in the level of MSW (that is, the equation includes significant dummy-variables). Changes in data collection standards over time provide one possible explanation.

For most regions, the equation gives a reasonable explanation of the historical development, but a few provinces have atypical development. In Hebei, the amount of waste collected shows a very large data-break from 2010 to 2015. In Inner Mongolia and Jilin, waste data contains considerable shifts in amounts and limited correlation with population and real household income, and in Heilongjiang the population and real household income increases while the amount of waste decreases. These atypical developments may be due to inconsistencies in data collection and for these provinces, results should be interpreted with caution. In Heilongjiang and Shanghai, the trend variable α_3^r is repressed over the initial four years of the projection to remove the correlation between time and projected waste quantities.

4.2. Short term projection

The 13th Five-Year Plan on urban waste management declares that the planned treatment capacity for MSW be 403 MMT in 2020, of which 216 MMT is for incineration, almost doubling the MSW incineration (MSWI) capacity from 2017 to 2020 (NDRC and MoHURD, 2016a). Most of Chinese MSWI capacity, 68% of capacity available in 2017, was installed after 2012, with capacity to treat 14 MMT installed in 2017 alone (MoHURD, 2019b, 2018). MSWI facilities have a design lifetime of 20 years (Guo et al., 2018), resulting in these investments being part of the infrastructure to 2039. Previous targets on MSW treatment capacity and incineration share set in the 12th Five-Year-Plan have been fulfilled, and investments in MSWI capacity are well underway. The utilization rate of incineration plants has not changed significantly during the last years; between 2012 and 2017 average utilization of installed incineration capacity reached 79%. Not utilizing full capacity is common in Chinese power generation projects (Lu et al., 2017). Assuming the same utilization rate means that 170 MMT (73%) of projected MSW would be incinerated in 2020.

In all provinces, MSW treatment capacity exceeds the projected mixed MSW quantities for 2020 (see Fig. 2). In provinces such as Anhui, Tianjin, Zhejiang, and Guangdong the planned MSWI capacity significantly exceeds projected mixed MSW quantities.

4.3. Long term projection

Looking beyond 2020, results from the different scenarios vary in terms of mixed MSW, sorted food waste, and energy content of mixed MSW. MSW quantities are aggregated from provincial level and sum to the national value discussed below.

4.3.1. Mixed MSW

Starting with mixed MSW at the national level, quantities range from 159 MMT in the Bio Sorting & Cap Scenario to 340 MMT in the Base Scenario by 2050, see Fig. 3a. Using the estimated coefficients for China nationally, as opposed to summing provincial projections, results in lower levels, reaching 285 MMT. In the Base Scenario and the Bio Sorting Scenario the same amounts of MSW are collected, the difference between these scenarios is that some of the food waste is sorted for separate treatment in the Bio Sorting Scenario. This shows that sorting of food waste according to the Bio Sorting Scenario would let levels of mixed MSW remain relatively stable throughout the period. More ambitious food waste sorting or setting a cap on mixed MSW could reduce mixed MSW quantities to levels lower than present levels.

The Bio Sorting & Cap Scenario begins to deviate from the Bio Sorting Scenario when the sorting efficiency differs. Quantities of mixed MSW are reduced when food waste is separated from mixed MSW and when caps on MSW generation are binding. The quantities of mixed MSW in the Bio Sorting & Cap Scenario are slightly below the Recycling & Cap Scenario as some provinces do not reach the cap for mixed MSW.

4.3.2. Sorted food waste

Looking at the national level for the entire period, the Bio Sorting & Cap Scenario, sorts most food waste see Fig. 3d. The difference between the Bio Sorting & Cap Scenario and the Bio Sorting Scenario in terms of sorted food waste is due to the rates of reaching full sorting efficiency. In the Recycling & Cap Scenario, sorting food waste is an intrinsic part of the cap. The assumption is that the waste composition remains the same as in the base year, meaning that there is a strong focus on recycling or avoiding waste, both for dry fractions and for food waste. This results in a smooth curve for food waste sorting efficiency ending at 57% in 2050.

4.3.3. Energy content

The calorific value of mixed MSW increases when food waste is separated from mixed MSW (see Fig. 3b). In the Base Scenario and the Recycling & Cap Scenario the waste composition is assumed to be the same throughout the period, meaning that the development corresponds to the MSW quantities, see Fig. 3c. For the other two scenarios, the energy content relates to the amounts of sorted food waste.

MSW can be used for different applications in the energy sector. MSWI is widely utilized. To sustain safe combustion of MSW and avoid the need for auxiliary fuel, the LHV of MSW needs to be higher than 5–6 GJ/ton (Chen and Christensen, 2010). As MSW in China in many cases has a lower LHV, auxiliary fuels are used to

Table 2
Estimated model coefficients (t-values in parentheses).

Estimated equation: $log(w_t^r) = a_0^r + a_1^r \cdot log(Y_t^r) + a_2^r \cdot log(U_t^r) + a_3^r \cdot T_t + \delta_i^r \cdot D_t^r$

	Constant	Income Y_t^r	Urban population U_t^r	Trend T_t	Dummy variables for breaks and shifts in the data D_t^r				Test-statistics	
Region	α_0	α_1	α_2	α_3	δ_1	δ_2	δ_3	δ_4	R^2	DW
National	−0.950	–	0.962	–	0.093	−0.068	–	–	0.98	1.83
	(−1.82)		(20.49)		(4.81)	(−5.53)				
Beijing	−1.118	0.053	0.947	–	0.116	0.197	–	–	0.96	2.19
	(−7.37)	(1.01)	–		(3.55)	(4.06)				
Tianjin	−2.872	0.357	0.643	–	0.462	0.173	0.216	–	0.94	1.37
	(−5.25)	(2.09)	–		(4.28)	(3.01)	(3.06)			
Hebei	5.362	–	0.153	–	−0.056	−0.215	−0.063	–	0.93	1.20
	(7.44)		(1.66)		(−3.71)	(−6.45)	(−1.30)			
Shanxi	2.551	–	0.467	–	0.475	0.198	−0.086	–	0.85	1.13
	(2.17)		(2.96)		(6.73)	(2.28)	(−1.81)			
Inner Mongolia	4.294	–	0.214	–	0.113	0.104	0.064	−0.072	0.86	2.19
	(9.21)		(3.30)		(3.94)	(3.92)	(3.32)	(−3.45)		
Liaoning	−1.244	0.041	0.959	–	0.051	−0.083	–	–	0.98	2.05
	(−56.44)	(3.54)	–		(3.68)	(−5.18)				
Jilin	−1.042	–	1	–	0.115	−0.066	−0.091	0.082	0.73	1.65
	(−59.38)		–		(4.62)	(−2.02)	(−2.79)	(1.70)		
Heilongjiang	4.140	–	1	−0.048	0.213	–	–	–	0.94	1.26
	(4.85)		–	(−6.49)	(3.13)					
Shanghai	−0.416	0.091	0.909	−0.010	0.223	0.166	0.197	–	0.93	2.03
	(−0.16)	(0.22)	–	(−0.29)	(5.05)	(5.30)	(5.93)			
Jiangsu	−1.790	0.211	0.789	–	0.164	–	–	–	0.97	1.42
	(−26.61)	(4.74)	–		(3.66)					
Zhejiang	−2.462	0.582	0.418	–	0.151	–	–	–	0.99	1.46
	(−38.99)	(20.18)	–		(5.86)					
Anhui	0.818	–	0.669	–	0.218	0.171	–	–	0.96	1.69
	(1.70)		(10.97)		(8.39)	(5.09)				
Fujian	−2.798	0.538	0.462	–	0.165	–	–	–	0.97	1.23
	(−21.90)	(9.58)	–		(2.50)					
Jiangxi	−1.511	–	0.952	–	0.082	−0.093	−0.106	0.162	0.96	1.22
	(−2.02)		(9.67)		(1.93)	(−2.53)	(−2.67)	(2.99)		
Shandong	5.892	–	0.158	–	−0.169	−0.341	0.104	–	0.94	2.81
	(3.13)		(0.72)		(−1.88)	(−6.03)	(1.64)			
Henan	2.167	–	0.547	–	0.041	−0.110	0.089	–	0.95	1.44
	(4.63)		(9.63)		(1.73)	(−4.49)	(2.29)			
Hubei	3.393	–	0.413	–	0.173	−0.109	0.052	–	0.98	2.52
	(8.40)		(8.20)		(8.44)	(−8.11)	(2.21)			
Hunan	0.710	–	0.706	–	−0.080	0.123	–	–	0.97	2.60
	(1.86)		(14.64)		(−4.24)	(3.69)				
Guangdong	−1.368	0.123	0.877	–	−0.053	0.084	–	–	0.95	2.12
	(−23.74)	(2.61)	–		(−1.22)	(1.76)				
Guangxi	−2.158	0.145	0.855	–	−0.118	−0.186	–	–	0.95	1.33
	(−15.04)	(2.24)	–		(−2.05)	(−5.10)				
Hainan	−2.337	0.273	0.727	–	−0.557	−0.154	0.275	–	0.97	1.57
	(−10.26)	(4.23)	–		(−6.98)	(−3.15)	(4.21)			
Chongqing	−3.081	0.557	0.443	–	0.261	0.194	–	–	0.96	1.12
	(−11.21)	(4.85)	–		(4.25)	(3.02)				
Sichuan	−1.840	0.147	0.853	–	0.173	−0.037	0.100	–	0.99	1.89
	(−37.14)	(5.02)	–		(6.71)	(−2.07)	(3.72)			
Guizhou	−1.006	–	0.906	–	−0.075	0.073	–	–	0.96	1.87
	(−1.81)		(11.57)		(−2.08)	(1.39)				
Yunnan	−2.216	0.200	0.800	–	0.095	–	–	–	0.97	1.82
	(−20.13)	(4.14)	–		(2.61)					
Tibet	−2.786	0.330	0.670	–	0.778	2.056	−0.401	–	0.98	1.52
	(−3.53)	(2.28)	–		(8.39)	(16.90)	(−5.26)			
Shaanxi	−2.148	0.301	0.699	–	0.286	−0.392	–	–	0.96	2.51
	(−17.98)	(5.72)	–		(716)	(−8.07)				
Gansu	5.753	–	–	–	0.119	0.013	0.060	–	0.94	2.33
	(42.85)				(−1.50)	(1.14)	(6.22)			
Qinghai	−1.647	0.070	0.930	–	−0.130	0.109	0.299	–	0.94	1.72
	(−2.35)	(0.43)	–		(−0.90)	(1.01)	(4.13)			
Ningxia	2.009	–	0.466	–	0.347	−0.396	–	–	0.81	2.66
	(2.66)		(3.54)		(3.82)	(−4.68)				
Xinjiang	3.258	–	0.378	–	0.088	−0.124	–	–	0.95	2.37
	(11.30)		(9.01)		(4.20)	(−8.03)				

Coefficients are estimated using the estimation program "TSP" method LSQ.

enable incineration (Guo et al., 2018). MSWI plants are designed for a specific LHV, meaning that apart from exceeding the minimum, it should be known and stable. With the consequential higher heating value of MSW obtained by sorting out food waste, increased LHV of MSW reduces auxiliary fuel requirements in MSWI.

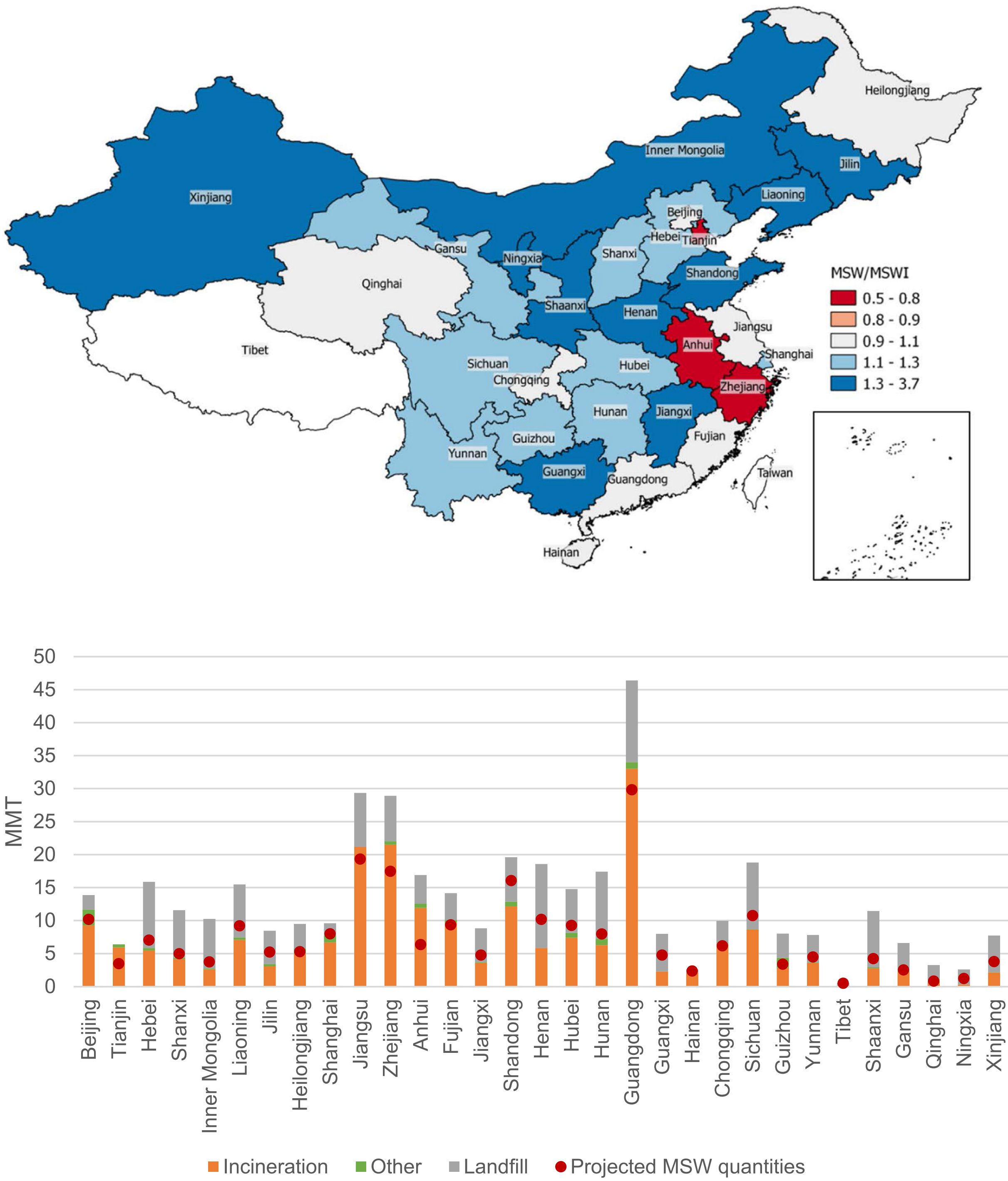

Fig. 2. Map showing the relationship between projected MSW quantities (this article) and planned MSWI capacity in 2020 (NDRC and MoHURD, 2016a), values below 1 indicating overcapacity in MSWI. Stacked bar chart showing all planned MSW treatment capacity (NDRC and MoHURD, 2016a) compared to projected MSW quantities (this article).

4.4. Regional results

Regional results for four selected provinces, Tianjin, Zhejiang, Anhui and Guangxi, illustrate specific trends. See supplementary material for results from all provinces. Fig. 4 shows the projected mixed MSW quantities by province and capita until 2050 in the base scenario. Levels are very high in Zhejiang, medium in Tianjin and low in Guangxi and Anhui. The provinces are selected to show a spread regarding collected waste quantities and have varied development levels, see Fig. 5.

Anhui is a province with plans for incineration capacity well above the projected MSW quantities. For Anhui province, the projected overcapacity in MSWI remains an issue throughout the period, provided that the MSWI capacity remains stable. Zhejiang presents a vast difference in mixed MSW in the different scenarios. The starting point for collected mixed MSW per capita was relatively high in Zhejiang, 1.04 kg/capita/day in 2017 (compared to the national average 0.72 kg/capita/day); this results in a cap on mixed MSW having a big effect. In Anhui the starting level for mixed MSW per capita was 0.50 kg/capita/day, resulting in the

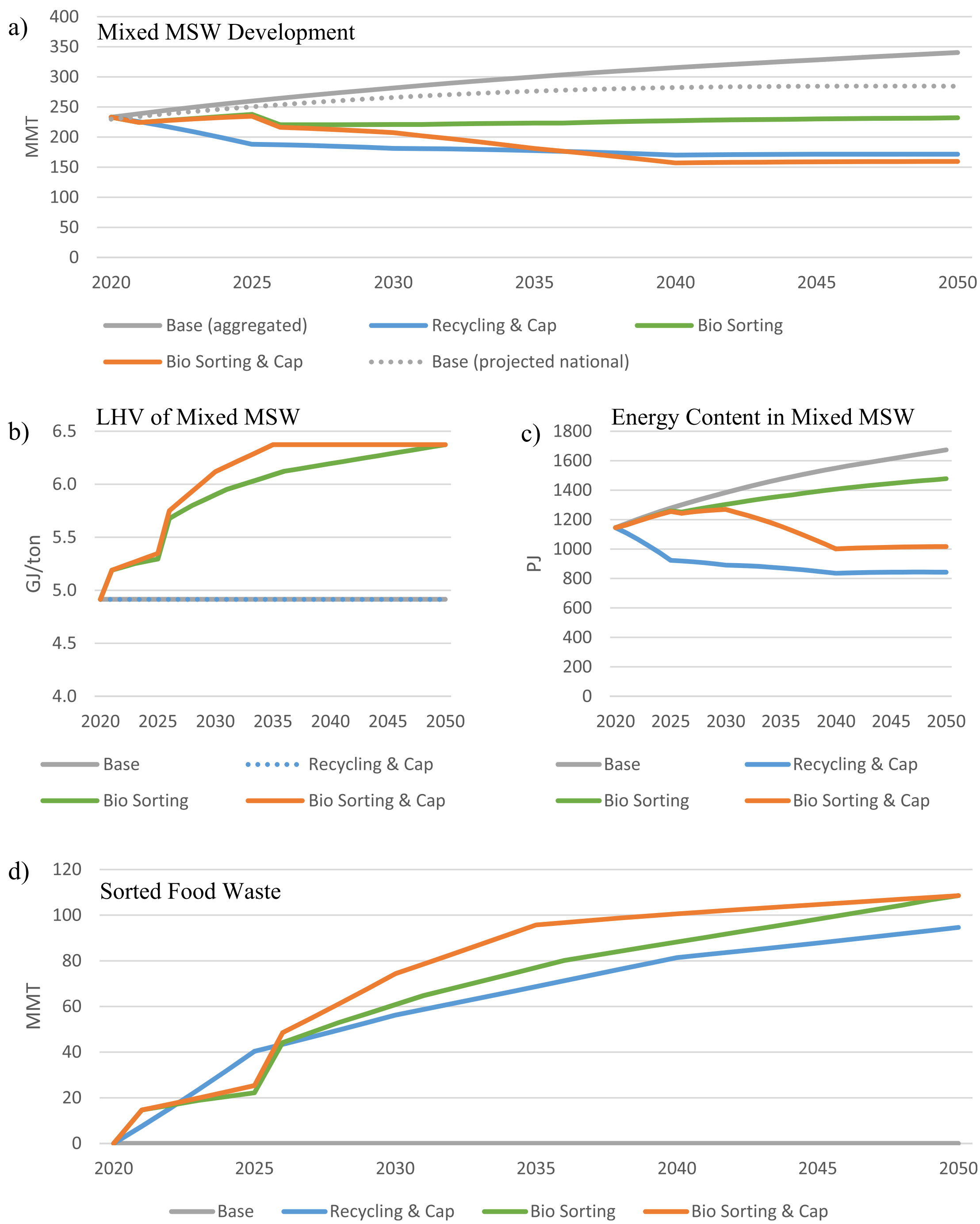

Fig. 3. Aggregated provincial results on national level.

cap not taking effect until 2031, when the Recycling & Cap Scenario diverges from the Base Scenario. The two other scenarios, with and without a cap, show the limited effect of the cap, as they follow similar paths.

In Tianjin, projected mixed MSW quantities stay below the 2020 MSWI capacity throughout the time period for all scenarios suggesting an overcapacity of MSWI in Tianjin, see Fig. 4. Collected MSW per capita starts below the national average at 0.65 kg/capita/day; from 2024 and thereafter it exceeds the national average in the Base Scenario. Since Tianjin is a province-level municipality, this is one of the 46 key cities and all of Tianjin is a key area for waste sorting, entailing early implementation of food sorting. There is a rapid decline in mixed MSW in the initial years as high shares of food waste are sorted from the mixed MSW. In Guangxi only 26% of urban population reside in any of the 46 key cities, the sorting of food waste is therefore implemented slowly, resulting in an initial increase of mixed MSW in the sorting scenarios. Collected MSW per capita starts at 0.50 kg/capita/day and increases to 0.60 in 2050, compared to the national average at 0.88 kg/capita/day. The planned MSWI capacity in Guangxi would enable incineration of less than half of projected mixed MSW in 2020 and would not exceed 55% if the MSWI capacity remains the same throughout the time-period.

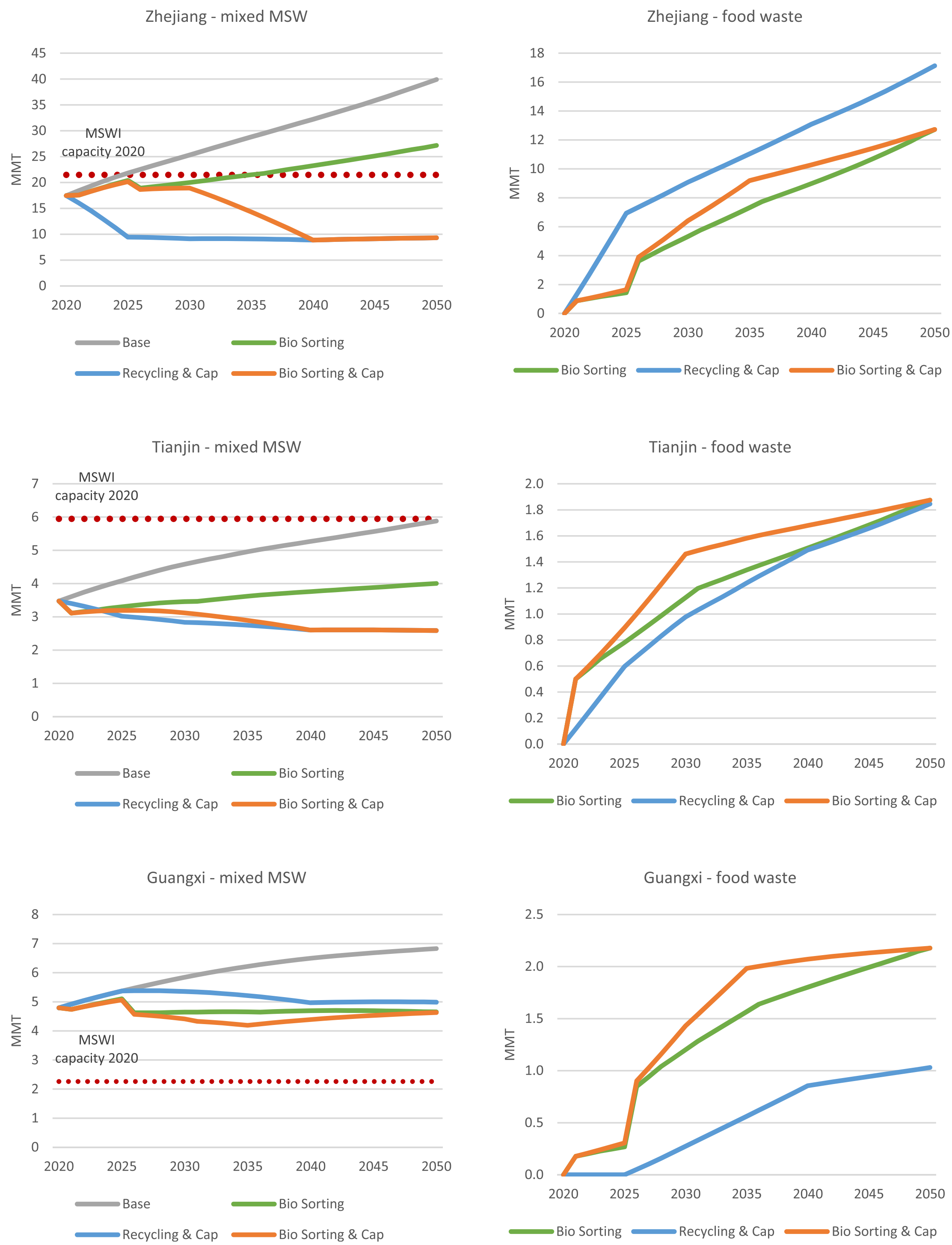

Fig. 4 (*continued*)

4.5. Sensitivity analysis

The underlying assumptions for development of parameters are associated with varying degrees of uncertainty. To assess the sensitivity of these parameters, a sensitivity analysis performed on the Bio Sorting Scenario shows the difference in mixed MSW and sorted food waste. The parameters urban population, household income, sorting efficiency, and share of food waste are assessed with an increase and a decrease of 10% compared to the standard values.

For mixed MSW, results are primarily sensitive to urban population and energy content, see Fig. 6a. The development of provincial distribution of urban population is associated with high degrees of uncertainty; provincial projections to 2050 would improve results. An increase in urban population leads to higher quantities of MSW. The same goes for household consumption, though this is not as sensitive a parameter as urban population. The assumed LHV does not affect the projected quantities, but the calculated energy content. For sorted food waste, share of food waste and sorting efficiency are the most sensitive parameters, see Fig. 6b.

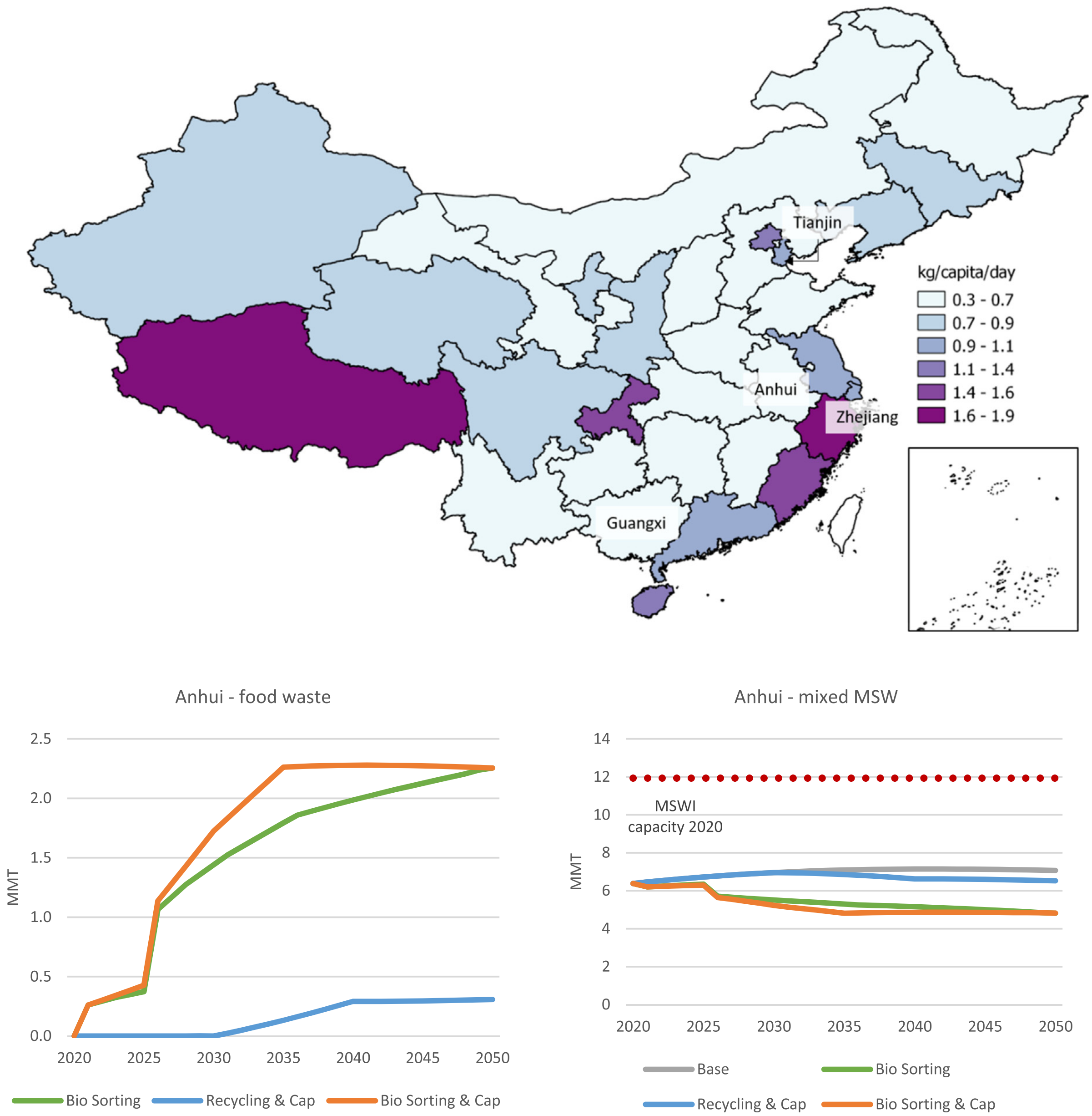

Fig. 4. Map with projected mixed MSW per capita and day by 2050 in the base scenario. Province titles provided for selected provinces. Graphs showing planned MSWI capacity in 2020 and development of mixed MSW and sorted food waste.

By the end of 2019, within the first year of implementation of the waste segregation scheme in Shanghai, the amounts of sorted food waste (Huanbao, 2020) and example of purity (Yi, 2019) corresponded to a sorting efficiency of 74%. This suggests that the assumptions regarding sorting efficiency and implementation speed used in this article could be conservative. If all key cities in 2020 and other areas in 2025 were to achieve the same results, the levels of sorted food waste would exceed the Bio Sorting Scenario by 65%, see Fig. 6d. The quantities of mixed MSW would be reduced by 18% in weight and by 10% in energy content, thus, LHV for mixed MSW would increase and reach 6.8 GJ/ton by 2026, see Fig. 6c. More efficient sorting of food waste means reduction in the need for treatment capacity for mixed MSW, for example MSWI.

5. Discussion

Predictions for 2030 mixed MSW quantities found in previous studies spanned between 247 and 500 MMT; whereas in this article the Base Scenario provincial results sum to 282 MMT. This is close to the results from Kaza et al. (2018), which is also the most recent. Kaza et al. (2018) use historical data from different countries and establish a correlation between GDP per capita and waste generation. The predicted corrrelation and projected GDP per capita and population result in 295 MMT of MSW in China by 2030.

Another recent study, by Chhay et al. (2018), employs and compares three methods for forecasting MSW; grey model, linear regression, and artificial neural network, using urban population, GDP, and energy consumption as variables. They found the artificial neural network model to be the most accurate and project a level of 247 MMT of MSW in China by 2030.

Wei et al. (2013) found GDP, urban population, and household consumption to be the most important factors and used multiple linear regression to project MSW quantities. The results show MSW quantities close to doubling from levels in 2020, to 500 MMT by 2030. Looking at results for 2020, Wei et al. (2013) show a MSW level at around 250 MMT, close to the results of 233 MMT reached in this article.

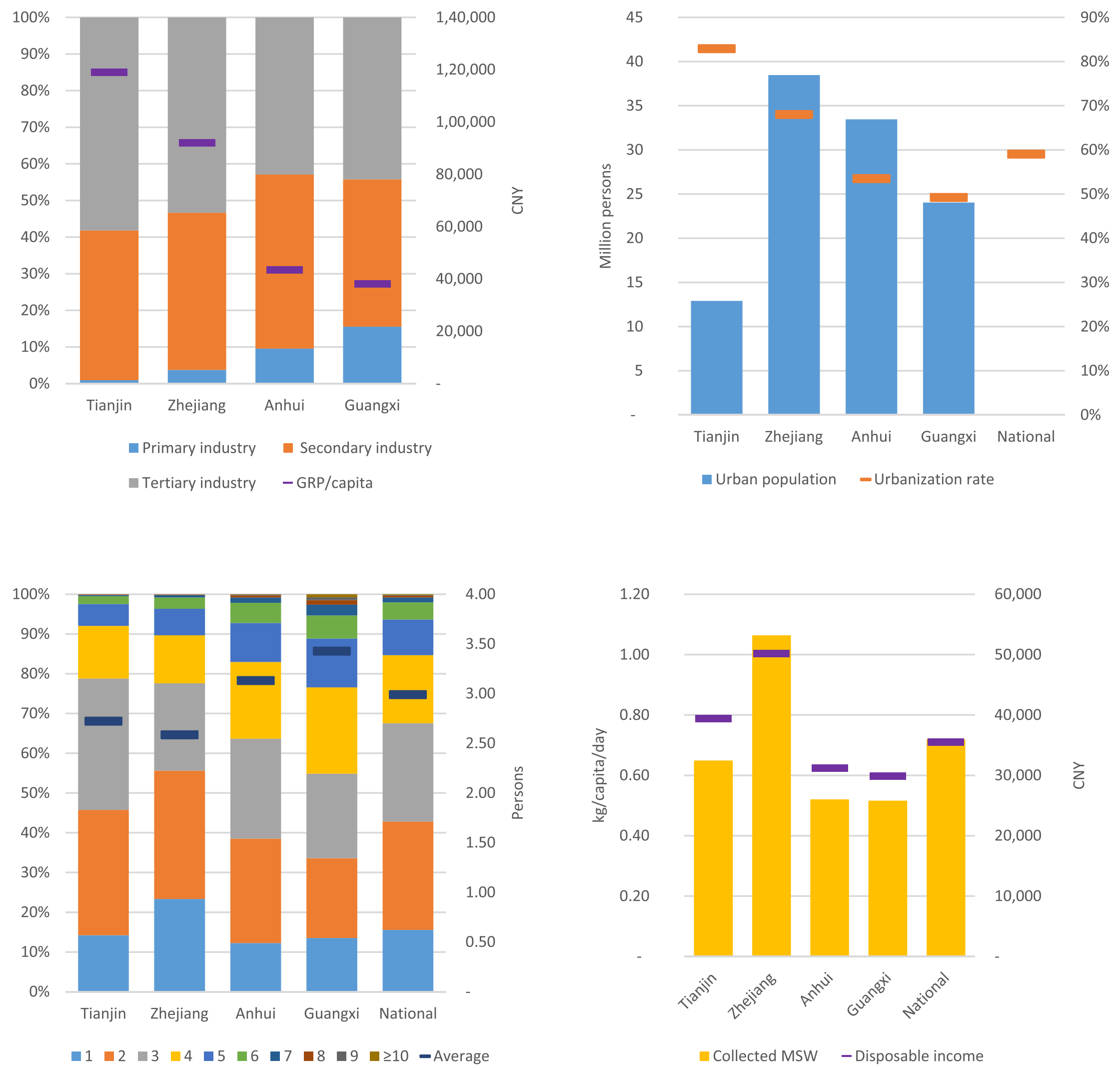

Fig. 5. Economic structure, urban population and urbanization, household size, and collected MSW and urban household disposable income for selected provinces in 2017 (NBS, 2018).

Chhay et al. (2018) use collected MSW data and consider this the generated MSW. These results disregard informal waste collection and waste recycling. Wei et al. (2013) use historical data on collected and transported MSW and categorize this as generated MSW, although informally collected MSW and MSW that is not collected is not included. Kaza et al. (2018) use the term "generated waste" but the data used for China does not cover recycled MSW. It is therefore assumed that MSW for China is limited to mixed MSW, making the results comparable to the Base Scenario in this article. Kaza et al. (2018) further projected 335 MMT MSW in 2050, compared to 340 MMT in the Base Scenario.

Given that the policy direction is moving towards efficient use of resources, the scenarios including sorting of food waste and/or restricting mixed MSW are more likely than the Base Scenario. Increased waste sorting and using resources more efficiently would mean substantially lower levels of mixed MSW. This article divides MSW in mixed MSW and sorted food, which enables an assessment of the required nature of treatment capacity. The methodology used in this article could be applied to other countries to regionalize waste projection and include policy scenarios, if historical data on regional level and projections on population and economic indicators are available.

The mixed MSW quantities projected in this this article are highly sensitive to projections in urban population and food waste quantities are highly sensitive to sorting efficiency, see Section 4.5. The sorting efficiency used was calculated as a share of the generated waste. In China, the data covers the collected waste, meaning that the sorting efficiency may be higher. This would result in larger quantities of sorted food waste and less mixed MSW as shown in the sensitivity analysis using the Shanghai sorting efficiency, see Section 4.5. Kaza et al. (2018) have shown that the share of food waste decreases as income levels rise, mainly due to an increase of recyclables. This is assumed to have limited affect since recyclable waste is not a focus of the projections in this article.

A limitation of this study is the lack of distinction between various types of wastes and the development of their quantities. With more ambitious waste reduction policies, including banning of specific single use plastic products, it is likely that MSW diminishes. The amount and composition of illegally dumped MSW is unknown. If the official system manages to collect more of the available waste, including waste now managed by the unofficial system, this would increase MSW amounts in official statistics.

Mapping and projecting resource potential is the first step of assessing the role MSW can play in a future energy system. Incin-

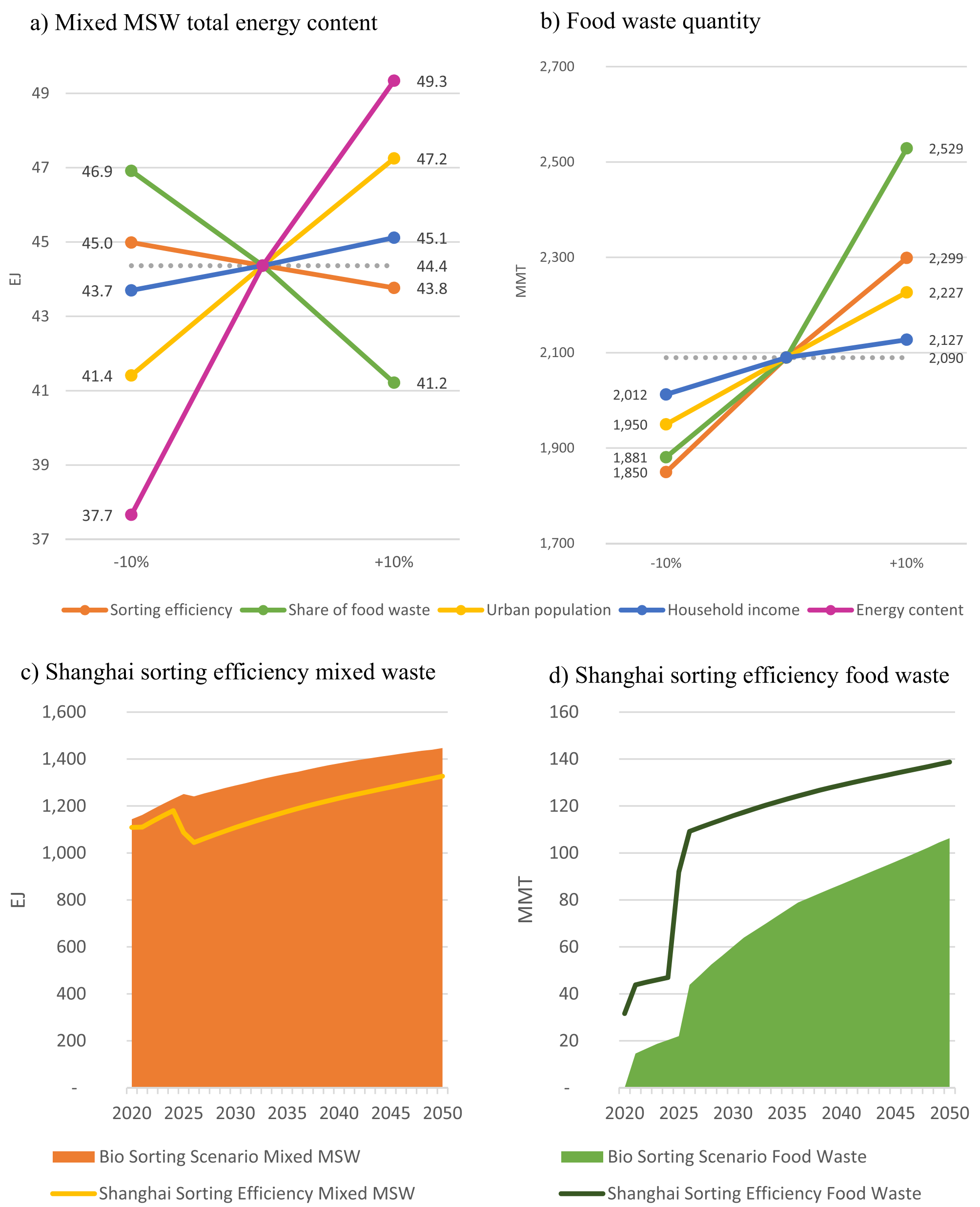

Fig. 6. Sensitivity to different parameters as deviation to total energy content for mixed MSW (a) and deviation of total tons for sorted food waste (b). National development of mixed MSW (c) and food waste (d) with Shanghai case sorting efficiency.

erating all collected MSW in 2017 would produce 68 TWh_{el}, assuming 23% electrical efficiency. This corresponds to 1% of electricity consumption (NEA, 2018). If heat was utilized as well, assuming 80% heat efficiency, MSW could cover 16% of district heating demand and thus play a more significant role in the energy system. In 2030, sorted food waste in the Bio Sorting Scenario could be used to produce 185 PJ of methane[5] to potentially substitute natural gas. This would contribute to reaching 24% of the biogas production targets set by the central government (NDRC, 2019). When using MSW in the energy sector the associated GHG emissions depend on emissions from the conversion processes and to a large extent on avoided energy production (Liu et al., 2017). As the energy mix changes over time, quantifying emissions requires insights into the energy system development. Using MSW scenarios in energy systems modelling would enable analysis of how MSW use in the energy sector could be optimized and contribute to an energy system based on clean energy, as researched by for example Pizarro-Alonso et al. (2018). This and the climate change benefits associated with the sorting and separate treatment of food waste are relevant areas for further research.

6. Conclusion

The methodology employed provided results in line with the most recent studies at national level. It revealed the importance of regional projections, as well as the advantage of combining econometric projections with policy scenarios to forecast waste quantities and required incineration and biological treatment capacities. Results show a risk of overinvestments in municipal solid waste incineration (MSWI) and landfill capacity as the planned capacity does not match projected MSW quantities in the different regions. Even without sorting food waste, there will

[5] Assuming 3.05 GJ methane output per ton of food waste input (Dung et al., 2014).

be overcapacity of MSWI in Anhui and Tianjin in 2030. Large investments in MSWI capacity could create a lock-in to incineration, developing less incentive for sorting and recycling. Provinces such as Zhejiang, with high initial levels of MSW per capita see a larger impact from the scenarios, which include a cap on mixed MSW. In the long term, provincial differences in MSW per capita are expected to continue in scenarios without a cap on generation of mixed MSW. In order to increase quality of Chinese waste projections, it is important to improve regional data, particularly with regard to sensitive parameters; urban population, waste composition, and sorting efficiency as shown in the sensitivity analysis.

As food waste makes up the majority of collected MSW in China, sorting this fraction is key in improving MSW management. Further, diverting food waste from mixed MSW will increase the energy content of mixed MSW and diminish the need for auxiliary fuel in MSWI. A separately sorted food waste fraction will enable production of, for example, biogas or feed. Results from the Shanghai waste segregation scheme in 2019 suggests that higher shares of food waste could be sorted from Chinese MSW than assumed in this article. This would increase the need for capacity to treat food waste and reduce the need for capacity for treating mixed MSW. Since sorting of food waste is part of the Chinese waste strategy, the implementation of this strategy and expected effects are important when planning for MSW treatment capacity.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary material

Supplementary data to this article can be found online at https://doi.org/10.1016/j.wasman.2020.05.014.

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Paper II

Requirements for a maritime transition in line with the Paris Agreement

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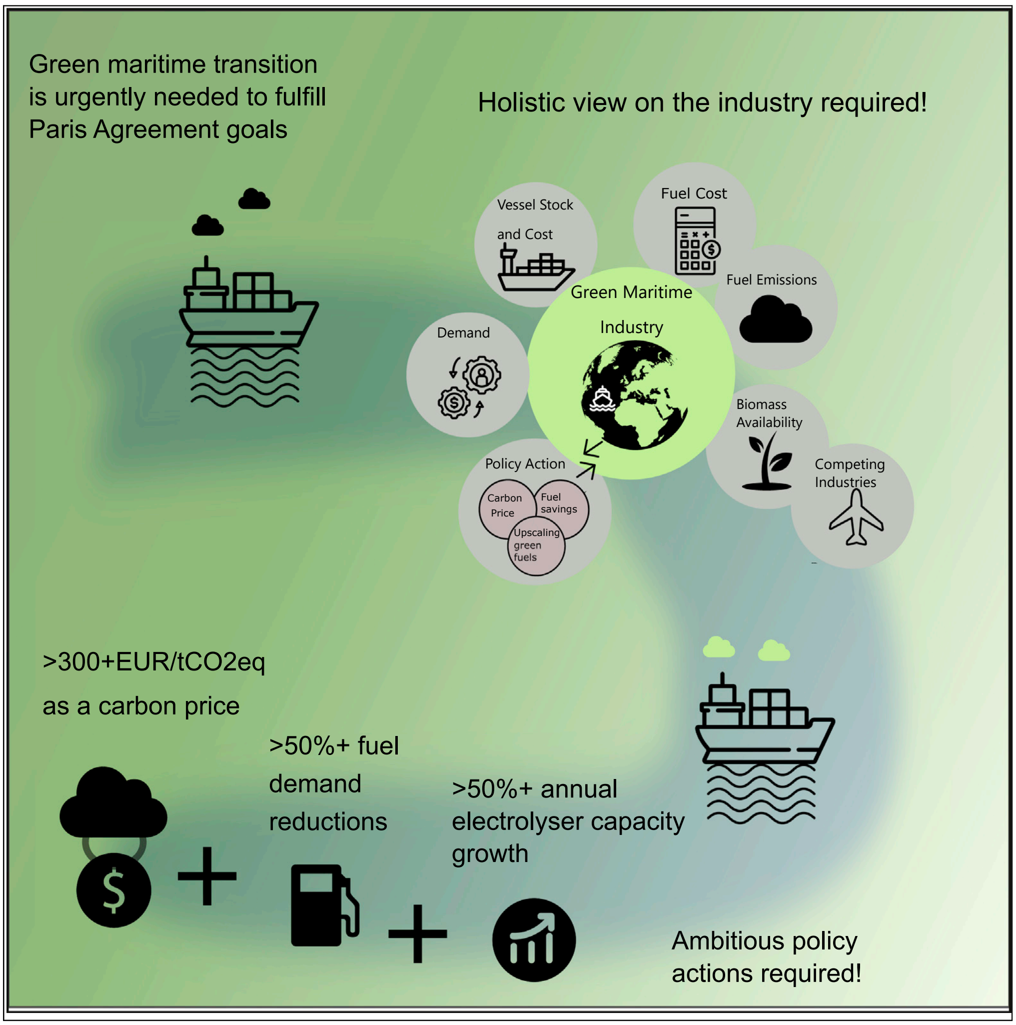
Requirements for a maritime transition in line with the Paris Agreement



Sebastian Franz, Nicolas Campion, Sara Shapiro-Bengtsen, Rasmus Bramstoft, Dogan Keles, Marie Münster

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Highlights

Holistic least-cost optimization model of global long-distance shipping is developed

Urgent transition of the maritime industry is required

Carbon price of 300EUR/tCO2eq and demand savings beyond 50% of future demand required

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Requirements for a maritime transition in line with the Paris Agreement

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SUMMARY

The shipping industry is a hard-to-abate sector in today's society. Although past studies have looked at levels of carbon pricing, fuel savings, and the upscaling of green fuel availability separately, we combine these critical parameters for a green transition of the shipping industry to show what it takes to reach sectoral emissions reduction targets in line with the Paris Agreement. We utilize a least-cost optimization model drawing on data on, e.g., emissions with lifecycle elements and the costs of green fuel production. We find that reaching maritime reduction targets for a green transition requires high growth rates for green fuel availability, carbon pricing beyond 300EUR/tCO_2eq, and at least 50% in fuel demand savings compared to today's demand projection for 2050. The results show the importance of immediate climate action if maritime emissions reduction goals are to be achieved.

INTRODUCTION

Reducing the emissions generated by the maritime sector is crucial to addressing the challenges of climate mitigation and meeting the Paris Agreement's targets. The path we choose for the next century will decide whether we will overshoot the reduction goals to stay within a 1.5°C rise in global warming as set out by the Paris Agreement. It is essential to identify an efficient and feasible roadmap to avoid carbon-intensive lock-in for the maritime industry.[1] Currently, the global maritime fleet is mainly fueled by Heavy fuel oil or very low sulfur fuel oil (VLSFO), maritime diesel oil (MDO), and partly by liquefied natural gas (LNG) (Smith et al., 2021). Switching to green fuels has been identified as having significant potential for GHG emissions reductions.[2,3] The two primary green fuels, which are derived from green hydrogen and/or biomass, are methanol produced from carbon and green electrolytic hydrogen, and ammonia produced from nitrogen and green electrolytic hydrogen. The green transition towards a massive usage of green fuels depends, among other factors, on the scaling up of global electrolyzer capacity.[4]

There are several different detailed approaches to reducing emissions in the maritime industry, many of them involving carbon pricing and fuel savings as an essential policy and technological tool.[5,3,6–15]

Although past studies[5,6,14–16] have looked at levels of carbon pricing, fuel savings, and the upscaling of green-fuel availability separately, we combine these critical parameters in a scenario for a green transition of the shipping industry to show what it will take to reach sectoral emission reduction targets in line with the Paris Agreement.

In this study, we push the research field by utilizing a least-cost optimization model, which encompasses (1) detailed fuel emission profiles featuring life-cycle elements, (2) costs of green fuel production, (3) constraints in upscaling green-fuel production capacities, (4) exogenous assessment of biomass availability, (5) emission reduction goals motivated by Paris Agreement narratives, and (6) two dimensions of climate action, namely carbon pricing and reduction in fuel demand. In doing so, we build on[2–4,17] all of which highlight the challenging task of bringing the shipping industry onto a transition pathway in line with the pledges made under the Paris Agreement.

For this type of analysis, it is essential to define emission reduction targets that not only focus on achieving net-zero by 2050 (International Energy Agency, 2021b), but strictly use emission reduction targets to avoid overshooting (sectoral) carbon budgets motivated by the Paris Agreement.[18] Thus, in this study, we used

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two maritime reduction targets to serve as a proxy for the 1.5°C global warming limited as formulated in the Paris Agreement. The two 1.5°C scenarios have been motivated by the IPCC narrative for a 1.5°C warming[19] and actual emission pathways from the latest IPCC report.[20] These reduction targets are more ambitious than that set out by the International Maritime Organization (IMO),[21] yet they can be motivated by reduction targets as set out recently by leading shipping companies.[22]

This study can be broken down into several steps. Firstly, we model the optimal location for the production of green fuels to come up with bottom-up data on underlying emissions, costs, and resource usage (for more details, see fuels for the maritime industry and general assumptions for the e-fuel modeling process and Campion et al.[23] After this, we investigate exogenous biomass availability scenarios for the maritime industry, which is essential in determining the availability of biofuels (for more details, see fuels for the maritime industry, exogenous biomass availability scenarios, and competing demand). In addition, we investigate the total cost of ownership and the availability of alternative engines for the shipping industry (for more details, see grey and blue ammonia and Sørensen et al.[24]). Finally, we combine these different modeling approaches and the resulting novel data to integrate them into one comprehensive least-cost optimization framework that allows us to analyze the dynamics and challenges of a green transition in the shipping industry.

We focus on the technological, economic, and environmental dynamics to transition towards a sustainable maritime industry. We use this holistic approach to distinguish the relationship between carbon-pricing efforts, savings in fuel demand, growth rates for green-fuel availability, and their transformational potential towards the Paris Agreement's pledges. Results highlight the importance of early[25] and efficient policy measures in international shipping to reach emission reduction goals in line with the Paris Agreement.

RESULTS AND DISCUSSION

Fossil fuels, biofuels, and e-fuels for the shipping industry

In this study, we model bottom-up Well-to-Wake (WTW) emissions, including upstream emissions and the underlying costs of, among other things, green ammonia (Haber–Bosch process using hydrogen from electrolysis), bio-e-methanol (biomass-to-methanol via thermochemical conversion boosted with electrolytic hydrogen), and e-methanol (CO2 hydrogenation using hydrogen from electrolysis and renewable CO2 from either direct-air-capture (DAC) or through point-source from a biomass-fired plant. (For more details, see Table S2 in the supplementary information). All green fuels are produced using 100% of solar PV and wind power without any connection to the public grid to ensure green electricity. The renewable power supply, fuel plant, and intermediate storage systems (hydrogen storage and batteries) are sized optimally to minimize the investment and operating costs for a given fuel demand. Four sites with good solar and wind profiles (Northern Chile, Western Sahara, northern Europe and Australia) are subject to testing, and the one with the lowest fuel production cost is chosen for reference. Compared to a system powered with grid electricity, the installed capacities need to be significantly oversized to satisfy the demand and avoid technical issues like frequent plant shut-downs. This is taken into account in the cost and WTW emissions analysis of green fuels (for more details, see Nami et al. 2021[26] and Campion et al. 2021[27]).

All analyzed green fuels take into account the pilot fuel oil, transportation to a central hub (Rotterdam) and profit margins (for more details, see general Assumptions for the e-fuel modeling process in the supplementary information). We show the final blended fuel cost in Figure 1. The respective fuels using biomass (LBG and MeOH-ebio) follow a sharp increase in the underlying biomass, as can be clearly seen for the LBG case. This price increase is motivated by global data from integrated assessment models (IAMs)[26,28]

The detailed bottom-up data related to green-fuel costs and WTW emissions is combined with a shipping stock model utilizing data on current and future engine technologies. We use data on the existing maritime fleet[29] and additional options for investing in new ships (taking into account all costs related to the total-cost of ownership[24]), as well as options to invest in new engine types that could handle both green fuels and conventional fuels without retrofitting costs (see Grey and blue ammonia in supplementary information) Our bottom-up modeling approach allows us to implement learning curves and emission-intensity improvements to produce green fuels (see Figure 4). These improvements can be seen in the underlying cost and emissions data for the respective fuels (see General Assumptions for the e-fuel modeling process and Fuel prices).

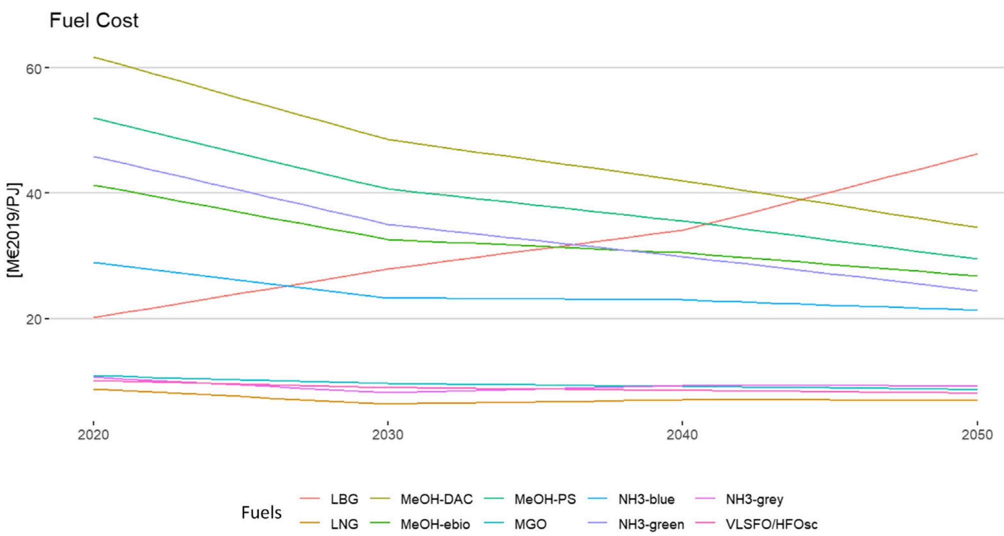

Figure 1. Blended fuel prices with electro-fuels powered using local renewable production

Ecological biomass potential and competing industries

One way to achieve the transition toward a sustainable maritime industry is to convert to biomass-based fuels. Some big players have already invested in a fueling pathway utilizing biogenic carbon to derive methanol (MeOH).[30] Yet, the question of ecological biomass availability* remains, as this is linked to great uncertainty (30 EJ – 100 EJ). We use the midpoint in this range for our scenario analysis in this study. However, in the limitations section, we perform multiple sensitivity analyses for the upper and lower boundaries of the exogenous biomass availability.

Similarly, there is uncertainty regarding the competing utilization of biomass between different sectors. In this study, we include the sectors listed in Figure 2 (for more details, see Cost reduction of e-fuels). We use the midpoint scenario related to ecological biomass availability and competing demand (see Figure 2), but perform multiple sensitivities with other settings in Figure 6. We assume that other industries also utilize biomass, yet certain industries are not prioritized. Thus we show at what point the available biomass cannot fuel the demand and thus adjust the available biofuels accordingly. Our modeling approach is even more optimistic than other research suggesting there is no biomass in maritime applications.[31] This analysis allows us to detail an available amount of biomass for MeOH-ebio, Liquefied Bio-Gas (LBG), or MeOH-Point Source (PS) fueling pathways.

Understanding greenhouse gas emission accounting and carbon pricing

In our approach, we have two scopes for GHG emissions. One scope is related to the GHG emissions including life-cycle elements (only related to indirect emissions of fuel infrastructure) (GHG emissions including life-cycle elements = direct GHG emissions (Well-to-Wake) plus upstream emissions related to fuel infrastructure) of a particular fuel. In this scope, we count the emissions related to building the infrastructure (e.g., steel processing, concrete, mineral extractions) used to build wind towers, solar PV panels, batteries, electrolyzers and fuel plant emissions, and ending with the final fuel emissions during combustion. More details about all the underlying assumptions for the cost and emission derivation of the analysis green fuels can be found in the Supplementary Information (section General Assumptions for the e-fuel modeling process to Exogenous Biomass availability scenarios). As can be seen, the underlying assumption is that the entire production of green fuels will become carbon-neutral in the years to come. This assumption is motivated by several plans to reach net-zero by 2050 for producing sectors. This plays an essential role when looking at upstream emissions, as these are the hardest emissions to reduce.[36,37]

We do not take land-use changes into account, but these could be assessed in a further analysis.

Furthermore, we assume that the biomass used is CO2-neutral, as only residual biomass is included (for more details, see Figure 2, also Franz et al. 2021[38]).

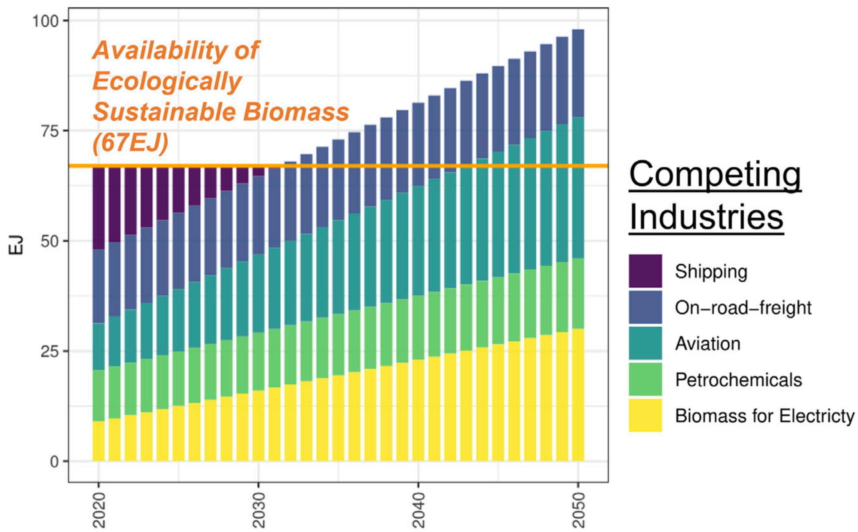

Figure 2. The availability and competition for ecologically sustainable biomass(*Ecologically sustainable biomass = the annual technical resource potential, taking into account the environmental sustainability aspects (for more details, see* supplemental information *section)*[†] from different sectors increase the challenges of climate mitigation significantly by reducing the available ecological biomass for the maritime sector

Availability data derived from (Gustafsson and Svensson, 2021; IEA Bioenergy, 2013; International Energy Agency, 2017, 2019; I.R.E.N.A., 2020; Oosterkamp, 2020); Data on competing industries from: Freight,[32] Aviation,[33] Petrochemicals,[34] and Electricity.[35] For more details, see Franz et al. 2021 (Franz et al., 2021).

The second scope of GHG emissions-accounting in our approach is related to the taxed GHG emissions. We only tax the WTW emissions without the upstream emissions (see Figure 3; purple parts of bars have not been taxed in this study) for building the fuel plant and the power supply infrastructure to avoid biased results by applying a carbon price twice. This is because GHG emissions related to, e.g., steel production are one of national GHG reduction targets; it is assumed that these emissions have already been taxed at the local level (e.g., via the EU ETS scheme) or as a share of import tariffs, as discussed by the EU Commission[39] they should therefore be excluded from the carbon taxation of the fuels. In both scopes, we assume no connection to the electricity grid. Thus, all the electricity used to derive green fuels comes directly from the respective fuel plant's specific mode of renewable electricity generation (PV or wind, depending on the modeled location. For more detail, see[26,27,38]). This approach guarantees that green fuels are produced from physically traceable green electricity.

Our bottom-up modeling approach allows us to implement learning curves and emission-intensity improvements to produce green fuels (see Figure 4). These improvements can be seen in the underlying cost and emissions data for each fuel (see General Assumptions for the e-fuel modeling process and Fuel prices). With this in mind, the way a carbon price is implemented is highly relevant, because we assume decreasing costs and emissions for green fuels (leading to zero emissions for Green Fuels in 2050 (see Figure 3)). Thus, the dynamics between revenues from carbon pricing and green transition efforts can be described as non-linear.

Scenario design in a least-cost optimization framework

In this work, the SEAMAPS model[38] (for more details, see STAR Methods section) is combined with two carbon-pricing schemes (see Table 1) to identify different green transition pathways (Figure 5).

In Table 1, we show the two baseline scenarios. For the reference scenarios, which should serve as a proxy for a 1.5°C global warming emissions reduction pathway, we used two different interpretations of the 1.5°C global warming emissions reduction goal (Table 2). The scenario called ''1.5°C (Net Zero (NZ) 2050)'' is motivated by the IPCC narrative for a 1.5°C global energy system mitigation pathway. The scenario called ''1.5°C (NZ 2070)'' is motivated by the maritime mitigation pathway for a 1.5°C compatible world in the latest IPCC report.[20] The difference between the two scenarios thus lies in the level of detail for the sectoral mitigation pathway. Although ''1.5°C (NZ 2050)'' assumes the same mitigation profile for all sectors, regardless of the sector-specific mitigation challenges – which are significantly higher for maritime than, for

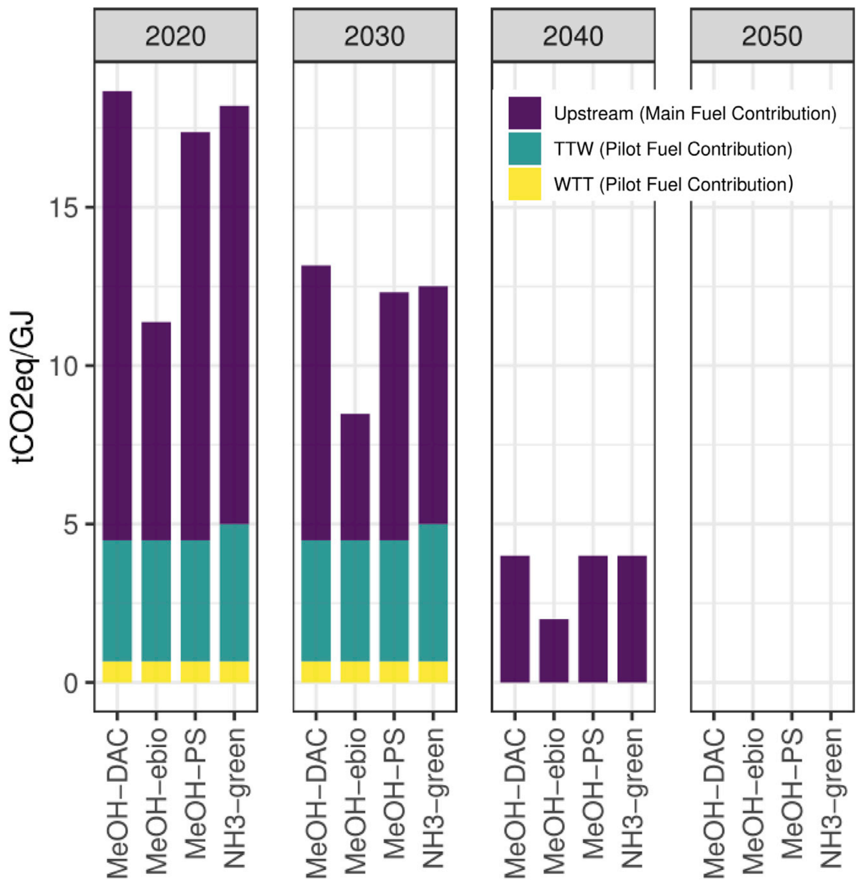

Figure 3. Emissions accounting for modeled green fuels blended with 5% pilot fuel (VLSFO in 2020/2030, DME in 2040/2050)

TTW: Tank to Wake (Pilot Fuel Contribution, (NH3 also includes boil-off-gases)); WTT: Well to Tank (Pilot Fuel Contribution). Upstream: emissions related to infrastructure (power supply, fuel plant, and storage systems). For more details, see Nami et al. 2021[26] and Franz et al. 2021.[38]

example, for light-duty vehicles[4]– the "1.5°C (NZ 2070)" scenario shows the shipping sector's emissions pathway set out by the IPCC to be in line with the Paris Agreement's goal of 1.5°C global warming.

Reaching Paris Agreement emissions reduction goals

When analyzing how far future fueling pathways and cumulated emissions are in line with the Paris Agreement, we find contrasting transition pathways and associated challenges toward climate mitigation. For Figure 4, we ran the SEAMAPS model several hundred times with different values for carbon-pricing and reductions in fuel demand. These fuel-demand reduction measures could include a change in the contractual design explicitly banning the logistic practice "steam fast, then wait," which incentivizes shipping companies to burn more fuel than necessary and thus emit up to 15% more globally scale.[42] Another significant fuel-saving potential lies in the fuel transition toward locally produced green fuels thus decreasing fuel trading volumes now accounting for 45% of global shipped trade by weight.[43]

Furthermore, measures could be related to improvements in engine design, ship design, hydrodynamics, and slow steaming in general.[3,13,44–47] Although carbon-pricing and reductions in fuel demand are only two possible measures, the magnitude of the challenge we are facing is evident. The ability to alleviate this involves reducing GHG emissions, including upstream emissions, and reducing the costs of green fuels, e.g., by accelerating the scaling-up of fuel production and the learning curves, thereby pushing down costs earlier. The reductions in fuel demand are implemented as a percentage reduction compared to SSP1 demand[29,48,49] in 2050 and are linearly interpolated. The reduction in fuel demand is spread over a time period of 30 years

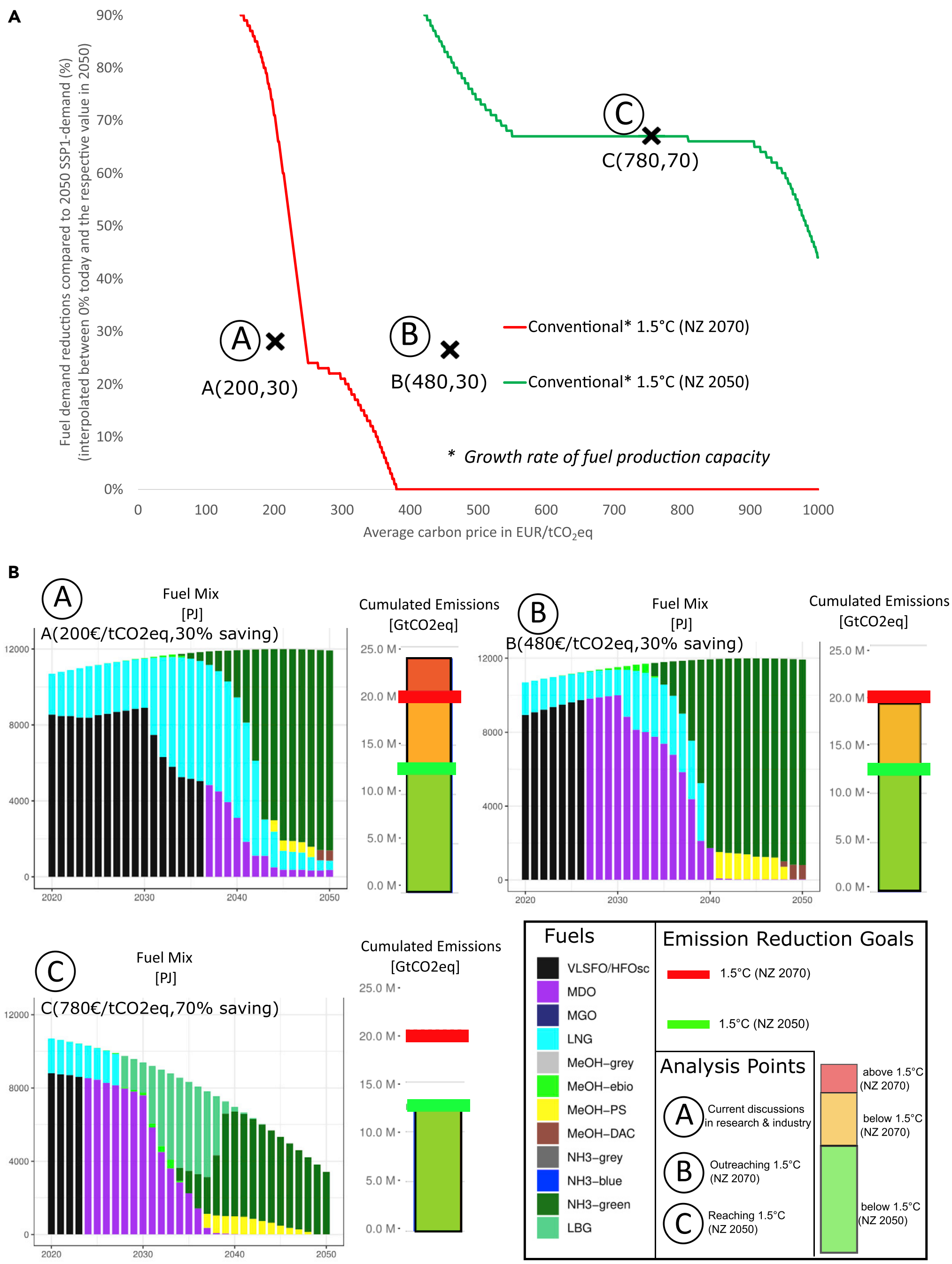

Figure 4. Global maritime mitigation pathways for certain levels of carbon pricing and fuel demand reductions

(A) solution space to reach Paris Agreement pledges.

(B) global maritime fueling pathways and cumulated emissions for certain combinations of carbon pricing and fuel savings.

(90% reduction compared to 2050 = 3% reduction per year compared to the SSP1 projection). Figure 4A shows the underlying interrelations between average carbon prices (x-axis) and fuel demand reductions (y-axis) for reaching either a 1.5°C (NZ 2050) or a 1.5°C (NZ 2070) emissions reduction target.

We find that achieving the maritime emissions reduction goals of limiting warming to 1.5°C (regardless of when we are predicted to reach net-zero) with a conventional growth in green-fuel production capacity of

Table 1. Scenario design of baseline scenario

Scenario Settings	Description
Carbon Pricing Scheme	Progressing Carbon Price ranging from 50EUR/tCO_2eq in 2020 to varying carbon pricing (xx-nn EUR/tCO_2eq) in 2050)
Scaling up Green Fuels	Conventional green fuel growth rate (50%/year) starting from 5PJ in 2020 and leading to exponential growth.[40,41]
Biomass Availability	Biomass Availability Constraint (x EJ in 2020 to n EJ in 2050) (see Figure 2)[38]
Fuel Demand	Shared Socioeconomic Pathway One (SSP1) - (IMO)[29]

50%[40] requires more ambitious policy action than the 200EUR/ tCO2eq currently discussed in industry and research.[5,6,14,16] In fact, in Figure 4A) we find that it either requires carbon-pricing beyond 300EUR/tCO2eq (on average within a 30-year horizon) and fuel savings of at least 30% in 2050 compared to SSP1 demand projections in 2050 , or carbon-pricing beyond 200EUR/tCO2eq but very ambitious fuel savings of up to 90% of total fuel demand in 2050.

To put the conventional growth (50% annual growth of electrolyzer capacity) of green-fuel capacity into context: historical solar PV capacity growth from 2009 to 2019 was between 24 and 89% per year, depending on the geographical region (low for EU, high for non-OECD); and historical wind-capacity growth from 2009–2019 was between 11 and 28% per year depending on the geographical region (low for EU, high for non-OECD) (BP, 2020). (For more details, see section 13 of the supplemental information, where we discuss different upscaling rates for capacities[50]) However, suppose it becomes more and more apparent that electrolytic green fuels are the only solution to achieving a green transition in hard-to-abate sectors. In that case, growth rates beyond solar PV growth, which at the time (2009–2019) was not and still is not the single option to invest in to generate renewable electricity, might be expected to meet or even to exceed the 1.5°C (NZ 2050) emissions reduction target.[50]

Assuming an unconventional growth rate (126% annual growth), which comes close to the diffusion speed of US nuclear weapons or World War II US aircraft,[40] a 1.5°C (NZ 2050) emissions reduction goal is achievable with average carbon-pricing levels beyond 350EUR/tCO2eq and no fuel savings or a combination of fuel savings and average carbon pricing of 300EUR/tCO2eq. A 1.5°C (NZ 2070) emissions reduction goal can be achieved with significantly less climate action, namely, average carbon pricing of 250EUR/tCO2eq alone, or average carbon pricing of 150EUR/tCO2eq and 80% fuel savings in 2050. (These findings can be seen in Exogenous Biomass availability scenarios in the Supplemental information.)

To model exponential growth in the availability of green fuels, we assume it will increase from today's value of around 5PJ[26,40,51] per year at a growth rate of 50% (conventional) or 126% (unconventional). We thus assume that green-fuel capacity starts growing once the fuel is being invested in. Using both conventional and unconventional growth rates shows the impact of increasing the speed of green-fuel production, yet this should not be interpreted as a maximum or minimum; rather, it should serve as a guide within a sustainable narrative (SSP1-type narrative).

Figure 4B shows three fuel mixes that are related to the marked points in Figure 4A. Point A marks the current discussion around fuel-demand savings and carbon pricing.[5,6,14–16] Point B exemplifies a fuel mix that is in line with the 1.5°C (NZ 2070) emissions reduction pathway, whereas point C shows a fuel mix that is just in line with the 1.5°C (NZ 2050) emissions reduction pathway. The future maritime fuel mix is based on the underlying carbon-pricing strategy. In the analyzed scenarios, we see many fossil fuels like VLSFO/HFOsc, especially LNG and MDO in the short to medium term. We identify green ammonia (NH3-green) as a predominant fueling option in the longer term. Above a carbon price of 300 EUR/tCO2eq, green ammonia becomes the cost-competitive fueling option and is thus utilized to a large extent.

Challenges and uncertainties regarding the operational feasibility of the fueling pathways described here exist in all scenarios. Yet, some fuels are more controversial than others. For example, blue ammonia (NH3-blue) could be used as a bridging fuel if it is considered to have a beneficial effect on global emissions compared to LNG[52,53] and is made available on a large scale. Green ammonia could potentially fuel significant parts of the future global fleet if the concerns raised regarding the safety of ammonia as a marine fuel are solved.[6,54] Ammonia is poisonous, explosive, and a potent fertilizer. Therefore, avoiding leakage into the air or the marine environment and ensuring its safe storage in harbors is essential. Furthermore, the indirect climate effects of hydrogen are starting to be discussed, not having been taken into account previously.[55] If they were, the arrow

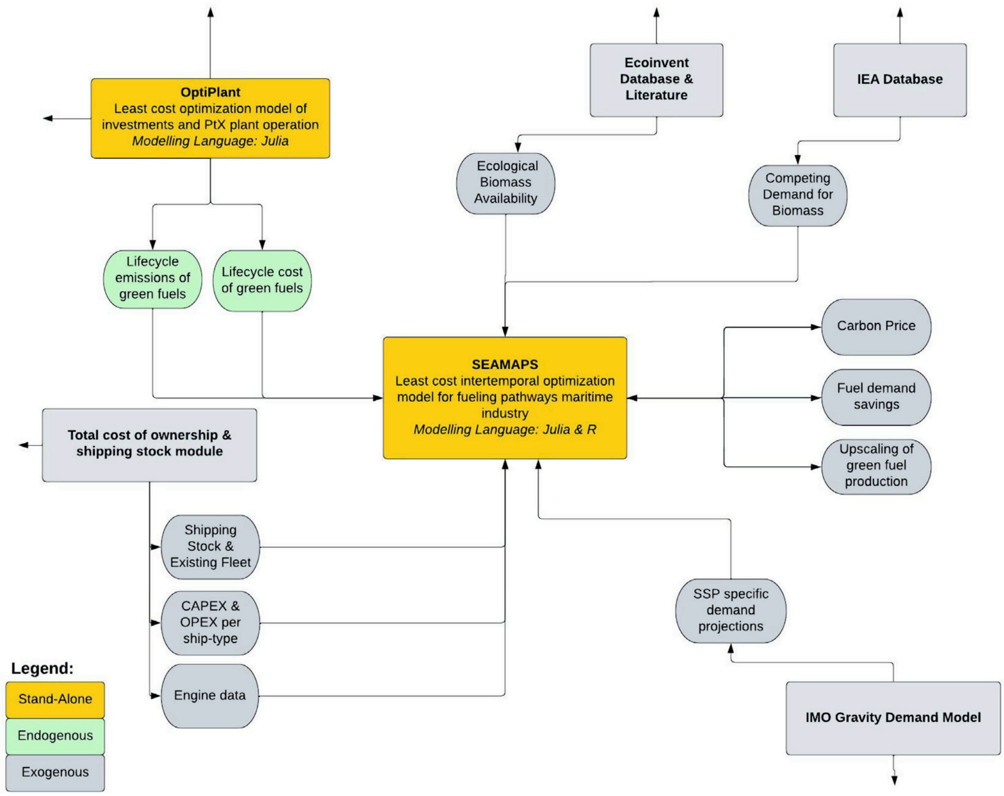

Figure 5. SEAMAPS modeling environment.

might point to fewer electro fuels and higher fuel demand savings. Similarly, discussions are ongoing concerning whether residual biomass can be considered CO2-neutral, which would push toward more electrofuels. However, if safety concerns can be solved in the years to come, green ammonia may become the dominant form of renewable energy and ultimately the dominant marine fuel.[56]

These levels of carbon pricing and fuel-reduction potentials diverge significantly from the findings of current research and industry reports.[5,6,14–16] This is because of our novel perspective on green fuels (including upstream emissions) and the optimization model's constraints on scaling up green-fuel production capacities. We performed a sensitivity analysis without these features and found that it is possible to reach net-zero by 2050 with a carbon price of less than 200EUR/tCO2eq and no fuel savings. However, the cumulated emissions will overshoot the defined 1.5°C emission reduction targets. This shows the weakness in using net-zero by 2050[35] as an emissions reduction goal since cumulated emissions, and thus a sectoral carbon budget, are more critical than evaluating the emissions at one specific point in time to avoid overshooting the Paris Agreement goals.[18] (true to the maxim, "sometimes it is more about the journey than the destination").

Limitations of the study

When modeling a global fleet of more than 60,000 vessels, including future fueling pathways, the development of certain technologies (e.g., CCS, DAC) and the availability of resources for the future, certain assumptions have to be made. In our case, the main assumptions are related to the cost development of green fuels and fossil fuels, the availability of biomass, and the growth of upscaling for specific technologies. In Figure 6, we show different sensitivity parameters that address the uncertainties with regard to the respective assumptions.

Figure 6 gives yearly emission profiles for different exogenous biomass availability scenarios and the main assumptions regarding fuel costs respectively. The underlying baseline scenario has been motivated by the current carbon pricing discussion (200EUR/tCO2eq)[5,6,15,16] and feasibility studies for fuel savings (30% by 2050).[3]

Table 2. Reference global warming scenarios in line with the Paris Agreement

Reference Scenarios	1.5°C (NZ 2050)	1.5°C (NZ 2070)
Short-Term GHG Emission Reductions	45% by 2030[19]	25% by 2030[20]
Reaching Net-Zero Emissions	100% by 2050[19]	100% by 2070[20]

One can see that different biomass availability scenarios do not necessarily change the emissions pathways significantly. The challenges of climate mitigation for the sector are slightly lower for the high biomass availability scenario because some biofuels like liquefied biogas (LBG) can serve as a bridging fuel in the early years of the modeled time horizon. However, this assumption has no significant impact, as biofuels are expected to increase in price significantly[28,31] in the future because of increased competition from other sectors, making them less likely to be used by the maritime sector.

Unlike biomass availability, the different pathways and learning rates included in the assumptions and modeling of green fuels and fossil fuels do have a significant impact on future mitigation challenges for the maritime industry. In Figure 6, it is evident that rises in fossil-fuel prices of up to 50% compared to the baseline prices in Figure 6 lead to lower emissions, as green fuels will become competitive earlier given the underlying carbon price. Following this argument, this effect could be expected to occur in the real world, given the rise in fossil-fuel costs in the present and the near past.[57] However, this effect also leads to a similar mechanism related to increased estimates of green fuel costs. In this case, the maritime industry's challenges regarding climate mitigation increase significantly.

Further research should focus on increasing the heterogeneity in different fueling pathways, both upscaling and emissions/cost-related. This feature could increase the level of detail significantly to allow us to draw a more precise picture of future fueling options. Furthermore, the perfect foresight constraint could be relaxed toward limited foresight by introducing rolling horizon investments. This additional feature would allow us to model the lock-in effects of specific fueling pathways, as we are now seeing long-term contracts in the maritime green-fuel supply.[58] Another interesting topic to look into would be detailed modeling of future fuel demand savings.[3] have already provided us with a sophisticated picture of possible fuel demand savings, suggesting that building on this work would be an interesting option. In addition to this, comparing the costs with the alternative use of fossil fuels offset by carbon capture storage (CCS) would be another exciting option to look at in further research.

Conclusion

This analysis has shown (1) that the Paris Agreement will not be met without significant improvements in fuel demand savings, and (2) that very high CO2 prices are required if this is the only measure implemented for achieving the Paris Agreement. It is also argued that policy options designed to ramp-up key technologies, such as electrolysis, thereby increasing the upscaling to unconventional growth levels, would assist the transition tremendously. If global CO2 prices cannot be implemented, standards or fueling mandates and other sticks could replace them. However, the difference in price levels between green and fossil fuels is still very high that efforts such as carbon pricing alone seem unrealistic. However, with the rising rivalry in the world and thus rinsing prices for fossil fuels one could expect lower challenges toward mitigating this sector.

With this in mind, one can see that the shipping sector is at a crossroads, and the coming years will be decisive for future challenges regarding climate mitigation. We find that achieving emission reduction goals in line with a 1.5°C (net-zero 2070) warming scenario given a conventional growth rate (50% per year) for the upscaling of green-fuel production capacities requires a progressive carbon price of 50EUR/tCO2eq in 2020 increasing to 550EUR/tCO2eq in 2050 and fuel savings of at least 30% in 2050 compared to an SSP1 demand projection. The maritime emissions reduction target for a 1.5°C (net-zero 2050) warming scenario requires even more ambitious carbon-pricing and fuel-savings measures. However, in line with,[59] we find that the future growth rate for scaling up green-fuel production capacities and the cost of green fuels are the most sensitive parameters for the future climate mitigation challenges of the shipping sector. They thus present a unique opportunity to bring the shipping industry onto a pathway that observes the 1.5°C (net-zero 2050) global warming emissions reduction goal.

These findings highlight the importance of acting now because of the long lifetimes of existing vessels in the next decade to prevent an overshoot of the 1.5°C emissions reduction goal. We know from global energy

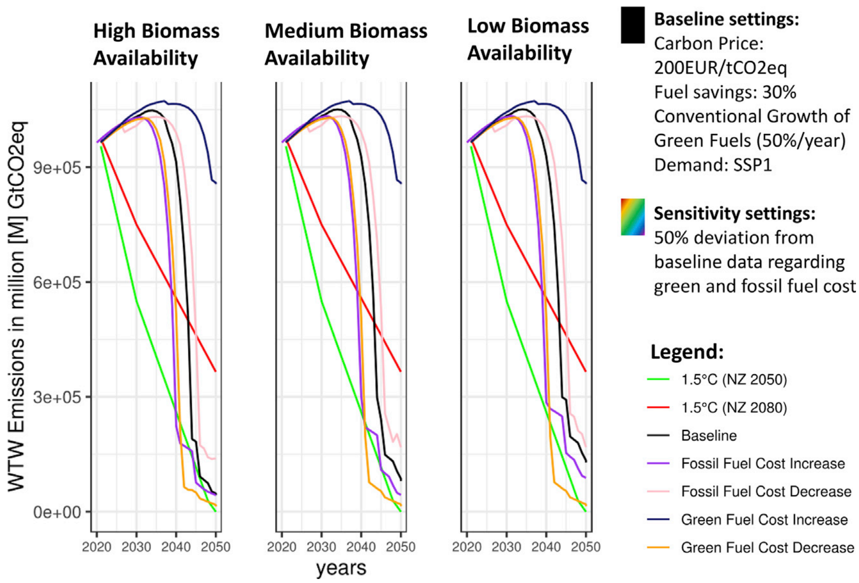

Figure 6. Sensitivity Analysis for main assumptions of the modeling approach

system analysis that immediate climate action can limit global warming to well below 2°C.[60] These quick climate actions should start now to ensure a green transition of the hard-to-abate sector[61] that is international shipping.

With the indicated levels of carbon pricing, fuel savings and growth rates for upscaling green-fuel production capacities, a shipping industry in line with the Paris Agreement is theoretically achievable. However, it requires a lot to reach the indicated levels of the respective instrument for a green transition pathway, e.g., technological progress and fuel demand savings (further development and investments in green-fuel production capacities, alternative engines, renewable/clean energy, and fuel savings in general), regulatory changes (uniform WTW emissions accounting standards, long-term sustainable fuel directives, new contractual designs[42]), and policy actions (ambitious carbon-pricing pathways and uniform expectations across stakeholders to drive investments in green technologies). Thus, the focus of the future climate policy for the maritime industry should be on accelerating the upscaling of green fuels, incentivizing green fuels, and enabling fuel savings as fast as possible, especially because the expected emissions in the next ten years will make it hard to get into line with the Paris Agreement given the limited amount of green fuels available. Now is the time to start a holistic transformation of the maritime industry to pave the way for a sustainable maritime future.

STAR★METHODS

Detailed methods are provided in the online version of this paper and include the following:

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- RESOURCE AVAILABILITY
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- METHOD DETAILS
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- QUANTIFICATION AND STATISTICAL ANALYSIS

SUPPLEMENTAL INFORMATION

Supplemental information can be found online at https://doi.org/10.1016/j.isci.2022.105630.

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AUTHOR CONTRIBUTIONS

S.F., R.B., N.C., and M.M. designed the study. S.F. performed the analysis, designed, and produced the figures, and wrote the manuscript with input from all co-authors.

DECLARATION OF INTERESTS

The authors declare no competing interests.

INCLUSION AND DIVERSITY

We support inclusive, diverse, and equitable conduct of research.

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STAR★METHODS

KEY RESOURCES TABLE

REAGENT or RESOURCE	SOURCE	IDENTIFIER
Deposited data		
GitHub repository with SEAMAPS code and data	This paper	https://github.com/SebastianFra/SEAMAPS
Software and algorithms		
Julia	The Julia Programming Language	https://julialang.org/

RESOURCE AVAILABILITY

Lead contact

Further information and requests for resources and reagents should be directed to and will be fulfilled by the lead contact Sebastian Franz (semfr@dtu.dk)

Material availability

This study did not generate new unique reagents.

Data and code availability

- All data have been deposited on our GitHub repository (https://github.com/SebastianFra/SEAMAPS) and are publicly available as of the date of publication.
- All original code has been deposited on our GitHub repository (https://github.com/SebastianFra/SEAMAPS) and ist publicly available as of the date of publication
- Any additional information required to reanalyze the data reported in this paper is available from the lead contact upon request.

METHOD DETAILS

Our least-cost optimization model is called "SEAMAPS".[62] SEAMAPS combines the transparency of emissions along the entire supply chain of green fuels, the constraints of upscaling green-fuel production capacities, representation of biomass availability, the emission reduction goals motivated by Paris Agreement narratives, decision modeling based on least-cost optimization, and the introduction of two dimensions of climate action (carbon-pricing and fuel savings) to understand the dynamics and challenges of climate mitigation. SEAMAPS is written in the mathematical programming language Julia and uses mixed-integer linear programming; its computing time for the analyzed set of scenarios is below 1 min (used solver: Gurobi), and all data and code are available as open source.[62]

In Figure 5, we show the modelling environment of SEAMAPS. It consists of multiple endogenous and exogenous data inputs.

The basic idea behind this model is least-cost optimization, which is used as the objective. The overall goal is to obtain the least-cost fueling options for the maritime industry. To achieve this, the objective function is minimized. The components of the objective function can be divided into two main parts, one which concerns all costs related to the fleet itself, including the investment costs for additional vessels, operations and maintenance costs. The second cost block is limited to fuel costs. The consumption of each vessel in the fleet is multiplied by the fuel costs (including fuel taxes, if any).

The objective function looks as follows:

$$min_{\partial,\beta,\theta,\varepsilon} \sum_{s,y} \pi_s * NB_{s,y} + \gamma_s * SS_{s,y} + \pi_s + \sum_{s,f,y} F_{f,s,y} * \left(\vartheta_{f,y} + \mu_{f,y}\right) \quad \text{(Equation 1)}$$

Where π_s is the investment expenditure for a new build (average) vessel of type s, $NB_{s,y}$ is new built ships of ship-type s in year y, γ_s is the operation and maintenance cost for a vessel of type s, $SS_{s,y}$ is ship-stock of ship-type s in year, $F_{f,s,y}$ is the amount of fuel used per fuel-type f, ship-type s and year y, $\vartheta_{f,y}$ is the fuel cost per fuel type and year,and $\mu_{f,y}$ is the fuel tax added on top of fuel cost.

Additional constraints are added to adapt the future fuel mix to the future climate mitigation challenges of this hard to abate sector.

The most relevant constraints of the SEAMAPS model are described in the following:

Transport demand

$$\forall_{sc,y} \; ; \; D_{t,sc} \; = \; \sum_{s} SS_{s,y} * \rho_{s,y} * \beta_{sc,s} \qquad \text{(Equation 2)}$$

This constraint limits the supply in the SEAMAPS model to the exogenous demand projections of the IMO[29]($D_{t,sc}$). We use an SSP1[48]-type demand. This ensures that supply and demand are matched and that there is no excess demand or supply in the model that could distort the results. It is important to note that the IMO demand has a strong influence on the results of the future fuel mix and that this variable might have to be replaced by endogenous demand projections in the future to create a more inherent modelling process. $SS_{s,y}$is the stock of ships s at year y, $\rho_{s,y}$ the average transport work of ship s in year y. $\beta_{sc,s}$ is a matrix relating the ship category (container, tanker, bulk, cargo, other) and the shiptype (ship category associated with a specific engine).

Fuel consumption

$$\forall_{s,y} \; ; \; \sum_{f} F_{f,s,y} * \; \alpha_{f,s} = SS_{s,y} * \; \rho_{s,y} \qquad \text{(Equation 3)}$$

The amount of fuel used by ships of type s in year y must be enough to satisfy the transport demand. The transport demand of the fleet of ships of type s is equal to the ship stock of that type (the number of ships of type s in the fleet) multiplied by the average transport work. The fuel consumption is calculated using the specific fuel consumption per fuel type and shiptype, $\alpha_{f,s}$. Any kind of fuel can be used to satisfy the demand, meaning that more than one fuel type can be used in the same year if the engine is a dual/multi-fuel engine.

Fuel availability

$$\forall_{f,y} \; ; \; \sum_{s} F_{f,s,y} \leq \omega_{f,y} \qquad \text{(Equation 4)}$$

For all fuels and all years, the amount of fuel used for the whole shipping fleet cannot exceed the fuel available, which is represented by $\omega_{f,y}$.

Upscaling green-fuel production capacities

$$\forall_{f,y} \; ; \; \rho_{f,y} \; = \; \rho_{f,y-1} * \tau \qquad \text{(Equation 5)}$$

For all fuels and all years, the available fuel $\rho_{f,y}$ is equal to the previous year's fuel availability multiplied by τ, which represents the expected yearly growth of green-fuel production capacities. This constraint is implemented in a way that the upscaling only starts once the model invests in the respective green fuel for the first time.In this study, we test different growth rates for the upscaling of green-fuel production capacities. Thus, we assume a conventional growth of 50% per year and an unconventional growth of 126% a year over 30 years (see Table 1). These two slopes have been motivated by diffusion speeds of historical solar PV growth and wind turbines for the case of conventional growth and the diffusion speed of US nuclear weapons and US aircraft during World War II for the case of unconventional growth.[40]

QUANTIFICATION AND STATISTICAL ANALYSIS

This study did not use any specific tools.

Paper III

Should Residual Biomass be used for Fuels, Power and Heat, or Materials? Assessing Costs and Environmental Impacts for China in 2035

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Should residual biomass be used for fuels, power and heat, or materials? Assessing costs and environmental impacts for China in 2035†‡

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Limiting global temperature changes under 2 °C in comparison to pre-industrial levels has been shown as crucial to sustain life on Earth; a central implication being to mitigate greenhouse gas emissions. Residual biomass is a valuable resource, that can replace greenhouse gas intensive fossil fuels. This study assesses large-scale scenarios for utilizing crop and forestry residues, animal manure, food waste, and sewage sludge from a system perspective, and simulates impacts to interrelated electricity and heating systems. The scenarios cover production of biofuels, electricity and heat, as well as materials and feed. Dynamic energy prices and marginal emissions are based on modeling the Chinese energy system towards 2035 in a partial equilibrium linear optimization model, optimizing investments and operation as well as electricity trade and transmission between regions. The resulting marginal emissions and system costs quantify impacts specific to the modeled Chinese energy system in 2035. Scenario costs are assessed including monetization of environmental impacts which were addressed based on a life cycle approach to reflect impacts on global warming, air pollution, marine- and freshwater eutrophication. The study finds that there are major benefits to utilizing residual biomass in all impact categories. Nitrogen leaching was found to pose the largest economic impact. The study furthermore shows that when comparing the climate impact of biomass use scenarios, it is important to include biogenic carbon as well as case-specific marginal emissions.

Broader context

Residual biomasses are valuable readily available carbon sources, which can replace fossil fuels. However, quantities are limited and their use are associated with different environmental and economic impacts. This work incorporates both economic and environmental aspects by combining energy system analysis and life cycle assessment to assess environmental impacts and costs from utilizing residual biomass. A life cycle view of greenhouse gas emissions, including biogenic carbon, as well as eutrophication and air pollution impacts is included. The system perspective enables an illustration of synergies between sectors using a partial equilibrium linear optimization model to optimize investments and operation of the electricity and district heating sectors. The work shows that using specific marginal energy mixes and emissions provide a detailed picture diverging from results using values common in best-practice life cycle assessments. Additionally, the work proves that the common practice of disregarding biogenic carbon emissions in energy system analysis is problematic as these have a great impact on results. The effects are proven on a large-scale as the study is applied to China year 2035 with regional assessments on provincial level.

Introduction

The world is facing severe challenges in terms of reducing human induced climate change.[1] At COP26, the importance of decreasing methane emissions was highlighted, illustrating the need to broaden the focus from fossil CO_2 alone. Limiting the use of fossil fuels is however still imperative. Fossil fuels are primarily used for energy purposes and 73% of global greenhouse gas (GHG) emissions can be attributed to the energy sector,[2] making the energy sector the cornerstone to addressing

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‡ Supplementary information available at DOI: 10.6084/m9.figshare.17143151

global warming. Biomass is a readily available renewable energy source, which can replace fossil fuels. The use of biomass may however result in other undesired environmental impacts. This may *e.g.* relate to particle emissions from traditional use of bioenergy for cooking and heating.[3] Another consequence may be loss of biodiversity. Due to competition for arable land, residual biomass has received particular attention in recent years, *e.g.* ref. 4–6. Yet, this does not imply that its use is always free of environmental and economic consequences.[7,8]

The Planetary Boundary Framework was introduced in 2009 to define key processes which impact global sustainability.[9] Here climate change was identified as one of the nine interlinked boundaries used to describe the limits within which humanity can function without surpassing the tipping points of the Earth system. The framework shows increasing risk of surpassing these tipping points for climate change and land use changes, but even higher risk for exceeding these boundaries when it comes to biosphere integrity (earlier called biodiversity loss[10]) as well as for nitrogen and phosphorous flows. Analyses of future uses of biomass should therefore go beyond climate change and take these aspects into account.

Energy system analysis uses models to simulate or optimize scenarios of current and future energy systems in order to generate insights for decision-makers. A system perspective enables a detailed representation of the energy avoided and substituted in different scenarios. This enables assessing the optimal resource allocation by integrating different sectors and capturing co-benefits, for example by showing how the value of a resource depends on in which energy system it is used.[11] In energy system analysis, GHG emissions have been limited to those of the conversion process itself, and often to fossil CO_2 only, as noted in for example Zappa *et al.*[12] A review of 1184 articles dealing with climate mitigation and energy systems shows no explicit breakdown of GHG emissions or how these are accounted.[13] Efforts have been made to expand the scope of GHG emissions and sources, for example in Venturini *et al.*[14] where land use change for primary biomass resources as well as methane emissions are included. However, even here, not all main GHG emissions are accounted for, and the GHG emissions induced or prevented as a consequence of implementing the process studied are disregarded (with the notable exception of land use changes). Biogenic CO_2 has often been disregarded, on the premise it is neutral, because the biomass simply releases the carbon it absorbed at the first place.[15] Yet, this shortcut has been repeatedly shown as flawed since this implies that no global carbon consequences can be assigned to biomass diversion for bioenergy use.[15–17]

Studies focusing on bioenergy and GHGs typically have a static view of the surrounding energy system with fixed annual values for energy avoided. This neglects capturing dynamic system aspects including the benefits of sector coupling and flexible consumption/production. One example is the study of Bentsen *et al.*[18] which assumes that the use of biomass for heat or power displaces natural gas heat and coal electricity. The study concludes that biomass utilization should be focused on residual biomass, be diversified and not overexploited, a conclusion that is also re-iterated in recent studies.[19] Similarly, Liu and Rajagopal,[20] besides illustrating the importance of including biogenic CO_2 emissions when assessing the use of residual biomass for energy purposes, also highlighted the inclusion of air and water quality impacts as important next steps. Liu and Rajagopal[20] use historical data on grid mixes for displaced electricity and natural gas for displaced heat, concluding that the impact from the displaced products is key when assessing optimal use of residual biomass. In a Chinese context, recent studies by Nie *et al.*[21] and Kang *et al.*[22] have simulated the potential of bioenergy to reduce GHG emissions. These do not take competing nor existing uses of residual biomass into account, as performed for example by Zhang *et al.*[23] for food waste. Common for those studies were however the static view of the avoided energy. This disregards the dynamic properties of the energy system, which are increasingly important with rising levels of inflexible renewable energy production.

This static view of not considering the site-, time- and condition-specific dependencies associated with the type of bioenergy to be integrated into the energy system at a given time and place is the common practice used in state-of-the-art environmental assessments, including life cycle assessments (LCAs). For example, Tonini *et al.*[6] made the generic consideration that coal-fired power plants (and only these) would react to a demand change in electricity from Denmark (scope 2015–2030), on the basis that this technology is the least competitive within the framework of political CO_2 reduction targets. In recent years, the widely used Ecoinvent life cycle inventory database supplied so-called consequential processes.[24] For electricity, forecasts based on prospective scenarios are used to derive marginal electricity mixes, as described in Vandepaer *et al.*[25] Albeit this is a significant improvement to the earlier normative approach, it is still disconnected from the interactions induced by the specific biofuel being integrated in the energy system.

To sum up, previous studies have shown the importance of assessing the consequences of bioenergy from residual biomasses, and taking into account (I) energy system integration and (II) environmental impacts encompassing life cycle GHG emissions including biogenic emissions and non-GHG emissions. Adding to this, as residual biomass resources are limited, (III) the impacts of both existing and competing uses should be included. As something novel, this study combines the strengths of energy system analysis with the strength of LCAs and a strategic bio-resource assessment to assess the consequences of the use of residual biomass at a country scale.

China is currently the most populous country and largest GHG emitter.[26] China's commitment to the Paris Agreement was recently confirmed with a new target for carbon neutrality by 2060.[27] The International Energy Agency highlighted the importance of this target, stating that China will play a major role in reaching the Paris Agreement.[28] With the long-term carbon neutrality target in mind, 2035 has been identified as an intermediate target year towards realizing the political vision of building a Beautiful China.[29] Part of this vision is reducing particle emissions, where there is a strong focus.[30,31] On a per capita basis China is not rich in biomass.[32,33] China is therefore an interesting case, when comparing environmental impacts of different utilizations of residual biomass.

We propose a stepwise approach including (Step 1) an assessment of residual biomass potential, (Step 2) the definition of biomass scenarios and associated electricity demand and heat production, (Step 3) modeling of the scenarios identifying dynamic electricity and heat prices, and finally (Step 4) the quantification and analysis of overall resulting energy, economic, and environmental impacts. The purpose of the contrasting scenario designs is to quantify impacts related to competing uses, rather than finding an optimum. The methodology developed in this study is applied to China as a case, which allows demonstration of large-scale implications of choices when it comes to the use of residual biomasses with a focus on energy. This study presents and demonstrates a methodology to assess the national performance of future scenarios for utilization of available rural and urban residual biomass resources by considering socio-economic costs, and key environmental impacts in 2035.

The aim of the study is to improve the state-of-the-art of (1) energy system analysis with biomass utilization by including a life cycle perspective and by representing biogenic carbon flows, non-CO_2 GHG emissions as well as key flows related to air and water quality impacts (2) LCA and socio-economic cost analysis by using dynamic energy system analysis to improve the accuracy of prospective background energy data in LCA and by including marginal emissions and energy prices in future scenarios and (3) strategic bio-resource assessments by including competing and existing use of biomass resources.

Methodology

The methodology consists of a four-step approach starting with a resource assessment and projections to define available residual biomass resources by 2035 (Step 1), followed by a formulation of scenarios for resource utilization (Step 2). Thereafter energy, economic, and environmental impacts are modeled and results are analyzed and discussed (Steps 3 and 4).

Resource availability, current uses, and projections

Step 1: The following five residual biomass streams are considered to present a comprehensive view of the most relevant available residual biomass resources in China: crop residues (CR), forestry residues (FR), animal manure (AM), food waste (FW), and sewage sludge from wastewater treatment (SS). While CR, FR, and AM are acknowledged to have a high potential in China[22,34,35] and in the broader bioeconomy,[36] improved SS management would result in substantial environmental impacts[37] and utilization of FW has a high political priority as well as energy system benefits (*e.g.* increasing calorific value of mixed municipal solid waste making it more suitable for incineration).[38] A two-stage procedure was used to derive available potentials for 2035. First, near-term data to quantify the current availability of these bioresources were collected in the literature, drawing essentially from official governmental data as well as from the scientific literature. The resource availability has been assessed at the regional level for China's 31 provincial level administrative divisions; Taiwan, Hong Kong, and Macao are excluded due to limitations in main data sources. The assessed quantities correspond to what Batidzirai *et al.*[39] defined as the ''ecologically sustainable potential'', namely the fraction available considering both current technological and technical constraints, as well as restrictions related to environmental protection. For example, for CR, it consists of the technically collectable available resources, where environmental sustainability constraints regarding erosion control and nutrients cycling in agricultural soils are considered, but do not include economic feasibility of how much of the available potential could reasonably be utilized. The second stage consisted to project these near-term ecologically sustainable potentials to 2035 (see supporting information section 1 on methodology and details), and to these an additional constraint to reflect economic feasibility is added, here considered as shares to apply on the projected potential to determine the final actual availability (Table S21, ESI†). The remaining portion (ecologically sustainable potential minus economic potential) is considered non-collected for utilization, and is, from this point onwards, referred to as the ''unutilized'' share. Both the utilized and unutilized shares are considered in all scenarios, meaning that the same resource quantities, specified in step 1, are considered in all scenarios.

Scenarios

Step 2: To illustrate the effects of different uses of residual biomass, four extreme scenarios are defined: (I) reference attempting to reflect a situation where residual biomasses are either not collected or minimally managed, (II) combustion where biomasses are either combusted directly in biomass plants or indirectly after being anaerobically digested to produce biogas; this reflects the prevailing current modern energy use, (III) green fuels where residual biomasses are used for biomethane and jet fuel production to enable substitution of fossil fuels that are difficult to replace and (IV) materials where non-energy uses are exemplified by using residual biomasses to produce building materials, fertilizers, and feed. See Fig. 1 for an overview of the scenarios, main technological conversion pathways considered per resource and scenario, and outputs. The three scenarios with product outputs (II, III, and IV) are from this point on referred to as utilization scenarios.

Biogas is generated from AM, FW, and SS in the two energy scenarios: Combustion and Green Fuels. Anaerobic digestion is chosen as the conversion technology for AM, SS and FW as the technology is well proven and there is a high prevalence of Chinese anaerobic digestion pilot projects and planned treatment facilities.[23] While biogas is combusted in either power only or combined heat and power biogas engines in the Combustion scenario, it is upgraded to biomethane in the Green Fuels scenario, where the share of CH_4 content of the gas is increased to approx. 97%, based on the Wobbe index of

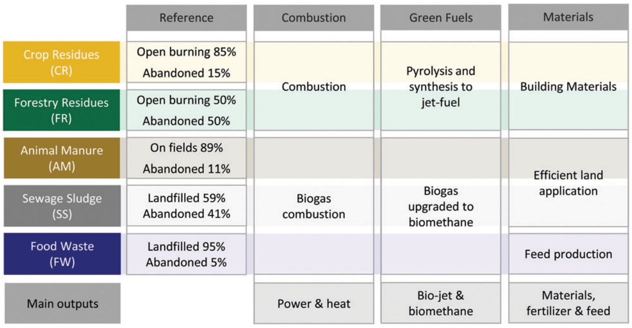

Fig. 1 Overview of scenarios showing the use of different residues and main outputs, see Fig. S1 (ESI†) for full system boundaries considered.

the gas currently supplied in the gas grid, among others.[40] This upgrade can be done by either removing the CO_2 content and contaminating gasses or by methanation of the CO_2 in the biogas with hydrogen.[41] In this study, half of the biogas is assumed upgraded through CO_2 removal and the remaining half is upgraded through methanation. All biomethane produced is assumed to substitute fossil natural gas.

The Combustion and Green Fuels scenarios also differ in how the CR and FR are used. In the Combustion scenarios, these are combusted in heat only boilers, condensing steam turbines for power only generation or in extraction steam turbines in cogeneration plants. For the Green Fuels scenario, there are numerous options for producing hydrocarbon fuels from these biomasses, which can directly replace fossil counterparts.[42] Pyrolysis and hydrothermal liquefaction (HTL) are two processes to convert dry and wet biomass to liquid fuels (bio-oils). Both options convert biomass to oil, char, and gaseous fractions. HTL has the benefit of being suitable for wet biomass fractions and potentially at high efficiency rates. However this is a novel technology with very high cost.[43] Pyrolysis has a higher technology readiness level than HTL and is hence used in this study as a representative of bio-oil production in 2035. Pyrolysis produces a stable biochar, allowing a long-term carbon sequestration and enabling negative carbon emissions.[44] In this study, gas and oil fractions from pyrolysis are reacted with hydrogen in a methanol synthesis process and upgraded to bio-jet,[45] see Table S1 (ESI†) for costs and efficiencies. Jet fuel is chosen as an output fuel as it is serves a transport demand that is forecasted to increase and is difficult to electrify.[46]

The hydrogen demand for methanol synthesis and biogas methanation processes in the Green Fuels scenario is generated through alkaline water electrolysis. The electricity demand to this end is based on efficiencies listed in Table S1 and electrolysis capacity assuming 4000 full load hours. Hydrogen storage is assumed to balance daily production, being loaded 12 hours per day. Hydrogen storage capacity, H_{2SC}, is set by electrolysis capacity, ELC, in MW, and h, hours storage per day, as well as efficiency of electrolyser in hydrogen output per electricity input, η, as shown in eqn(1) (quantified using parameters presented in Table S1, ESI†).

$$H_{2SC} = \mathrm{ELC} \times h \times \eta \quad (1)$$

Surplus heat is extracted from methanol synthesis, electrolysis, and methanation processes and made available for urban district heating networks.

The Materials scenario illustrates competing non-energy uses of residual biomasses. Here CR and FR are used as long-lasting building materials. More specifically, CR is used to produce plant fiber blocks for insulation in buildings as a substitute for fiberglass, based on Revuelta-Aramburu *et al.*[47] FR is used to produce engineered wood flooring and substitutes ceramic tiles, as described by Geng *et al.*[48] For AM and SS, the Materials scenario considers their use as fertilizers, through non-excessive application on land, resulting in 35% of nitrogen (N) and 3% of phosphorous (P) being lost in water. Here it is assumed that all N and P that is not lost in water replace corresponding mineral N and P fertilizers. FW is used to produce animal feed through insects: FW is fed to black soldier fly larvae/prepupae and subsequently converted into black soldier fly meal, which can be used for feed, hence replacing marginal feed and avoiding the land use changes resulting from additional feed demand (see Section 2b for details, ESI†). Finally, in the Reference scenario, the use varies by resource and is specified in Fig. 1. For all resources a share is abandoned, meaning that it is dumped on land or in waterways for no further use. Both CR and FR are either burnt openly or abandoned. Open burning results in significant $PM_{2.5}$ emissions[49,50] as well as some CO_2e emissions.[51] Abandoned CR is left on land and 4.3% of the carbon is assumed to be sequestered. For abandoned FR left on land, 5% of the carbon is assumed to be sequestered and 10% of the remaining carbon to be lost as CH_4.[52] The field application of AM in the Reference scenario is assumed to be inefficient with high nutrient losses due to over-application, resulting in 55% N and 11% P lost in water.[53] For abandoned AM, half is assumed to be dumped in waterways and half on land, resulting in both GHG emissions as well as N and P losses as specified in Section 2c of ESI.† In the Reference scenario, FW is not sorted from mixed municipal waste, but is landfilled together with mixed waste. The abandoned FW is assumed to be left in unauthorized dumpsites and is modeled as a simple landfill. Abandoned SS is assumed to be discharged in waterways while landfilled SS is modeled as a sanitary landfill. See Section 2c of ESI† for details on all uses in the Reference scenario. All scenarios except the Reference involve an "unutilized" share of biomass. This share is considered to be managed in the same way as in the Reference scenario.

Modeling framework

In the final steps, the energy, economic, and environmental aspects are combined. To this end, a spreadsheet tool, Bio3E, was developed. Bio3E first models the four scenarios defined in Step 2, with the final endeavor to quantify the project costs incurred, societal costs, and selected environmental impacts. The Bio3E tool, is soft-linked to an Electricity and District heating Optimization model (EDO) which enable a detailed representation of future heat and electricity production in China, and how these are affected by the residual biomass scenarios, as illustrated in Fig. 2. Residual biomass resources

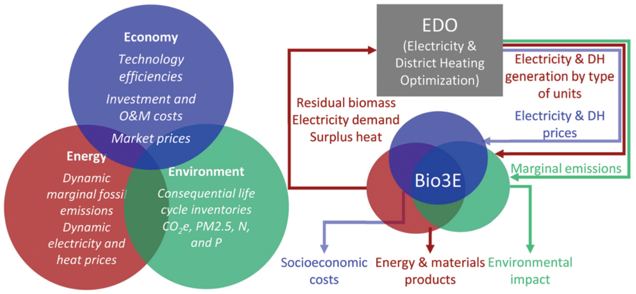

Fig. 2 Conceptual illustration of the Bio3E model (left; available as Excel spreadsheet in the data repository material) and overview of the link to the electricity and district heating optimization model, EDO (right).

(Step 1), quantified additional electricity demand, and surplus heat production from the scenarios (Step 2) are provided from Bio3E to EDO on an annual level for each province. Here the electricity and district heating production is optimized to minimize costs and fulfill future heat and electricity demands (Step 3). The output from EDO provides dynamic electricity and district heating generation by type of unit and fuels, prices as well as marginal CO_2 emissions (not CO_2e) from the supply of these two energy services. Marginal emissions are those from the plants operating at the margin.[54] Results from EDO in sub-daily time steps are aggregated on annual level for year 2035. Bio3E uses the output from EDO as an input to calculate the resulting socio-economic costs (Step 4a) and environmental impacts (Step 4b) from the energy and material uses of the residual biomasses for each scenario.

Step 3: The electricity and district heating optimization model (EDO) is built on the Balmorel model[55] and is used by the Energy Research Institute of the National Reform and Development Commission to supply annual renewable energy and energy transformation outlooks for China. EDO is a partial equilibrium linear optimization model minimizing costs, while meeting electricity and heating demand. The model represents current dispatch in China at provincial level and is subject to a number of constraints, for example on fuel availability, generation and transmission capacity. Investments are optimized using myopic foresight within a year.

The input data used in the EDO is based on the CREO2020 Below 2 °C Scenario with the same capacity investments constraints regarding CAPEX, O&M, fossil fuel costs, and construction pace.[56] For the Combustion scenario, the resources defined in Step 1, as well as reduced municipal solid waste quantities available for incineration following sorting of food waste in the three utilization scenarios, are fed into EDO on provincial level. A constraint is implemented in EDO for the Combustion scenario, stipulating that all CR, FR, and biogas from AM, SS, and FW must be utilized. In the Green Fuels scenario, the additional electricity demand for electrolysis and methanation is entered as a flexible demand on provincial level. This entails electricity consumption being moved in time, typically from peak-hours to off-peak hours, providing flexibility to the energy system. Flexibility benefits include allowing for additional integration of variable renewable energy and reducing need for peak capacity investments. The flexibility of electricity demand for electrolysis units is modeled as equal to 12 hours per day, which represents the scale of the hydrogen storage assumed necessary for methanation. The surplus heat from methanol synthesis and methanation (in the Green Fuels scenario) is added with a flat supply profile, using the same level for all hours. Surplus heat from electrolysis, on the other hand, is linked to the electricity demand profile as this makes up 99% of electricity demand. Neither surplus heat utilization options are associated with any cost.

Step 4a: Residual resource costs are limited to costs associated with collection and transportation of residues, as detailed in Table S4 (ESI†). These are the total costs for CR and FR while costs for biogas from AM, FW, and SS is calculated in Bio3E using data listed in Table S1 (ESI†) and methane yields are detailed in Section 2 of ESI.† These resource costs are used as input in both EDO and Bio3E. The outputs of EDO are fed back to Bio3E to calculate costs on a levelized cost basis and compare the different scenarios. Electricity and district heating prices are calculated in EDO for each scenario (Fig. 2) and used in Bio3E to assess the cost for hydrogen production and revenue from district heating utilization (Green Fuels scenario). The socio-economic cost for electricity and district heating investments and operations are imported from EDO to Bio3E and the difference between the scenarios are calculated in Bio3E. Investment costs for anaerobic digestion, biogas upgrading through CO_2 removal and methanation, electrolysis, hydrogen storage, pyrolysis, and methanol synthesis of pyrolysis gas are annualized using a discount rate of 5.9%, the rate used in CREO2020.[56] Levelized costs are calculated using the investment cost (IC) and discount rate (DR) and project lifetime in years (y), see eqn(2).

$$\frac{\left(\frac{\mathrm{IC}\times\mathrm{DR}}{1-(1+\mathrm{DR})^{-y}}\right)+\mathrm{O\&M}}{\text{Produced product}} \qquad (2)$$

Externality costs represent the overall economic cost resulting from the emission of one additional unit of pollutant. Quantifying externality costs entails putting a price on biophysical emissions, and is associated with high degree of subjectivity. For instance, recent estimates quantified the societal cost of CO_2 to range from 65 to 6500 RMB per t CO_2.[57] In this study three levels and methods are considered, see Table 1. The first being societal cost based on

Table 1 Overview of externalities costs for carbon dioxide equivalents (CO_2e), fine particulate matter ($PM_{2.5}$), nitrogen (N), and phosphorus (P) in renminbi year 2019 (RMB_{2019})

	Societal cost (base)	Tax (used in sensitivity analysis)	Alternative societal cost (used in sensitivity analysis)
	RMB_{2019}/kg	RMB_{2019}/kg	RMB_{2019}/kg
CO_2e	2.92[e]	0.13[d]	1.05[f]
$PM_{2.5}$	228[c]	2.62[b]	Base cost used
N	368[a]	1.88[c]	28.7[f]
P	1085[a]	6.02[c]	239[f]

[a] Jinxiu *et al.*[59] [b] Hu *et al.*[60] [c] Wang *et al.*[61] [d] Projected CO^2 cost for 2035 from Slater *et al.*[62] [e] Ricke *et al.*[57] [f] Pizzol *et al.*[58]

Chinese assessments of societal costs, the second being the tax levels, *i.e.* the upfront costs for discharging pollutants, and the third being an alternative assessments of societal costs by Pizzol *et al.*[58] The first method is here used as baseline (base) while the two latter are considered in sensitivity analyses.

Step 4b: The quantification of the environmental impacts related to the four scenarios is, unlike classic energy system analysis, based upon life cycle principles. Concretely, this implies that (I) not only fossil CO_2 emissions are taken into account, but also the two other well-mixed GHGs (namely CH_4 and N_2O). It also involves the inclusion of selected non-GHG substances flows, namely particulate matter ($PM_{2.5}$), nitrate losses to water (NO_3^-) and overall phosphorus losses to water are included, see Table 2. Using LCA principles also implies that (II) not only the emissions occurring during the conversion processes are considered, but also those of upstream (*e.g.* transport) and downstream (*e.g.* digestate management) processes (Fig. S1 and Tables S2, S5, ESI†). Moreover (III), the avoided emissions resulting from the numerous services displaced with the final products are accounted for (from the avoided fossil-based kerosene for aviation to the avoided soybean, maize, and palm oil production and related land use changes as insect meal is produced from food waste and used as feed ingredient; detailed in ESI†). Similarly, the net change in emissions resulting from the services provided and displaced through the co-products use are counted (*e.g.* surplus heat used for district heating and replacing marginal heat, or avoided mineral fertilizers production as digestates from anaerobic digestion are applied on farmlands). Finally (IV) as this study deals with limited resources which would not react to a demand change, being secondary products generated from the demand of another main product, an attempt to reflect the counterfactual use of these limited resources was made, here through the Reference scenario. Yet, the assessment is not an LCA *per se*, which would have also included all other carbon, nitrogen, phosphorus and overall substance flows affected. Also, though the key co-products are considered (surplus heat, digestate, biochar), minor ones (*e.g.* resins and veneer for engineered flooring, binders for insulation, insect oil and frass from black soldier flies or those typically disregarded in LCAs like the oxygen co-produced from electrolysis or fly and bottom ashes management from combustion) were excluded to ensure tractability.

The substances accounted for (Table 2) were selected as markers to reflect four key environmental impacts, namely climate change, eutrophication of marine and freshwater (nitrate and phosphorus losses to water) and air pollution ($PM_{2.5}$). These are acknowledged as key environmental impacts of energy systems.[63] While air pollution is particularly important in relation to the health-damaging particles resulting from incomplete biomass combustion,[3] eutrophication is acknowledged as a major damage connected to organic wastes and in particular manure management.[64] Eutrophication, or rather "biogeochemical N and P flows", is also a planetary boundary for which the safe operating space has been greatly exceeded, hence the high relevance of reflecting this impact. Table 2 summarizes the key methodological aspects related to the quantification of environmental impacts.

While the CO_2 emissions resulting from the scenario's electricity and heat services stem from the EDO output, the N, P, and $PM_{2.5}$ flows from electricity and heat production are taken from the life cycle inventory database Ecoinvent v.3.5, see Table S7 (ESI†). Similarly, all emission data (GHG, N, P, and $PM_{2.5}$) on avoided services as well as inferred transport are from Ecoinvent v.3.5. The emission flows related to the processes in the Reference scenario are calculated using IPCC guidelines[65,66] and data from literature, see Section S2 (ESI†) for details. Emissions from anaerobic digestion, pyrolysis, digestate management, material, and black soldier fly meal production are based on published life cycle inventories or estimation methods used in these (see Section S2, ESI†). Processes which involve a share of carbon sequestration are listed in Table S15 (ESI†), along with the sequestration share considered.

Results

Resource data

Fig. 3 summarizes the quantified residual biomass potentials to 2035. The ecologically sustainable potential sums up to 14.3 EJ

Table 2 Overview of environmental impacts and metrics considered

Impact	Substance considered	Metric considered	Comment[a]
Climate change	CO_2 (incl. biogenic carbon sequestration), CH_4, N_2O	kg CO_2 eq.	These substances are the three most important well-mixed GHGs, both in terms of concentration and radiative forcing.[67] These are aggregated into CO_2e, based on Myhre *et al.*,[67] considering the GWP_{100} with climate carbon feedback (CCFB).
Air pollution	$PM_{2.5}$	kg $PM_{2.5}$	Particulate matter is the sum of all solid and liquid particles suspended in air. Here only direct $PM_{2.5}$ emissions are included as an indicator for air pollution.
Eutrophication, marine	Nitrate, to water	kg N eq.	Nitrate (or N losses to water) is used as an indicator, albeit it is not the only contributor to marine eutrophication. It is expressed as N eq. based on the characterization factors of the Environmental Footprint Life Cycle Impact Assessment method.[68]
Eutrophication, freshwater	Phosphate and phosphorus, to water	kg P eq.	All phosphorous losses to water are used as an indicator for freshwater eutrophication, aggregated and expressed as P eq., also based on the Environmental Footprint Life Cycle Impact Assessment method.[68]

[a] Carbon dioxide (CO_2), methane (CH_4), nitrous oxide (N_2O), particulate matter up to 2.5 μm ($PM_{2.5}$), nitrogen (N), phosphorus (P), Climate Carbon Feedback (CCFB), Global Warming Potential (GWP).

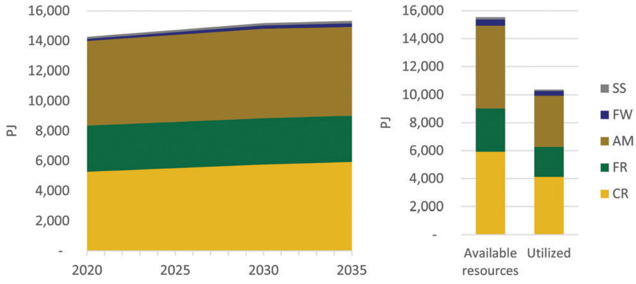

Fig. 3 Ecologically sustainable residual biomass potential in China from 2020 to 2035 (left; considered as available resources). The potential assumed to be utilized (economic feasibility), totals 10.4 EJ out of 15.3 EJ available resources in 2035 (right). The same available resources (quantity and streams) is considered in all scenarios.

in 2020, and increases to 15.3 EJ in 2035. To put this in perspective, around 100-300 EJ residual biomass is available worldwide.[69,70] Of this 15.3 EJ potential, a total of 10.4 EJ was quantified as economically feasible to utilize in 2035. The delta between the ecologically sustainable (or available) potential and utilized resources represents the unutilized share.

Scenario outputs

Fig. 4 shows, for all scenarios, an overview of energy and material flows, along with the products generated and avoided. For the energy scenarios, Combustion and Green Fuels, the diagram shows the specific avoided energy services, as a result from the optimization in the EDO model. In all scenarios, the avoided products are indicated with grey boxes. For example, the different flows regarding CR in the four scenarios is as follows. The material flow in the Reference scenario shows that most of CR is burnt and the rest is abandoned. In the Combustion scenario, CR is combusted for electricity and heat, 32% of the energy is lost in the conversion, but 17% is used to substitute a mix of electricity and 50% a mix of heat production. For the Green Fuels scenario, 4120 PJ of CR feeds a pyrolysis process, hereafter the gas and bio-oil go through methanol synthesis with an input of 1648 PJ hydrogen from electrolysis, to produce 2472 PJ bio-jet which substitutes fossil jet fuel. The methanol synthesis, electrolysis, and methanation produces heat of which 20% is used to substitute other heat sources for district heating and the pyrolysis also produces biochar as an output. In the Materials scenario, CR is used to produce an insulation material without losses, substituting fiberglass insulation. The biomass resource input is the same in all scenarios, but in the Green Fuels scenario, there is a significant additional electricity input, primarily used for electrolysis. The required 1416 TWh corresponds to a 12% increase of Chinese electricity demand.

Fig. 5 shows that all utilization scenarios significantly outperform the Reference scenario in terms of GHG emissions, pointing to the benefits of utilizing residual biomass. It also reflects that including biogenic emissions and carbon sequestration have a major impact on results. For instance, isolating the fossil emissions shows the Reference and Materials scenarios being almost on par, which is far from being the case when all biogenic emissions are included. In the two energy scenarios, the Green Fuels scenario would still be preferable compared to the Combustion scenario, the preference for the Green Fuels scenario is strongly enforced when biogenic CO_2e emissions as well as carbon sequestration are included. The largest contributors to biogenic non-CO_2 GHG emissions are, in all scenarios, from unutilized resources. This is notably due to CH_4 emissions from abandoned FR and AM. Adding to this, N_2O emissions from applying AM on fields is a noteworthy non-CO_2 contributor. One key difference between the utilization scenarios is the avoided emissions from substituted fuels and sequestrated biogenic carbon. In the Combustion scenario the avoided fuel emissions stem from avoided electricity, while in the Green Fuels scenario it is the net of emissions from the required electricity for fuel production, primarily for electrolysis, and avoided emissions from substituted fossil jet fuel and natural gas. The fossil emissions from transport are made up by a combination of combusted diesel during transport, which makes up two thirds of the transport GHG emissions, and the emissions from fuel extraction, infrastructure, and vehicles. The avoided fossil material emissions are from avoided mineral fertilizer. When all GHG emissions are taken into account, the Materials and the Green Fuels scenarios, have the lowest emissions. In both scenarios, not all carbon from the biomasses is emitted due to long-term sequestration, see Table S15 (ESI†). This is mainly in form of biochar from pyrolysis in the Green Fuels scenario and sequestration of carbon in building materials in the Materials scenario. However, the sequestration of the latter is tied to the lifetime of the material and uncertainties remain on the actual recalcitrance of biochar in soils regarding the former.[71] The fossil emissions from transport are the same in the two energy scenarios, and reduced in the Materials scenario as there is no additional transport considered for AM and SS spread on fields. In the Reference scenario, transport emissions are from landfilling only. For details on how different processes contribute to GHG emissions, see Section 3c (ESI†).

Fig. 6 highlights that most of the $N_{eq.}$, $P_{eq.}$, and $PM_{2.5}$ emissions come from the unutilized share of the resources. Of utilized resources, $N_{eq.}$ and $P_{eq.}$ losses primarily stem from AM utilization. N losses are very similar in the three utilization scenarios. The lowest N losses are found in the Materials scenario due to avoided marginal feed production (as a result of using FW to produce black soldier fly meal). Differences in P losses reflect the avoided power and heat production in the Combustion scenario and the additional use of electricity adds to the P losses in the Green Fuels scenario. The P losses from AM utilization is the main contributor, and this is slightly lower in the Materials scenario with efficient land application of AM, in comparison to P losses from digestate spreading in the Green Fuels and Combustion scenarios. Adding to this, the avoided ceramic tile reduced P losses in the Materials scenario. When the set share of resources are utilized (Table S2, ESI†), 3.3 Mt N and 0.5 Mt P could be saved from waterways in the utilization scenarios compared to the reference scenario (Fig. 6). Putting this into perspective, efficient utilization of residual

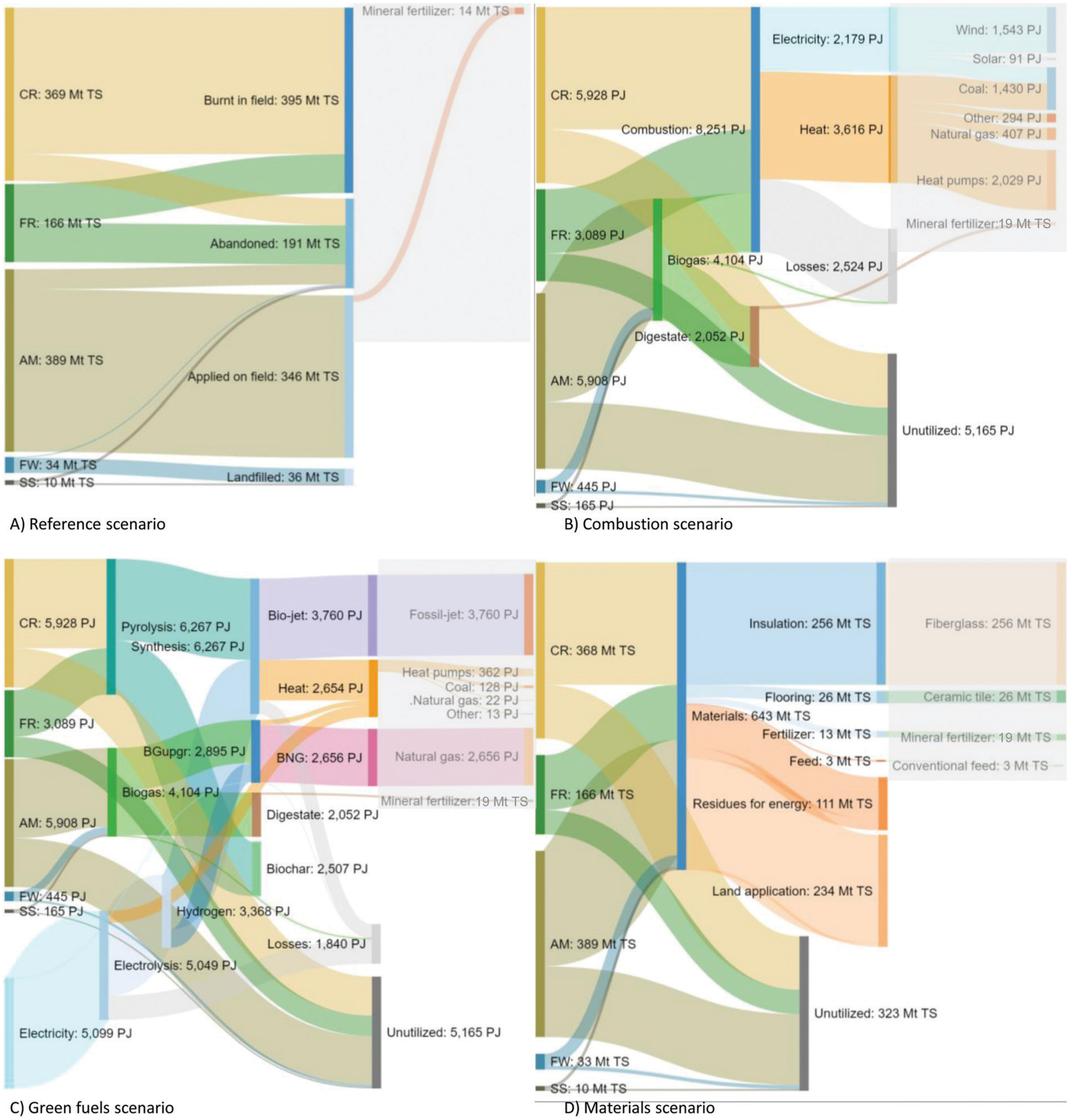

Fig. 4 Overview of energy (B and C) and material (A and D) total solids (TS) flows (*i.e.* dry matter) for Crop Residues (CR), Forestry Residues (FR), Animal Manure (AM), Food Waste (FW), and Sewage Sludge (SS) in the different scenarios. The unutilized resources are the same in the three utilization scenarios (B, C, and D) and follow the same distribution as the Reference scenario (A). Avoided energy and materials are shown in the grey-shaded box to the right for each scenario. BGupgr: Biogas upgrading through methanation or CO_2 removal, BNG: Biomethane.

biomass could contribute to reducing the extensive problem with over-application of mineral fertilizers in China. In 2012, 31 Mt mineral N and 6.5 Mt mineral P were applied, but the actual needed quantities could be as low as 5 Mt mineral N and 0.2 Mt mineral P, provided optimized application, including use of AM, SS, and FW as fertilizers.[72] Emissions of $PM_{2.5}$ are almost exclusively from the unutilized share of biomasses (Fig. 6), and more precisely from open burning of CR and FR. Yet, a miniscule proportion is from the combustion of CR and FR for electricity and heat production in the Combustion scenario. The utilization scenarios would result in a reduction of $PM_{2.5}$ emissions of 2.6 Mt compared to the Reference scenario, equivalent 21% of national $PM_{2.5}$ emissions in 2010.[73] As for GHG, all utilization scenarios outperform the Reference scenario for N, P, and $PM_{2.5}$.

Fig. 7 shows the resulting avoided and required electricity and heat generation mix in the Combustion and Green Fuels scenarios, obtained from the EDO model. This is compared to the Materials and Reference scenarios, where no biomass is used for electricity and heat generation. When residual

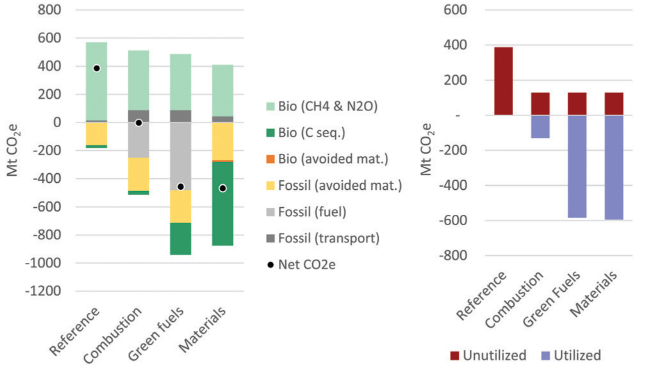

Fig. 5 GHG emissions (by type) associated with the different scenarios including carbon sequestration (C seq.) and CO_2e from avoided materials (avoided mat.) (left). Fossil (avoided mat.) cover avoided use of mineral fertilizers and building materials while Bio (avoided mat.) cover avoided feed production. Net CO_2e emissions breakdown by unutilized and utilized resources (right). In million tonnes carbon dioxide equivalents (Mt CO_2e).

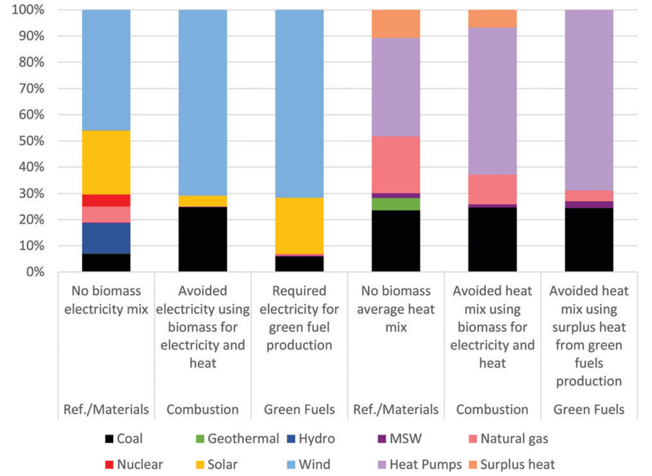

Fig. 7 Required and avoided electricity and heat by source in the Combustion and Green Fuels scenarios. MSW: Municipal Solid Waste.

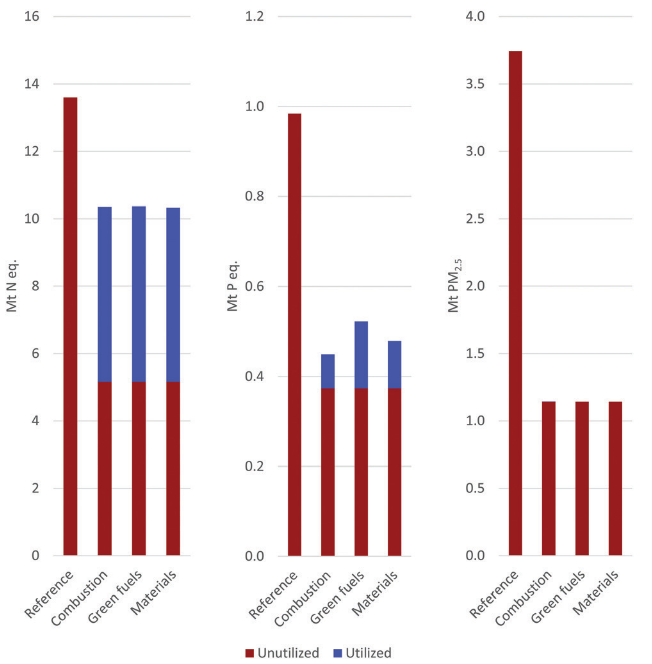

Fig. 6 Million tonnes (Mt) of Nitrogen (N) eq., Phosphorous (P) eq., and fine Particulate Matter ($PM_{2.5}$) emissions in the different scenarios, with breakdown by utilized and unutilized biomass.

biomass is used to generate electricity and heat in the Combustion scenario, a mix of primarily wind, coal, and solar power is avoided while biomass covers 4% of electricity demand. Biomass is only available for electricity and heat in the Combustion scenario, as the use of biomass for electricity and district heating in the explored scenarios are limited to residual biomass. The Reference and Materials scenarios have the same resulting power and heating mix, as these scenarios do not affect the demand or production of power and district heating.

Due to flexible consumption, the additional electricity demand to power fuel production in the Green Fuels scenario is primarily covered by wind and solar power. As it is not fully covered by renewable electricity, the Green Fuels scenario, as modeled herein, poses a risk of increased fossil fuel demand, which must be avoided. Regarding heat, the use of biomass in the Combustion scenario reduces the use of heat pumps, coal, natural gas, and surplus heat compared to the average heat mix without residual biomass use. In this scenario, heat from biomass contributes to 32% of the overall heat in the Chinese district heating networks. In the Green Fuels scenario, 20% of generated surplus heat from fuel production is utilized in district heating networks and the rest does not match the heat demand and is therefore lost. This surplus heat utilization covers 5% of district heating demand and mostly substitutes the use of heat pumps, municipal solid waste as well as coal in combined heat and power plants.

System cost

Fig. 8 shows system costs in the different scenarios without any price on externalities.

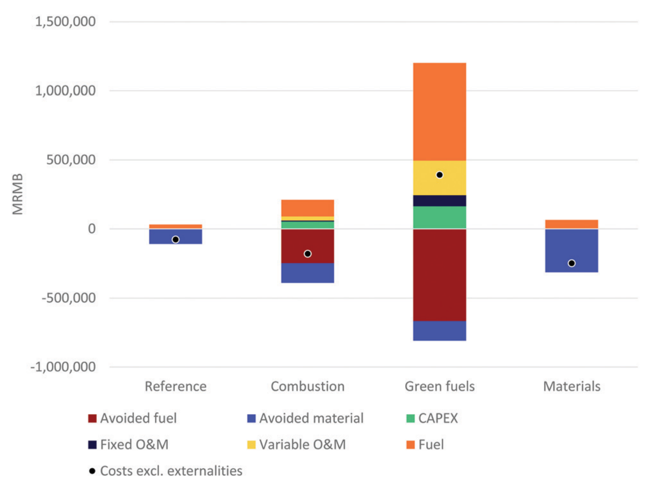

Fig. 8 System costs by scenario without externalities in million renminbi (MRMB) for all four scenarios, the net system costs is indicated with a dot.

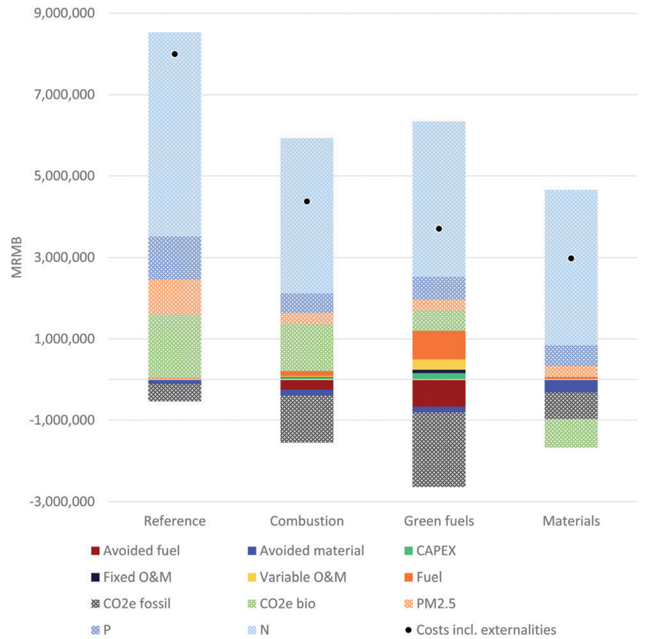

Fig. 9 Socio-economic costs of scenarios with externalities priced using societal costs in million renminbi (MRMB) for all four scenarios, the net system costs is indicated with a dot.

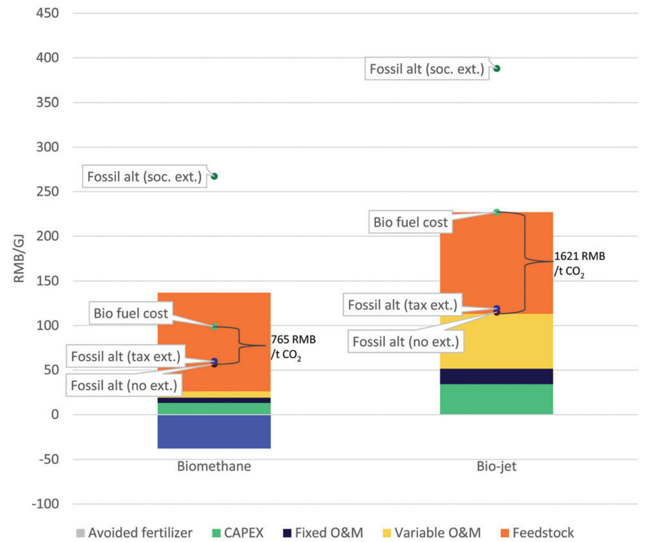

Fig. 10 Cost for biomethane and bio-jet in the Green Fuels scenario compared to fossil alternatives (alt) with different levels pricing of externalities (ext.), societal (soc.), tax, and no pricing of externalities (see Table 1 for externalities pricing levels) as well as the required price on CO_2 to close the gap between bio fuels and the fossil alternative.

Including socio-economic costs, using a life cycle perspective of emissions and other environmental externalities, does not only increase the resulting costs, but the order of scenarios by cost is also changed, see Fig. 9.

This is most evident in the Reference scenario, where the externality cost of improper management of residual biomass results in very high costs making the scenario go from being net negative, without pricing externalities, to the most costly scenario. Fig. 9 further illustrates the problem of only focusing on fossil CO_2 emissions, when assessing the socio-economic costs of biomass utilization, which is common when performing energy system analysis. This is particularly relevant regarding the Reference scenario, which goes from negative GHG emission when limited to fossil CO_2e to an increase of GHG emissions when biogenic CO_2e emissions are included.

Looking at the calculated cost to produce biofuels, the resulting biomethane price is 99 RMB per GJ and bio-jet 227 RMB per GJ. Biomethane becomes profitable compared to natural gas when societal externality costs are included, see Fig. 10. The gap between biofuel and fossil fuel cost could be filled with a CO_2 tax. If only pricing the fossil CO_2 this needs to be 763 RMB per t CO_2 for natural gas and 1621 RMB per t CO_2 for jet kerosene to make the biofuels cost competitive. The resulting electricity price for electrolysis in the Green Fuels scenario is 221 RMB per MWh, which is lower than the average price at 255 RMB per MWh. Using the average electricity price would result in higher biofuel prices with biomethane at 104 RMB per GJ and bio-jet at 236 RMB per GJ. Comparing the fuel prices in Fig. 10 to prices found in literature shows that the biomethane and bio-jet prices are within the range found in other studies. Prices for biomethane depend greatly on feedstock prices and lie in the range 80–178 RMB per GJ[74] or 107–249 RMB per GJ.[75] For hydrocarbons through pyrolysis prices are reported in the range 167–294 RMB per GJ[74] and specific assessments for bio-jet through pyrolysis from 161 RMB per GJ[76] to 253 RMB per GJ.[42] Comparing the produced biomethane to projected demand[56] shows that produced biomethane could reduce import dependency of nautral gas by 38%. For bio-jet, the volumes produced exceed the projected demand for jet kerosene for domestic travel in 2035.[56] This points to the potential for producing other liquid fuels, which are in high demand.

Sensitivity analysis on use of marginal emissions

This study illustrates the use of a dynamic energy system perspective. Using a static view, the marginal electricity and heat would not have been case-specific, which would affect the environmental impact of the two energy scenarios. Best-practice among LCA practitioners is to use spatial and temporal specific marginal electricity mixes. For China the future marginal mix is based on the International Energy Agency Stated Policies scenario.[25] This sensitivity analysis compares, for the Combustion and Green Fuels scenarios, the climate change impact result depending on electricity and heat mixes as well as GHG factors used. The comparison is between; (I) a base case based on the mixes shown in Fig. 7, and CO_2 from EDO; (II) the EDO mix with the same mix as in the base case but quantified using GHG data (associated to each technology) from Ecoinvent, specified in Table S7 (ESI†); (III) a static mix considering the marginal electricity mix for China 2030–2040 used in Vandepaer *et al.*[25] and assuming that the marginal heat is from natural gas, a typical assumption made in LCA studies (*e.g.* Tonini *et al.*[6,77] and Brassard *et al.*[8]). It should be noted that while the "base" and "EDO mix" cases involve different mixes for induced and avoided electricity and heat mixes, the "static mix'' does not distinguish between induced and avoided mixes. While the CO_2 emissions in the base case are limited to the direct operation emissions from combustion of fuels, they have a detailed representation of plant types for each fuel and their efficiencies. The GHG emissions factors from Ecoinvent have a wider scope, including background data for upstream and downstream emissions, but are generic in terms of specific technologies used. All environmental impacts included in this study are tested (see Fig. S5, ESI†), but only the climate change impact is shown in Fig. 11, being the impact with the most significant changes. In the Combustion scenario, the CO_2e emissions in the base case are considerably higher than the EDO mix and Static mix cases. The CO_2e impact of the electricity mix used in the three cases for the Combustion scenario are very similar, but the difference here lies in the heat, more precisely the avoided heat, see Fig. S5 (ESI†). In the EDO mix the avoided heat is mostly from use of heat pumps and when this is compared to the Static mix the avoided emissions are much higher in the Static mix, as it assumes that natural gas heat is avoided. For the Green Fuels scenario, on the other hand, the difference primarily stems from the electricity, as the impact from heat is relatively small, see Fig. S5 (ESI†). The additional electricity needed for Green Fuels in the base case is considerably less GHG intensive than the Static mix, which includes more coal, see Fig. S6 (ESI†). The resulting difference in avoided fossil CO_2e emissions between the base and the Static mix not only increase the difference in GHG emissions between the two energy scenarios, but also changes the priority from a GHG perspective. This shows the importance of detailed modeling of marginal electricity and heat generation for comparing competing use of biomass for energy.

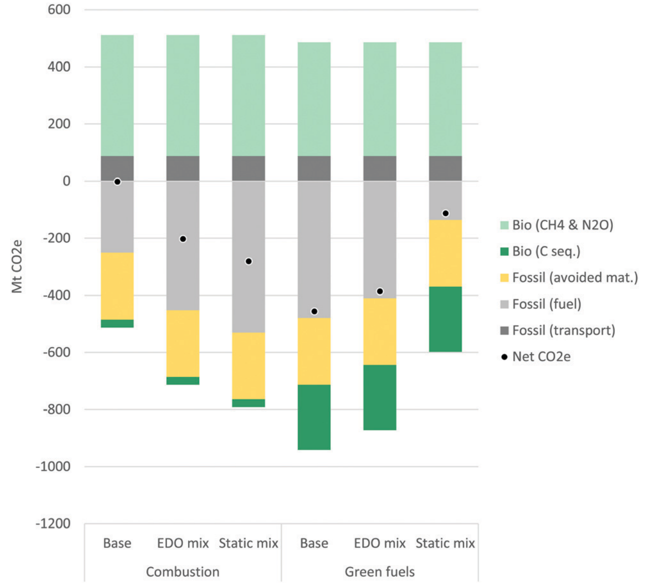

Fig. 11 Sensitivity analysis on marginal energy mixes for the Combustion and Green Fuels scenarios in million tonnes carbon dioxide equivalents (Mt CO_2e). EDO mix using Ecoinvent factors described in Table S7 (ESI†) to quantify the mix of additional and avoided electricity and heat. Static mix using marginal electricity mix for China 2030–2040 from Vandepaer *et al.*[25] and assuming natural gas for heat, see Fig. S6 (ESI†). The Fossil (fuel) GHG emissions covers both avoided natural gas and jet kerosene as well as added emissions from use of additional electricity (in the Green Fuels scenario) and avoided fossil emissions from substituted electricity and heat production (in the Combustion scenario).

Sensitivity analysis on system costs

The data used for this assessment is associated with varying degrees of uncertainty. To illustrate the sensitivity of different parameters, a number of them are chosen and tested. The parameters chosen include various cost elements as well as pricing of externalities. The overall system costs for the affected scenarios are shown as a relative change compared to the base scenario in Fig. 12. All scenarios are subject to a sensitivity on resource collection and transportation costs (Coll. & Trans. Cost) of ±50%. However, only the Materials scenario is sensitive to changes in this parameter. This is seen in the deviation from the base for collection and transportation costs for the variants related to the Materials scenario (yellow data labels in Fig. 12). Here the difference is larger compared to the same parameter being tested for the other scenarios. The Combustion scenario (blue data labels in Fig. 12) is sensitive to changes in both heat and electricity prices. For the Green Fuels scenario, with pink data labels, a number of capacity costs are tested. For hydrogen production through electrolysis, Bloomberg New Energy Finance (BNEF) assumes electrolyzer costs substantially lower in China compared to the rest of the world.[78] This has not been confirmed by other studies.[79] The assumed global cost development from BNEF is used in this study although it is considerably lower than other studies,[78] at 126 $USD per kW in 2035. A sensitivity analysis is carried out with an increase of electrolyzer cost of +50%, while hydrogen storage is assessed with ±50% in cost. Similarly, due to uncertainties, the pyrolysis and methanol synthesis CAPEX for bio-jet production is tested with a sensitivity of ±50%; this is the CAPEX parameter to which the scenario is most sensitive. The resulting bio-jet fuel is assumed to be sold at the same price as fossil-jet. There could be a high demand for green aviation fuels, which is why a 50% increase in bio-jet value is tested. The result being a significant increase in the profitability of the Green Fuels scenario. Oxygen is a potentially high value by-product from electrolysis. With a price of 336 RMB per t O_2,[80] the difference between venting oxygen from electrolysis and selling it would significantly reduce the cost of the Green Fuels scenario. Selling all oxygen at this price would have a higher impact on system costs than utilizing surplus heat. Oxygen could potentially be utilized for oxyfuel combustion to increase combustion efficiencies and facilitate carbon capture. The avoided costs for materials are also associated with high uncertainty, which is why it is subject to sensitivity analysis. When the avoided material cost is reduced with 50%, the profitability of the Materials scenario is challenged. The most substantial impact is from avoided CR material cost due to the high quantities and utilization rate of this fraction. Regarding feed costs, despite the substantial decrease in avoided cost, collection and transport of FW is the main cost for FW utilization.

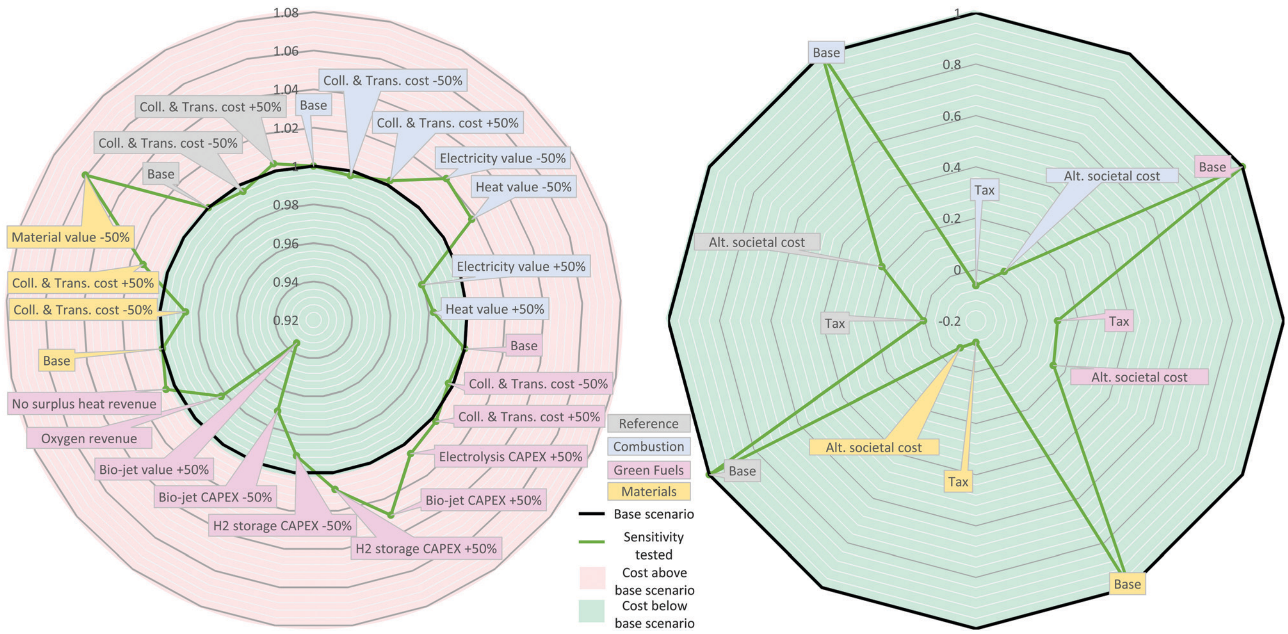

Fig. 12 System costs are displayed relative to the base of each scenario (illustrated using grey, blue, pink and yellow data labels). The numerical values show the difference from the base, which is indexed to 1. Variants in the red area have a higher cost than the base and variants in the green area have a lower cost than the base. Sensitivity to changes in selected cost parameters are shown for a variety of one-at-the-time analysis, performed for all scenarios (left). Different ways of pricing externalities, using tax rates and an alternative (Alt.) societal cost, presented in Table 1, are tested (right).

As previously described, there is an immense impact from how externalities are priced, see Table 1. A sensitivity analysis is carried out with alternative societal cost values for CO_2e, $PM_{2.5}$, N, and P,[58] shown in Fig. 12. This is compared to the base scenario with societal costs and the tax applied to all assessed life cycle externalities. The largest difference is in the Reference scenario, as this scenario is associated with the highest environmental impacts. The value is negative in both sensitivities in the Materials scenario as well as the tax level in the Combustion scenario, meaning that the economic benefits of the scenario outweigh its costs.

Discussion and perspectives

While this study presents separate utilization scenarios, combining them would be highly relevant for further studies, in particular in the perspective of optimizing residual biomass uses. In such scheme, resources could be disaggregated (*e.g.* AM by type of manure) for varied use and cascaded by product value and environmental benefit. The Materials scenario performs well both in an economic and environmental perspective, but is also associated with some uncertainty. A first limitation of the Materials scenario is that the utilization is based on a small number of cases without proven widescale applicability and there is a high degree of uncertainty regarding how much residual biomass can effectively be utilized in this manner. For building materials there is a considerable uncertainty related to the lifetime of the materials and their degradability during and prior to their use. The case investigated herein serves to illustrate an extreme case with long lifetime, and for this reason disregarded end-of-life management. One other option for materials utilization is for generating more rapidly cycling chemical products such as disposable plastics. In such case, the end-of-life and hence carbon release and potential additional supply of services should be considered, such as incineration with energy recovery or littering at the other end of the spectrum. Similarly, different dynamic end-of-life scenarios could be investigated and compared for building products with long lifetime, including energy recovery. The Green Fuels scenario is also uncertain, as the pathway from pyrolysis of residual biomasses *via* methanol to jet fuel production has not been demonstrated at full scale yet. Again the scenario demonstrates positive potentials of further exploring the option, *e.g.* in combination with the use of residual biomass for materials.

It is clear that the pricing of externalities determines the prioritization between scenarios, here an increased price on fossil carbon would further affect the results and favor the Green Fuels scenario, due the high substitution of fossil fuels, see Fig. 5. When societal externality costs are included, the Reference scenario is the scenario associated with the highest costs, which is why utilizing the resources should be of high priority. The Reference scenario reflects an extreme situation with poor management of resources, with high environmental impacts. These are specifically GHG emissions from abandoned FR, N and P losses from abandoned AM, and $PM_{2.5}$ emissions from open burning of CR and FR. Unutilized FR is shown as a main contributor to GHG emissions, but the share of unutilized FR burned and left in forest is based on a very rough assumption. While some studies[8,77] disregard CH_4 emissions from FR left in forests, this study considers that 10% of carbon is assumed emitted as CH_4.[52] This might be a conservative assumption; for instance Ros *et al.*[81] propose a range of 0–3%. Using 0% CH_4 from FR left in forests results in a reduction of 172 Mt CO_2e in the Reference scenario and 53 Mt CO_2e in the other scenarios, corresponding to a 35% and 15% reduction in biogenic non-CO_2 GHG emissions, respectively.

Not only is residual biomass a valuable resource for sustainable carbon, but not utilizing this resource is associated with high environmental burdens in terms of environmental damage in the form of eutrophication, air pollution, and GHG emissions. The results show a possible net reduction between 349 and 644 Mt CO_2e in the utilization scenarios for 2035. As a comparison, in 2014 total GHG emissions in China made up 11 186 Mt CO_2e.[82] Eutrophication is associated with high degrees of uncertainty. N and P losses are important, which is why they are included, but their quantification is associated with several simplifications. How much N and P are lost depends on local soil conditions and agricultural management practices, which makes it difficult to generalize. The results of this study show that impacts from N and P losses are substantial when compared to a reference scenario, which includes abandonment of AM. This points to the benefits of proper AM management.

The ecological sustainable resource potential is relatively stable under the set assumptions, see Fig. 3. Whereas the implementable potential of mobilizing resources is associated with higher degrees of uncertainty. This could be investigated further. Availability can for example be linked to the carbon price, as a higher price on carbon increases the profitability of collecting residual biomass for energy utilization.[83] Furthermore, including the avoided cost of eutrophication would increase the profitability of utilizing these resources. Ideally, the resource collection and transportation costs should be regionalized as the national averages used in this study are associated with high degrees of uncertainty, but as shown in the sensitivity analysis this has limited impact on overall costs.

This study presents limited options for residual biomass utilization. Further research could include more technology options and illustrate cascading effects from combining resources. Bioenergy with carbon capture and storage (BECCS) has not been considered in this study, although this pathway could hold great prospects of achieving negative CO_2 emissions.[69] Recent studies on BECCS have concluded great potential for BECCS to enable negative emissions.[22,84] Although BECCS have not been a focus of this study, the methodology developed in our study could be expanded to include BECCS in the Combustion scenario and assess economic, environmental, and energy impacts. Preferred utilization pathways by resource can be specified further by isolating one or modelling a combination of resources.

Conclusion

Residual biomass is limited but is a valuable fossil free carbon source, which should be utilized efficiently, whether for energy or non-energy services. This study shows, in a Chinese context, that not utilizing these resources results in major environmental impacts with high GHG emissions while causing substantial eutrophication and fine particle emissions. For the environmental impact categories assessed in this study, the Materials scenario (reflecting uses for construction materials, fertilizers, and feed) performs best for limiting GHG and is on par with the Green Fuels scenario (reflecting production of biomethane and bio-jet fuel) for $PM_{2.5}$ emissions, whereas the Materials scenario performs marginally better than the other utilization scenarios regarding N losses. The Combustion scenario (reflecting heat and power production) is better than the others regarding P losses. Looking at costs, the Materials scenario is the least costly option both with and without externalities. The Green Fuels scenario presents the highest cost, but when costs of externalities are included, it becomes on par with the Combustion scenario. While the ranking between different utilization scenarios is associated with uncertainty, they all greatly outperform the Reference scenario, showing value of utilizing these residual resources.

Various technology costs in the Green Fuels scenario are associated with high degrees of uncertainty, significantly affecting the profitability of this scenario as shown in the sensitivity analysis. Costs related to the Materials scenario are also associated with great uncertainty. The costs of the Materials scenario are shown to be very sensitive to the avoided costs for materials produced. However, there is no energy utilization in the Materials scenario. Combining uses from different scenarios and studying cascading effects would alleviate uncertainties, making this an interesting topic for future studies.

The study looks at 2035, at which time the technology options considered could be widely available. For the Green Fuels and Materials scenarios, this is an optimistic but not unrealistic outlook. It must be stressed that achieving these potentials require urgent action and can contribute to the Chinese climate neutrality target of 2060. The system costs are highly sensitive to the monetization of externalities. For all impact categories the tax levels in place are far from the studied levels of societal costs and do not grant the same prioritization. The aim of this study was to strengthen assessments of sustainable pathways for use of residual biomass by combining three methods: (1) energy system analysis, (2) life cycle assessments and (3) strategic bio-resource assessments. The study has shown the importance of combining the three approaches. First, the study shows that (1) energy system analysis is more representative and insightful for decision support when biogenic GHG emissions are included. Doing so significantly impacts the results when assessing utilization pathways for residual biomass. The study also underlines the importance of specifically considering eutrophication, which can be a determining factor when assessing the best utilization pathway for resources such as animal manure. Regarding (2) life cycle assessments, the study has shown that results are sensitive to the marginal emissions from energy applications, showing the importance of combining LCA with energy system analysis to identify the specific marginal mixes for state-of-the-art LCAs. Regarding (3) strategic bio-resource assessments, the assessments were used to generate scenarios to address the energy and environmental consequences of competing uses. It was shown that including existing uses is essential to appraise the relevance of utilization pathways.

The methodology proposed in this study can be applied to other locations as well as other resource streams. Bio3E can be soft-linked to other energy system models, which calculate electricity and heat generation, investment and operational costs, and which have a high temporal resolution to provide dynamic prices.

Abbreviations

AM	Animal manure
BECCS	Bioenergy with carbon capture and storage
BNEF	Bloomberg New Energy Finance
BNG	Biomethane
CAPEX	Capital expenditure
CH_4	Methane
CO_2	Carbon dioxide
CO_2e	Carbon dioxide equivalents
CR	Crop residues
DH	District heating
EDO	Electricity and District heating Optimization model
FR	Forestry residues
FW	Food waste
GHG	Greenhouse gas
GJ	Gigajoule
IPCC	Intergovernmental Panel on Climate Change
LCA	Life cycle assessment
Mt	Million tonne
MSW	Municipal solid waste
MW	Megawatt
MW h	Megawatt hours
N	Nitrogen
N eq.	Nitrogen equivalents
N_2O	Nitrous oxide
NO_3^-	Nitrate
O&M	Operations and maintenance expenditure
P	Phosphorous
P eq.	Phosphorous equivalents
PJ	Petajoule
$PM_{2.5}$	Particulate matter $\leq$ 2.5 micron
SS	Sewage sludge
TW h	Terawatt hours

Author contributions

Sara Shapiro-Bengtsen: conceptualization, data curation, formal analysis, investigation, software, methodology, project administration, visualization, writing – original draft. Lorie Hamelin: conceptualization, data curation, writing – review and editing. Lars Møllenbach Bregnbæk: software, methodology. Lele Zou: data curation. Marie Münster: conceptualization, methodology, supervision, writing – review and editing.

Conflicts of interest

There are no conflicts to declare.

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Paper IV

Quantifying the Benefits of Refining Side Streams When Optimizing Use of Residual Biomass

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ARTICLE

Quantifying the Benefits of Refining Side Streams When Optimizing Use of Residual Biomass

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Residual biomass is a valuable resource in the transition away from use of fossil fuels, which is imperative to limit global warming. This study compares optimal use of residual biomass; crop and forestry residues, animal manure, food waste, and sewage sludge under varying conditions in different scenarios. Use of residual biomass competes with conventional production to satisfy end-use demands for various fuels, plastics, feed, fertilizer, flooring and insulation. The scenarios illustrate making residual biomass available for production of energy products to non-energy use, and lastly to include refining side streams. The scenarios are modeled using a network flow model which is linked to a partial equilibrium electricity and district heating model and the studied system is co-optimized in a least-cost optimization. Environmental indicators: global warming, eutrophication, and particulate emissions are included and each associated with a cost. The study is applied to China and the results are shown for year 2050. The study finds that including use of residual biomass in non-energy sectors leads to lower system costs and emissions. Going further and including refining of side streams leads to further benefits in terms of system costs, reduced greenhouse gasses, nutrient losses and particulate emissions. The study quantifies the value of residual biomass and shows that extended possibilities for use of residual biomass has significant benefits.

Introduction

Global warming, mostly caused by combustion of fossil fuels, is a major threat to life on Earth as we know it [1]. Use of fossil fuels must be drastically reduced to meet climate change mitigation targets [2]. Climate change is a key planetary boundary, not to be surpassed to maintain operating conditions for humanity on Earth, and biodiversity is another [3]. These are two of the interlinked planetary boundaries, which have been quantified and assessed to have been exceeded, along with land-use change, biochemical flows of nitrogen and phosphorus [3], and most recently novelty entities, i.e. man-made materials with large-scale impacts such as plastics and heavy metals [4]. When moving away from using fossil carbon, biogenic carbon becomes increasingly important. The climate neutrality of biomass can be discussed as land use changes have climate change impacts and the growth cycle of biomass should be considered [5]. At the same time biomass is unique as the only easily accessible renewable source of carbon, which can replace fossil carbon, when creating carbon-based fuels and chemicals. Biomass is expected to play an increasingly important role in the energy sector with a threefold increase in use of bioenergy from 2020 to 2050, transitioning from traditional household use of biomass for cooking and heating to modern use in central facilities including converting biomass into biofuels [6]. In biomass feedstock, there is a distinction between first generation biomass, produced for the specific purpose, and residual biomass, i.e. biogenic waste streams from various activities [7]. Residual biomass resources e.g. crop residues, forestry residues, animal manure, municipal solid waste, and sewage sludge can be categorized as renewable, but as they are limited [7], they should be utilized efficiently and effectively.

Biomass used for energy purposes will, according to the International Energy Agency, stem from waste streams to an increasing degree, from 20% waste biomass in 2020 to 61% waste biomass in 2050 [6]. Adding to this, non-energy sectors are also shifting away from the use of fossil fuels and are looking at residual biomass as a sustainable feedstock with a long term demand equal to or exceeding residual biomass availability [8–10]. This points to an increased demand for residual biomass and a need to assess appropriate allocation of these resources. One key reason for limiting the biomass resources to residuals is the concern related to biodiversity loss. Ángel Galán-Martín et al. [11] showed the impacts on planetary boundaries for different pathways for methanol production, including using biomass in form of wood, crop residues, or energy crops. In the cases when biomass was used as a carbon or hydrogen source, the only pathway which had a positive impact on biodiversity was the one exclusively dependent on residual biomass, in that case crop residues. Regarding energy crops, yields are projected to decrease due to climate change and adding to this there are concerns regarding biodiversity and other ecological trade-offs [12].

When residual biomass is not utilized for energy or non-energy purposes, it must still be managed. Therefore, residual biomass

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Electronic Supplementary Information (ESI) available.

use is not only a question of using these resources, but what often is described as waste management as these are by-products from primary activities, such as food production or consumption [13]. The use of residuals should be contrasted with what otherwise would happen to the residuals, to show that both scenarios for utilization and minimal waste management, result in a series of impacts [14]. Many studies on utilization of residual biomass for energy purposes disregard demand from non-energy sectors [15–17]. Tsiropoulos et al. [18] e.g. presents an integrated systems analysis including aviation and chemicals sectors in a case study on the Netherlands using both residual biomass and first generation biomass. However, the study does not include reference use of residual biomass and quantified environmental impacts are limited to CO_2 emissions, without addressing other planetary boundaries.

China is on the path of an extensive transition of the energy sector and society to peak carbon emissions by 2030 and reach the carbon neutrality target by 2060 [19]. Use of residual biomass can play an important role in reducing emissions and attaining these targets. Residual biomass has proven great potential to contribute positively to the Chinese energy system while reducing greenhouse gas (GHG) emissions [20,21]. It has been shown that there are environmental benefits of uses of corn straw where mineral fertilizer can be substituted [22]. This points to the relevance of including substituted materials, such as mineral fertilizer, when assessing use of residual biomass. It has also been shown that there is great value in utilizing residual biomass compared to the reference, when assessing scenarios for use of residual biomass in China to produce electricity and heat, green fuels, or materials [23]. That study did however not quantify synergies between or valorization of side streams in the different utilization pathways. A central concept of the circular bioeconomy is that biomass should be used for high value products and subsequently cascaded to lower value products [24]. With biorefinery, biomass is refined to substitute fossil fuels by delivering bio-based fuels and chemicals [25]. While biorefineries are central in producing biobased fuels and chemicals, the value of side streams should be quantified. The present study valorizes and optimize utilization of side streams from biorefinery and other bio-based production. As something new, the present study both includes refining of side streams and reference use of residual biomass, while quantifying several environmental indicators at scale facilitating assessment of the impacts in terms of greenhouse gas emissions as well as nutrient flows and fine particulate matter (PM2.5) emissions. By including non-energy use and environmental impact indicators in energy system analysis the study broadens the way energy transition pathway analyses traditionally are conducted.

The objective of the present study, in the case of China, is to determine least-cost allocation and use of residual biomass, while avoiding additional pressure on relevant planetary boundaries at risk of being exceeded. Adding to this, direct particulate emissions are included as an impact due to its relevance in a Chinese context [26] as well as a strong link to human health, being a major cause of premature deaths [27]. The value of using residual biomass in different sectors will be illustrated by including a detailed representation of the energy sector, competing uses for the residual biomass from non-energy sectors, and including a reference use for unused resources. This comprehensive overview enables a comparison between different uses across sectors as well as combining uses and use of co-products across sectors. This will show to which uses and under which circumstances the residual biomass can generate the most value. By comparing different scenarios for biomass use, going from limiting use of residual biomass for energy purposes, to expanding the model to include non-energy purposes and lastly to include utilization of side streams, illustrating the value of the model development. This study contributes with a novel perspective in energy system analysis by including extended use and refining of side streams from use as well as reference use of residual biomass in a cost optimization along with key environmental indicators compared to a reference use of residuals.

Methodology

Modeling framework

The network optimization model OptiFlow [28] is used to model the value of biomass use. OptiFlow is an open-source generalized spatio-temporal network optimization model, which has a bottom-up approach, and is a deterministic partial equilibrium model. The OptiFlow model is generic and can represent any processes and flows based on node-arc relationships. The model allows optimization of investments and operation of the network. Furthermore, OptiFlow can perform a multi-criteria optimization based on the Pareto optimality approach [29], but the present study computes the least-cost solution. OptiFlow can be used in a stand-alone mode to identify the optimal pathways, but the model can also be integrated with an electricity and district heating optimization model, such as Balmorel [30], which has been performed in previous work by, for example, Bramstoft et al. [28] and Lester et al. [31]. The Chinese energy and district heating optimization model, EDO [32], which is based on Balmorel, is used to model the Chinese electricity and district heating system. EDO is linked to OptiFlow and the two models are co-optimized, see Figure 1 for a conceptual overview.

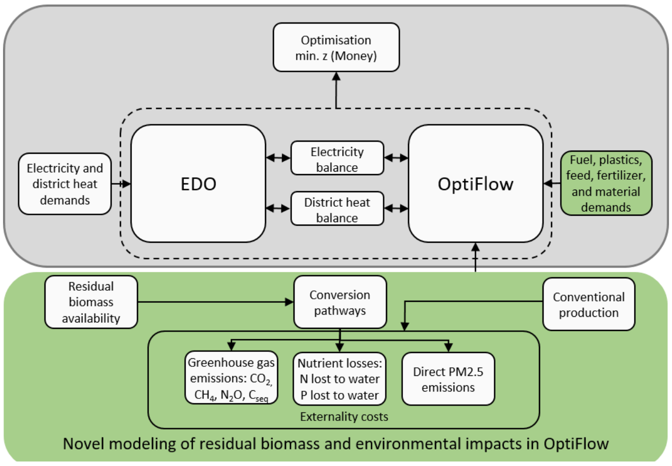

Figure 1: Conceptual illustration of the modeling framework.

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The objective function of the combined EDO and OptiFlow modeling framework is to minimize total system costs subject to a number of constraints. Simplified versions of four main equations used to facilitate the hard-linking between EDO and OptiFlow are presented in Eq. (1) – (4). For a comprehensive description, see Bramstoft et al. [28].

Minimize

$$Z = \sum_{\substack{a \in \mathcal{A} \\ t \in \mathcal{T} \\ g \in \mathcal{G}}} c_g^{vO\&M} \cdot p_{a,t,g} + \sum_{\substack{a \in \mathcal{A} \\ g \in \mathcal{G}}} c_g^{fxO\&M} \cdot \left(p_{a,g}^{ex} + p_{a,g}^{new}\right) + \sum_{\substack{a \in \mathcal{A} \\ g \in \mathcal{G}}} c_g^{CAPEX} \cdot p_{a,g}^{new} + \sum_{r,r' \in \mathcal{R}_{r,r'}^{exp}} c_{r,r'}^{CAPEX} \cdot p_{r,r'}^{tr,new} + \sum_{\substack{a \in \mathcal{A} \\ t \in \mathcal{T} \\ p \in \mathcal{P}^{Econ} \\ f \in \mathcal{F}^{Money}}} V_{a,t,p,f}^{B,OptiFlow} + \sum_{a,p | \mathcal{X}_{a,p}^{AP}} c_p^{CAPEX} \cdot V_{a,p}^{CAP,OptiFlow} \tag{1}$$

Subject to

$$\sum_{\substack{a \in \mathcal{A}_r^R \\ g \in \mathcal{G}^{el}}} p_{a,t,g}^{el} + \sum_{r' \in \mathcal{R}_{r',r}^{imp}} p_{r',r,t}^{tr} - \sum_{r' \in \mathcal{R}_{r,r'}^{exp}} p_{r,r't}^{tr} - \sum_{\substack{a \in \mathcal{A}_r^R \\ g \in \mathcal{G}^{el,Sto}}} p_{a,t,g}^{el,toSto} + \sum_{\substack{a \in \mathcal{A}_r^R \\ g \in \mathcal{G}^{el,Sto}}} p_{a,t,g}^{el,fromSto} - \sum_{\substack{a \in \mathcal{A}_r^R \\ g \in \mathcal{G}^{el,VRE}}} p_{a,t,g}^{el,curt} + \sum_{\substack{a \in \mathcal{A}_r^R \\ p \in \mathcal{P}^{el} \\ f \in \mathcal{F}^{el}}} V_{a,t,p,f}^{B,OptiFlow} = d_{r,t}^{el} \quad \forall \quad r \in \mathcal{R}, t \in \mathcal{T} \tag{2}$$

$$\sum_{g \in \mathcal{G}^{dh}} p_{a,t,g}^{dh} - \sum_{g \in \mathcal{G}^{dh,Sto}} p_{a,t,g}^{dh,toSto} + \sum_{g \in \mathcal{G}^{dh,Sto}} p_{a,t,g}^{dh,fromSto} - \sum_{g \in \mathcal{G}^{dh,VRE}} p_{a,t,g}^{dh,curt} + \sum_{\substack{p \in \mathcal{P}^{dh} \\ f \in \mathcal{F}^{dh}}} V_{a,t,p,f}^{B,OptiFlow} = d_{a,t}^{dh} \quad \forall \quad a \in \mathcal{A}, t \in \mathcal{T} \tag{3}$$

$$V_{a,t,p,f}^{B,OptiFlow} = \sum_{\substack{p'' \epsilon \mathcal{P} \\ |(a,p',p,f) \epsilon \mathcal{R}_{a,p',p,f}^{APPF}}} V_{a,t,p',p,f} - \sum_{\substack{p' \epsilon \mathcal{P} \\ |(a,p,p'',f) \epsilon \mathcal{R}_{a,p,p'' f}^{APPF}}} V_{a,t,p,p'',f} \quad \forall \ a \in \mathcal{A}, t \in \mathcal{T}, p \in \mathcal{P}^{\mathcal{B}}, f \in \mathcal{F} \tag{4}$$

The objective function in Eq. (1) considers variable operation costs including fuel use and environmental costs for a technology, g, when consuming or producing commodity, $p_{a,t,g}$, in area a, at each time-step, t. Furthermore, fixed annual operating and maintenance (O&M) costs are included. Annualized capital expenditures (CAPEX) are considered both for investments in technologies, g, represented by c_g^{CAPEX}, and in transmission infrastructure denoted by $c_{r,r'}^{CAPEX}$. OptiFlow and EDO are hard-linked in the objective function, and therefore, monetary flows i.e. investment and operation costs computed in OptiFlow are added in the objective function. By adding the sum of the variable $V_{a,t,p,f}^{B,OptiFlow}$, all operational costs including fuel and environmental costs from OptiFlow are considered in the overall objective function. Furthermore, the CAPEX of new investments in processes, p, in OptiFlow are considered as well.

Eq. (2) describes the electricity balance equation and ensures balance between electricity demand and production at all time-steps, while considering the possibilities of import/export via transmission, charging/discharging of storage assets, and curtailment of variable renewable energy generation. The net electricity generation/consumption in OptiFlow, $V_{a,t,p,f}^{B,OptiFlow}$, is hard-linked into the electricity balance equation, ensuring simultaneous optimization between the two models. Likewise, Eq. (3) ensures heat to be balanced for the entire EDO-OptiFlow system in each area, a, at each time-step, t.

Eq. (4) represents the process call buffer ($\mathcal{P}^B$) in OptiFlow that facilitate the linkage to EDO. In general, a node-arc (Process-Flow) relationship is used to represent a network in OptiFlow. In general processes can be categorised into source ($\mathcal{P}^{So}$), sink ($\mathcal{P}^{Si}$), buffer ($\mathcal{P}^B$), as well as other processes used for representing storage, transport, as interior processes that facilitate multiple in and out flows of processes. Buffer processes $p \epsilon \mathcal{P}^B$ facilitates interactions of flows entering $V_{a,t,p',p,f}^{B,OptiFlow}$ and/or leaving $V_{a,t,p,p'',f}^{B,OptiFlow}$ the defined system boundary. In this way, the flows of the buffer processes are used to link net electricity and heat in the respective electricity and heat balance equations, as well as the monetary flow values are linked in the objective functions to take into account, e.g. costs of environmental externalities. The nature of the Eq. (4) yield that both sources and sinks can be represented by Eq. (4), as sources only have a flow entering the system boundary, e.g. resources or feedstock, and flows from sink processes are only leaving the system conditions, such as demands.

OptiFlow is used to model the use of residual biomass, conventional production of products, and demand for end-use fuels, plastics, feed, flooring, insulation, and fertilizer. Year 2030 and 2050 are modeled. The study presents results for year 2050, but year 2030 is also modeled to include a midway point in the transition.

The bio-based products produced using residual biomass are associated with production costs and environmental impacts. Demands for end-use products are specified and the set demand can be met using residual bio-based or conventional production. In the model there are no limitations on conventional products assuming they are traded on global markets, they are merely represented with a flat price and associated environmental impacts. Bio-based production is limited by the availability of domestic residual biomass resources. This permits studying the optimized allocation of these resources as the cost-optimization model finds the least-cost option for allocation of residual biomass resources. The model is driven by costs associated with utilization of biomass which compete with costs for conventional products as well as costs associated with environmental impacts.

Modeling of scenario configurations

The scenarios in this study are designed to showcase the extended use of residual biomass and test the significance of modeling and facilitating extended use and refining when quantifying use of residual biomass. The three main scenarios explored in this study are; the Energy scenario, where residual biomass is used for energy purposes, the Multipurpose scenario where the use of residual biomass is extended to other sectors, and Industrial Symbiosis which is an expansion of the Multipurpose scenario to include refining of side streams. In all scenarios, the same end use demands are satisfied. Figure 2 illustrates the overall flows included in the scenarios moving from resources in rectangles to the left to products in hexagons to the right, where the solid lines denote options for the energy scenario, while the dotted lines denote options for the remaining scenarios and the dashed lines only for the industrial symbiosis.

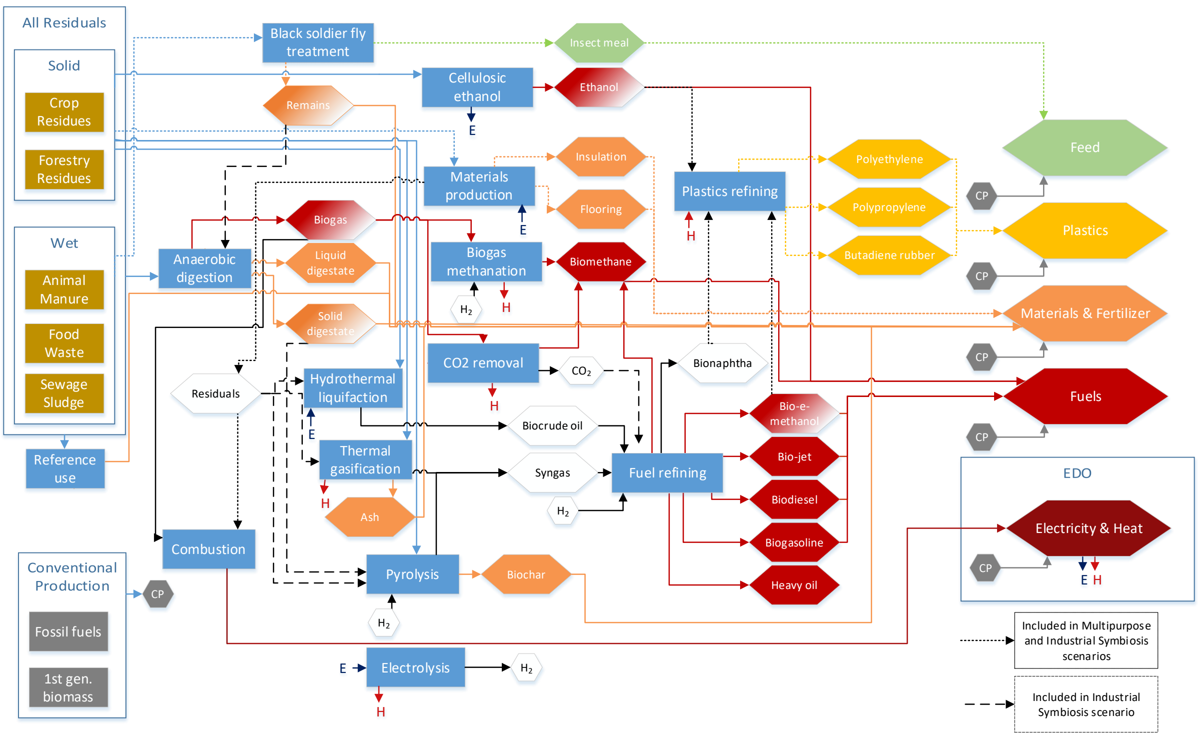

Figure 2: Overview of modeled network and end-product categories to the right with electricity (E) and heat (H) intensive processes. The link to the electricity and district heating optimization model, EDO, is shows in the bottom right of the figure. Processes are in blue boxes, green hexagons represent feed, yellow represent plastics, orange represent materials or fertilizer, red fuels, and the gradient hexagons can either be used as fuel or as input for further refining processes.

Modeling biomass use in OptiFlow

In this study, OptiFlow is applied to model the network outlined in Figure 2. Solid and wet residual biomass fractions go through conversion processes and the different products are either refined further or used as end-products. This broad representation of processes is used to identify least-cost production pathways. Constraints are included in OptiFlow to ensure that all residual biomass is used. Either they are used for producing bio-based products or minimally treated, in a so-called reference use. The reference use is meant to represent a situation where resources are not collected for production of bio-based products and is not associated with any economic cost apart from the externality costs resulting from environmental impacts, see Supplementary Information 8 for details on reference use. The resource potentials and demands as well as prices on externalities and conventional products are defined exogenously, see sections Resource availability, Conventional production, Demands, and Externality costs.

Side stream refining

In the industrial symbiosis scenario, side streams from one process can enter another upgrading process. For example, the remains from black soldier fly treatment for feed production can be used as input to anaerobic digestion and solid digestate from anaerobic digestion can be used for pyrolysis, as outlined in Figure 3. Regarding GHG emissions, land application entails emissions of CH_4, N_2O and some sequestration of carbon, denoted as –C. In anaerobic digestion some of the CH_4 generated is lost due to methane slips during the process. Nitrogen (N) and phosphorus (P) are applied on land where a set share is assumed to be utilized by crops and the rest lost in water and to the air, as N_2O also is quantified. The end-products in this example help in meeting the demands for feed and fuel. These demands can be met either by using bio-based production or with conventional production, which is associated with specific environmental impacts.

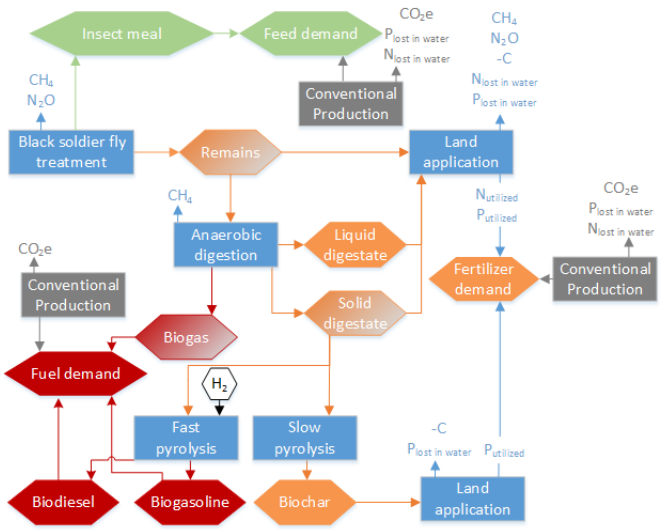

Figure 3: Overview of modeled uses of compost from production of feed through the black soldier fly process in the Industrial Symbiosis scenario.

Environmental impact indicators

Environmental impacts considered are global warming, freshwater and ocean eutrophication as these impact critical planetary boundaries, and air pollution, due to challenges with this in China. The impacts are indicated by quantifying GHG emissions, N and P lost to water, and direct PM2.5 emissions. There is no allocation of emissions or impacts from primary biogenic products to residuals [33]. This means that impacts from crop and forestry cultivation are not included when utilizing residues from these activities. Similarly the impacts associated with food production or consumption are not included in the utilization of food waste and sewage sludge. The impacts are quantified starting from the transportation or storage of the residuals and throughout the conversion and end-use of the residuals. Flows of N and P lost in water and used as fertilizer are tracked in OptiFlow. N and P lost in water is associated with a cost and N and P used as fertilizer is assumed to replace a demand for N and P fertilizer, competing with the cost of mineral N and P fertilizer. Fine particulate matter to air, direct PM2.5 emissions, are tracked for conversion processes and associated with a cost. These are most relevant in the reference use, as the PM2.5 emissions are substantial here, stemming from open burning of crop- and forest residues. GHGs are quantified for each process and associated with a cost per GHG species. This provides the opportunity to use varying global warming potential metrics.

Global warming is quantified through an inventory of the main GHG species; CO_2, CH_4, and N_2O associated with different pathways of biomass using the metric CO_2-equivalents (CO_2e). GHG emissions are converted to CO_2e using Global Warming Potential (GWP) conversion factors. In the present study, biogenic carbon is considered neutral, resulting in a GWP for biogenic CO_2 of zero, as described by Muñoz and Schmidt [34]. Using a 100 year time horizon, GWP100, biogenic CH_4 has a GWP of 27 compared to 29.8 for fossil CH_4, this to account for the methane oxidation of CH_4 [35]. For N_2O the GWP used is 273 and for fossil CO_2 it is one [35].

Eutrophication is exacerbated when N and P leach into water, and these two indicators are used to quantify freshwater and ocean eutrophication. Both N and P are essential biochemical flows to sustain life on Earth. For the arable land in China, the limits for mineral fertilizer application equals to 6.6 Tg N/year and 0.9 Tg P/year [3]. With applications of 31 Tg N/year and 6.5 Tg P/year there is currently massive over-application of mineral N and P fertilizer on Chinese soils [36]. This results in eutrophication being a major issue in China [37,38]. N and P in residual biomass (primarily animal manure) should be used to displace mineral fertilizer and not to add eutrophication. To this end, the amount of N and P used to replace mineral fertilizer as well as N and P ending up in waterways is quantified. Eutrophication is highly dependent on the locally specific soil quality, but in the present study generic data on shares of N and P leaching in to water is used for all of China. This means that the eutrophication quantification is associated with high degrees of uncertainty.

Air pollution comprises a number of substances and processes as well as both direct and secondary pollutants [39]. Addressing air pollution is relevant in a Chinese context as air quality is of great concern [40]. Despite the fact that official inventories state PM2.5 emissions from agriculture to be zero [41], research specifically investigating emissions from open burning of residues suggests open burning to substantially contribute PM2.5 [42]. In the present study, direct particulate emissions are used as a proxy for air pollution by quantifying emissions of particulate matter with a diameter ≤2.5 µm, called PM2.5.

Data for main scenarios and sensitivity analysis

The following section presents an overview of input data for the main scenarios as well as sensitivity scenarios which are analyzed to address uncertainty and inform how sensitive the results are to changes in different parameters.

Conversion pathways. There are multiple options for conversion pathways that could be included for each resource stream. In the present study, the options included are listed in Table 1. See Supplementary Information 10-21 for data on costs and efficiencies used.

Table 1: Conversion processes included for resources with main outputs and scenarios where they are included.

Main output	Conversion process	Crop Residues	Forestry Residues	Animal Manure	Food Waste	Sewage Sludge	Available in scenarios
Feed	Black soldier fly treatment			✓	✓	✓	Multipurpose & Industrial Symbiosis
Materials		Insulation	Flooring				Multipurpose & Industrial Symbiosis
Biogas	Anaerobic digestion	✓		✓	✓	✓	All
Bio-methanol SNG	Thermal gasification + synthesis	✓	✓				All
Bionaphtha Bio-diesel Bio-jet	Thermal gasification + Fischer-Tropsch	✓	✓				All
Ethanol	Cellulosic ethanol	✓	✓				All
Biocrude oil	Hydrothermal liquefaction	✓	✓				All
Bio-gasoline Bio-diesel	Fast pyrolysis	✓	✓				All
Carbon sequestration		Insulation	Flooring				Multipurpose & Industrial Symbiosis
	Thermal gasification	✓	✓				All
	Slow pyrolysis	✓	✓				
	Anaerobic digestion			✓	✓	✓	
	Reference use	✓	✓	✓	✓	✓	
	Black soldier fly treatment			✓	✓	✓	Multipurpose & Industrial Symbiosis
N fertilizer	Anaerobic digestion	✓		✓	✓	✓	All
	Hydrothermal liquefaction	✓	✓				
	Reference use			✓			
	Black soldier fly treatment			✓	✓	✓	Multipurpose & Industrial Symbiosis
P fertilizer	Anaerobic digestion			✓	✓	✓	All
	Thermal gasification	✓	✓				
	Hydrothermal liquefaction	✓	✓				
	Slow pyrolysis	✓	✓				
	Reference use			✓			

Hydrogen is needed as input to several of the fuel production routes. This hydrogen is produced through water electrolysis and options for AEC, PEM, and SOEC electrolyzes are included. Upgrading processes using output listed in Table 1 are listed in Table 2.

Table 2: Included upgrading of intermediate products.

<table>
<tr><th></th><th>Biogas</th><th>Biocrude oil</th><th>Ethanol</th><th>Bio-methanol</th><th>Bionaphtha</th></tr>
<tr><td>SNG</td><td>CO_2 removal
Methanation</td><td></td><td></td><td></td><td></td></tr>
<tr><td>Bio-jet</td><td></td><td rowspan="4">Hydrotreatment</td><td></td><td></td><td></td></tr>
<tr><td>Bio-diesel</td><td></td><td></td><td></td><td></td></tr>
<tr><td>Bio-gasoline</td><td></td><td></td><td></td><td></td></tr>
<tr><td>Heavy-bio-oil</td><td></td><td></td><td></td><td></td></tr>
<tr><td>Power and heat</td><td>Boiler</td><td></td><td></td><td></td><td></td></tr>
<tr><td>Polyethylene</td><td></td><td></td><td>Catalytic dehydration + polymerization</td><td rowspan="2">Methanol to olefins + polymerization</td><td rowspan="3">Steam cracking + polymerization</td></tr>
<tr><td>Polypropylene</td><td></td><td></td><td></td></tr>
<tr><td>Polybutadiene</td><td></td><td></td><td></td><td></td></tr>
</table>

The possible pathways for side streams from processes differ in the different scenarios. In the Industrial Symbiosis scenario refining of side streams are included, see Table 3 for an overview.

Table 3: Overview of available pathways for side streams in the different scenarios.

<table>
<tr><th></th><th>CO_2 from biogas to SNG</th><th>Residues from materials production</th><th>Solid digestate from anaerobic digestion</th><th>Residue from black soldier fly treatment</th><th>Available in scenarios</th></tr>
<tr><td></td><td>Venting</td><td></td><td></td><td></td><td rowspan="4">All</td></tr>
<tr><td>Power and heat</td><td></td><td>Boiler</td><td></td><td></td></tr>
<tr><td>P fertilizer</td><td></td><td></td><td rowspan="2">Land application</td><td rowspan="2">Land application</td></tr>
<tr><td>N fertilizer</td><td></td><td></td></tr>
<tr><td>Biogas</td><td></td><td></td><td></td><td>Anaerobic digestion</td><td rowspan="7">Industrial symbiosis</td></tr>
<tr><td>Methanol
SNG</td><td></td><td>Thermal gasification + synthesis</td><td></td><td></td></tr>
<tr><td>Bionaphtha
Bio-diesel
Bio-jet</td><td>Fischer-Tropsch</td><td>Thermal gasification + Fischer-Tropsch</td><td></td><td></td></tr>
<tr><td>Ethanol</td><td></td><td>Cellulosic ethanol</td><td></td><td></td></tr>
<tr><td>Biocrude oil/heavy-bio-oil</td><td></td><td>Hydrothermal liquefaction</td><td></td><td></td></tr>
<tr><td>Bio-gasoline
Bio-diesel</td><td></td><td>Fast pyrolysis</td><td>Fast pyrolysis</td><td></td></tr>
<tr><td>Biochar</td><td></td><td>Slow pyrolysis</td><td>Slow pyrolysis</td><td></td></tr>
</table>

The conversion technologies used in this study are of varying maturity levels, see Supplementary Information 10-21 regarding cost assumptions. The learning curves for conversion technologies used are associated with varying degrees of uncertainty as cost projections regarding widely used technologies are typically more certain than technologies with lower readiness levels. To address this a sensitivity analysis with slow technology development is performed where the investment costs for year 2030 are used for year 2050 and a linear interpolation is used from current values to 2050. Regarding insulation and flooring from crop and forestry residues, this is based on a few cases and large-scale applicability is highly uncertain. In this sensitivity analysis, the option to use crop and forestry residues for insulation and flooring is removed from the model. Additionally, the use of sewage sludge for feed though black soldier fly treatment could be associated with regulatory issues, which is why that option is also disregarded in this sensitivity analysis. In general, in this slow technology development sensitivity analysis, technologies with a stable cost outlook benefit whereas conversion technologies with optimistic cost reduction projections are at a disadvantage.

Resource availability. All collectible biomass residues in the categories crop residues, forestry residues, animal manure, food waste, and sewage sludge are considered. The resources are assessed for each of China's provincial level administrative divisions. Hong Kong, Macao, and Taiwan are excluded due to limitations in main data sources. Inner Mongolia is divided into north and east, following the electricity grid regions, making 32 province level regions. For crop residues, quantities retained in field for soil improvement are excluded. See Figure 4 for an overview of resource availability by province in 2050 and see Supplementary Information 2-6 for details. The costs of residual biomass consist of collection costs and transportation costs, specified in Supplementary Information 23. Use of by-products are not associated with any cost as the plants are assumed to be co-located.

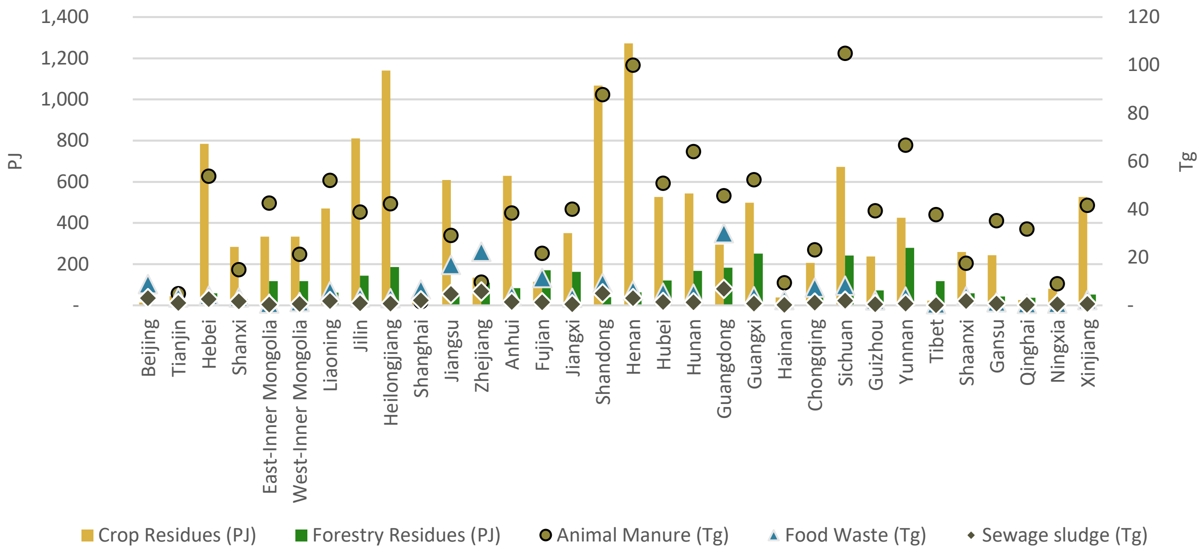

Figure 4: Overview of residual biomass resource availability by province in 2050. For references see Supplementary Information 2-6.

Conventional production. Conventional products compete with residual-bio-based products to satisfy the same demand in the model. These are mostly fossil based alternatives and are all associated with costs and environmental impacts. The environmental impacts of conventional products are generally extracted from the ecoinvent database [43] and consequential life-cycle data are used. The study explores potential scenarios for future development and the consequential approach permits estimating system changes. See Supplementary Information 9 for specific processes and versions. Data on conventional prices and fuel price projections can be found in Supplementary Information 23. All costs are converted to 2019 RMB using the inflation rates from the World Bank [44] and for discounting investment costs, a discount rate of 5.9% is used, corresponding to the discount rate used by the Energy Research Institute (ERI) [45].

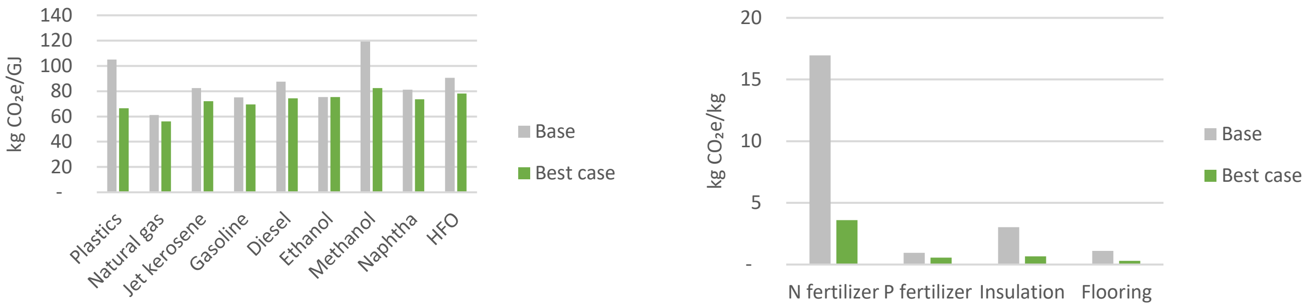

Figure 5: Overview of base case CO_2e emissions for conventional production of products and best case used in the sensitivity analysis.

Regarding environmental impacts, it is assumed that the conventional production of products remains similar to what it is today and current data is used. A sensitivity analysis with a best case is constructed for future conventional production. In the best case it is assumed that the electricity and heat sectors approach carbon neutrality. Therefore GHG emissions from the electricity and heat intensive processes are excluded from current conventional production emissions to reflect this development, see Figure 5. For N, P and PM2.5 the impacts are kept the same as in the main scenarios.

Another key aspect of conventional production is the price the products. The sensitivity to this parameter is tested with a sensitivity of ±50% of the prices in the main scenarios. Conventional products are placed in the following four categories: fossil fuels and plastics, feed and ethanol, fertilizer, and construction materials.

Demands. The model is set to fulfill set levels of minimum demands, while reducing costs, which is why these are key input parameters. Projections for demand by end-use products are shown on the national level in Figure 6 and are detailed in Supplementary Information 22. Demands are set at regional levels, where China's provinces are divided into the six regions North, Northeast, East, Central, South, and Northwest.

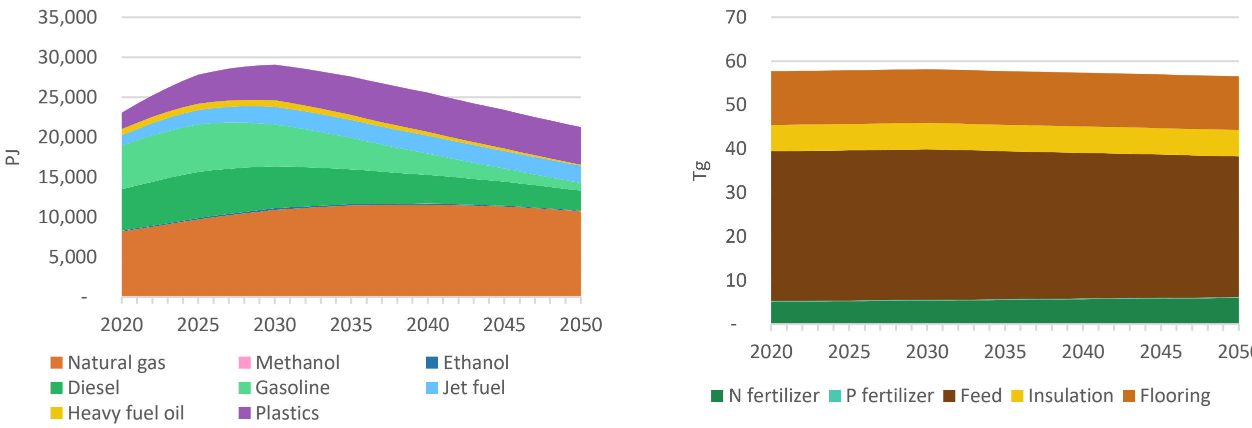

Figure 6: National demands for fuels and plastics (left), and national demands for fertilizer, feed, and construction materials (right).

Externality costs. A China specific social cost level is used with following costs; 2.9 RMB/kg CO_2e [46], 368 RMB/kg N lost in water [47], 1085 RMB/kg P lost in water [47] and 228 RMB/kg PM2.5 emitted to air [48]. Pricing of externalities are highly debated and can be performed using a range of different methods, causing the externality costs to be subject of a sensitivity analysis. The two levels used in sensitivity analysis are listed in Table 4, along with the social cost levels used in the main scenarios. The alternative social costs are non-China specific, average costs, from Pizzol et al. [49] and the current policy level represent the current Chinese tax levels [48,50,51]. The current policy level is far lower than the alternative social cost level, which is considerably lower than the China specific social cost level.

Table 4: Overview of costs for environmental externalities used in the different sensitivity scenarios in RMB 2019/kg. CO_2e costs are assumed to differ in year 2030 and year 2050 for the current policy scenario.

	Social cost	Alternative social cost	Current Policy	
			2030	2050
CO_2e	2.9	1.0	0.09	0.17
N lost in water	368	29	1.9	
P lost in water	1085	239	6.0	
PM2.5	228	*228	2.6	

* Due to lack of data on alternative social cost for PM2.5 emissions, the China specific social cost value is used.

Results and analysis

The following presents and analyzes aggregated results for China for year 2050.

Main scenarios

The energy and main mass flows for the Energy scenario are shown in a Sankey diagram in Figure 7. Available residual biomass resources are shown to the left. These are the same in all scenarios. Under the residual biomass resources are the specific electricity, heat, and hydrogen input needed in each scenario. End-products are shown towards the right side of the diagram. These products can be produced through conversion of residual biomass or by conventional production, which is shown by the gray flows from the top right corner. The residual biomass that is not utilized and ends up in reference use is shown in the bottom right corner as reference use. Feed, materials, and plastics are covered fully by conventional production, while the residual resources are primarily used for fuel, power and heat production.

In the Energy scenario, the crop residues are primarily used through fast pyrolysis to produce bio-gasoline and bio-diesel. Crop residues are also used in hydrothermal liquefaction (HTL) as well as in thermal gasification to produce synthetic natural gas (SNG) and methanol (MeOH) and in anaerobic digestion for biogas. The main use of forestry residues is fast pyrolysis and HTL with biocrude oil from this process being upgraded through hydrotreatment. Crop and forestry residues are also used in cellulosic ethanol processes to cover all ethanol demand. The methanol demand is exceeded in the Energy scenario. This is a representation of the high cost of not utilizing the resources, as these are associated with the imposed externality costs, making it more profitable to produce more MeOH than the minimum demand. In a case with lower externality costs, using the current policy level listed in Table 4, the resources end up in reference use instead, as shown in Figure 13. In the Energy scenario, the only utilization pathway for wet biomass is through anaerobic digestion. For animal manure and sewage sludge, all available resources are treated in anaerobic digestion. For food waste, one fourth of the resource ends up in reference use. The biogas generated is upgraded to SNG through a CO_2 removal process. This option is preferred by the model to the methanation option, where hydrogen is added and the CO_2 in the biogas is converted to SNG through hydrogenation. When the CO_2 is removed through upgrading in the Energy scenario the biogenic CO_2 output is vented as there is no option for further refining of the biogenic CO_2 stream in the Energy and Multipurpose scenarios.

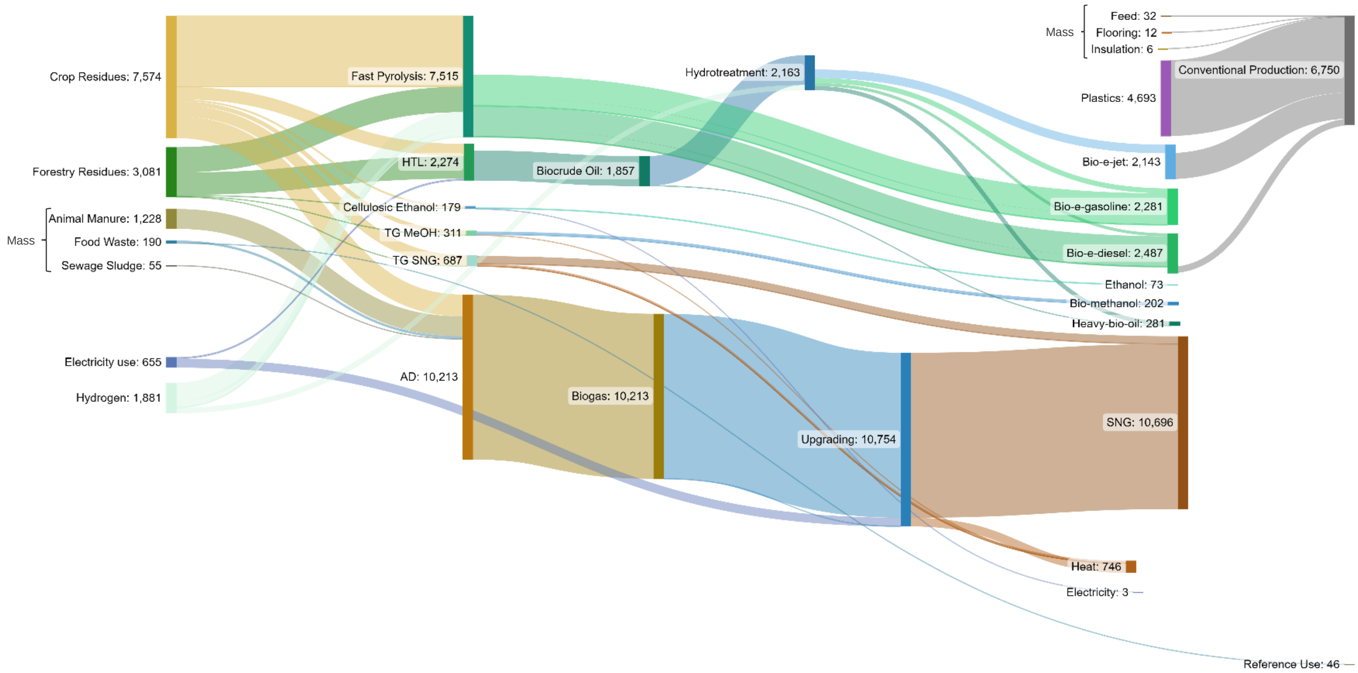

Figure 7: Energy and mass flows in the Energy Scenario. Flows in PJ unless noted as mass, which are in Tg. Flows with value of less than 1 PJ or 1 Tg are not shown.

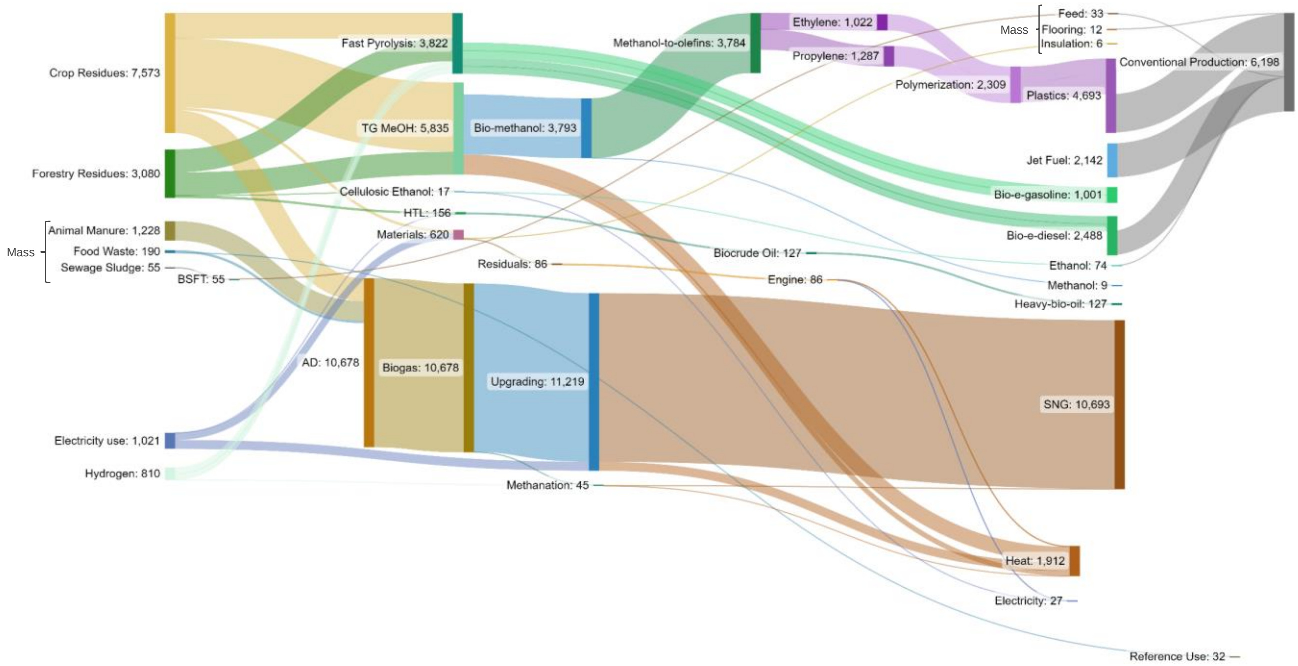

Figure 8: Energy and mass flows in the Multipurpose Scenario. Flows in PJ unless noted as mass, which are in Tg. Flows with value of less than one PJ or one Tg are not shown.

In the Multipurpose scenario, a full range of new options are included to show residual biomass use in non-energy sectors as shown in Figure 8. Seventeen percent or 32 Tg of food waste ends up in reference use in the Multipurpose scenario, which is less than in the Energy scenario. In the Multipurpose scenario, the largest share of crop and forestry residues are used in thermal gasification, with a subsequent methanol synthesis process. This enables production of bioplastics through a methanol-to-olefins process and subsequent polymerization into plastic polymers. The wet biomass is mostly used for biogas, but sewage sludge is used to produce insect meal for feed through black soldier fly treatment, the remains are composted and spread on land. All insulation demand is covered by use of crop residues and the residuals from this process are used for heat and power, as this is the only option in this scenario. When refining of side-streams are included, in the Industrial Symbiosis scenario, even less food waste ends up in reference use (11% or 21 Tg), and there is a smaller share of demands covered by conventional production as shown inFigure 9.

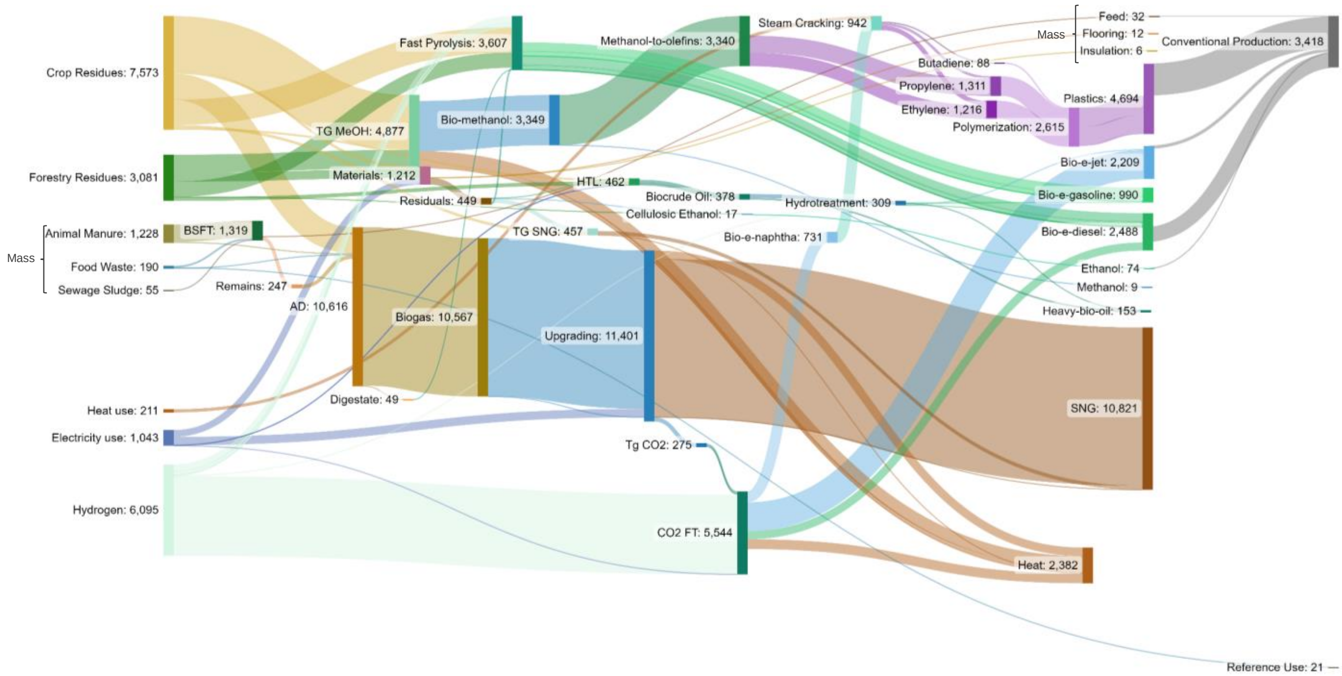

Figure 9: Energy and mass flows in the Industrial Symbiosis Scenario. Flows in PJ unless noted as mass, which are in Tg. Flows with value of less than one PJ or one Tg are not shown.

In the Industrial Symbiosis scenario, the option to use anaerobic digestion of black soldier fly treatment remains is fully utilized and solid digestate from this digestion is used in fast pyrolysis to produce bio-gasoline. Biogas is, also in the Industrial Symbiosis scenario, upgraded using CO_2 removal. In this scenario most of the CO_2 stream is used for in a Fischer–Tropsch process to produce bio-jet, bio-diesel, and bionaphtha. It is evident that with the extended opportunities for use of residual biomass, more resources are utilized. The high collection cost for source separation of food waste, combined with rather low environmental impacts in the reference use scenario, makes this the last fraction to be utilized.

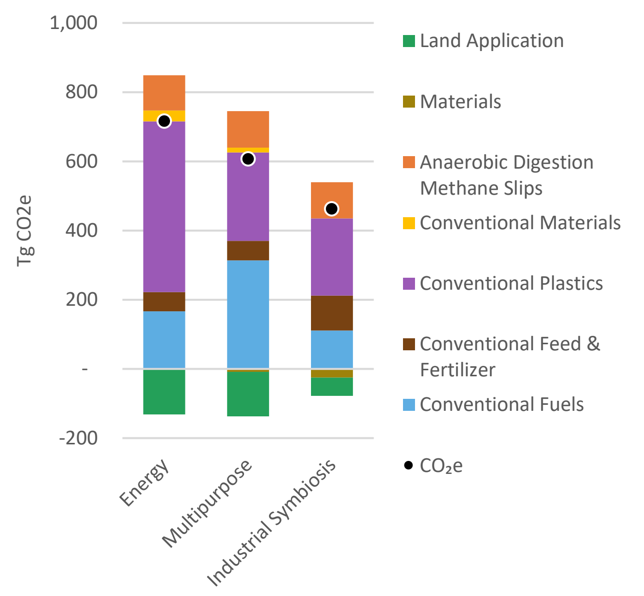

Figure 10: Overview of GHG emissions and carbon sequestration in the main scenarios.

The GHG emissions and carbon sequestration associated with each scenario are shown in Figure 10.For more details on origin and GHG species, see Supplementary Information 26.1. In the Energy scenario, most GHG emissions stem from the use of conventional fuels. In the Multipurpose scenario the overall GHG emissions are reduced but the use of conventional fuels is increased because of diversion of some residual biomass resources to produce plastics. The use of conventional N fertilizer is increased in the Industrial Symbiosis scenario. This is because side streams, particularly solid digestate, which are applied on land and used to replace mineral fertilizers in the Energy and Multipurpose scenarios, are used for fuel production in the Industrial Symbiosis scenario. For this reason, the negative emissions, primarily from carbon sequestration due to land application of solid digestate, are reduced in the Industrial Symbiosis scenario.

Nutrient losses are comparable in the Energy and Multipurpose scenarios while they are significantly reduced in the Industrial Symbiosis scenario as seen on the logarithmic scale in Figure 11 This is due to pyrolysis of solid digestate. Specified nutrient

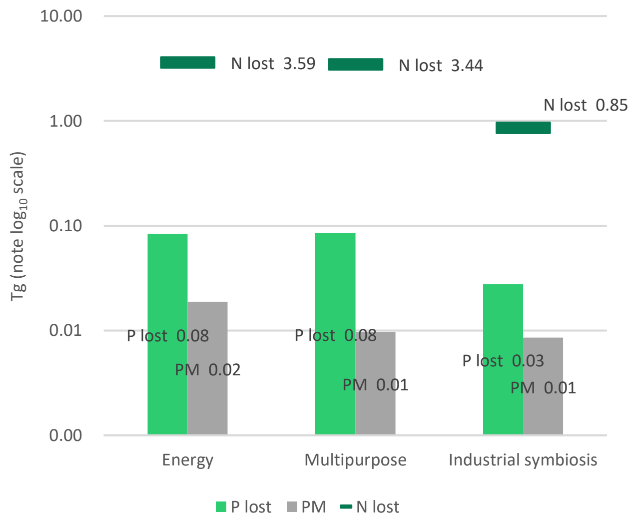

Figure 11: Nutrient losses to water and PM emissions in the three main scenarios on a logarithmic scale.

flows with N and P utilization and losses for the main scenarios, are provided in Supplementary Information 26.2. PM emissions are also lower. These stem primarily from use of conventional plastics in these scenarios, which is why they are highest in the Energy scenario. The Industrial Symbiosis offers the most options and is therefore also associated with the lowest costs. The Energy scenario system costs are 37% higher and the Multipurpose scenario is 27% higher than the Industrial Symbiosis scenario. These dramatic differences in costs are to a large degree due to externality costs. Comparing the Energy and Industrial Symbiosis scenarios with current policy externality costs, on the other hand results in the Energy scenario costs being only 1% higher than the Industrial Symbiosis scenario.

Sensitivity scenarios

Using different ways of pricing externalities has a major impact on results. In the following section, the results for the three scenarios are compared when using three different levels of externality costs: 1) the China specific Social costs as illustrated in the main scenarios above, 2) Alternative social costs and 3) the Current policy level, all specified in Table 4 and results shown in Figure 12.

When using the Current policy level in the Energy scenario, the entire natural gas (NG) demand and most of the diesel (DF) demand is covered by fossil fuels, see Figure 12. Natural gas demand is fully covered by use of residuals converted to SNG in the three main scenarios, but this depends on the externality costs. When they are reduced, so is the share of natural gas demand covered by SNG produced from residuals. Production of insulation (IN) and plastics (PL) are also heavily affected and start being feasible with the Alternative social costs, while use for flooring (FL) only appears in the Industrial Symbiosis Scenario with the highest Social costs.

Figure 13: Overview of demands met by conventional products or use of residuals in the main scenarios and sensitivity scenarios with alternative social costs and current policy externality costs. FE: Feed, IN: Insulation, FL: Flooring, PL: Plastics, JF: Jet Fuel, DF: Diesel, GF: Gasoline, ET: Ethanol, ME: Methanol, HF: Heavy fuel oil, NG: Natural gas, NF: N fertilizer, PF: P fertilizer.

Figure 12: Overview of residual biomass to reference use in the main scenarios and sensitivity scenarios with alternative social costs and current policy externality costs.

All crop residues and most wet biomass end up in reference use when using the Current policy level in the Energy scenario as shown in Figure 13. The share of resources going to reference use is reducing as more options are included for residual biomass utilization and as externality costs increase. In the Multipurpose scenario with Current policy externality costs, sewage sludge is utilized for feed production through black soldier fly treatment, but there is still 76% of animal manure going to reference use. In the Industrial Symbiosis scenario with Current policy externality costs, the animal manure going to reference use is reduced to 7%. This happens as the possibility of refining side streams makes it profitable to utilize animal manure for black soldier fly treatment, when the remains from this process can be used as input for anaerobic digestion.

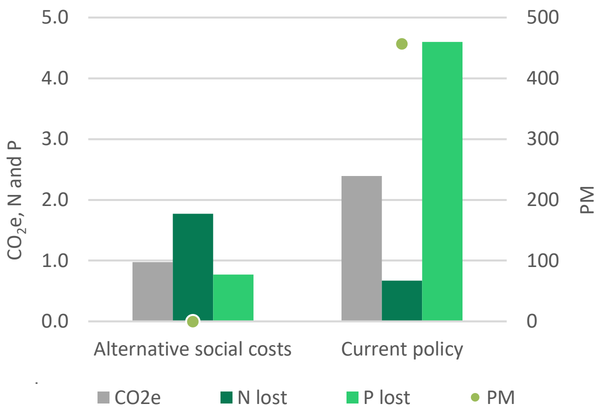

Figure 14: Relative difference of GHG emissions, N and P losses as well as PM emissions in the externality costs sensitivity scenarios compared to the Industrial Symbiosis scenario using China specific Social costs.

Going into more detail with the sensitivity scenarios on Industrial Symbiosis, reduced externality costs have significant impacts when comparing the main Industrial Symbiosis scenario to the Alternative social cost and Current policy externality cost. The GHG emissions are almost twice as high in the scenario with Alternative social costs and 2.4 times the emissions with the Current policy levels, see Figure 14. The nutrient losses are also significantly higher with lower externality costs. The current policy case shows a vast increase in PM emissions, which is 456 times the levels in the Industrial Symbiosis scenario with the highest social costs. These stem from open burning of crop residues as 91% of crop residues are not utilized, meaning that they end up in reference use. The reduced externality costs result in lower system costs in these scenarios, 11% lower with alternative social costs and 24% lower with current policy costs. The results from the sensitivity scenarios are compared to the Industrial Symbiosis scenario with China specific social externality costs for the remaining sensitivity scenarios, as this is the main scenario associated with the lowest costs and environmental impacts. Figure 15 provides an overview of changes in demand covered by residuals in various sensitivity scenarios compared to the Industrial Symbiosis scenario.

The two first sensitivity analyses illustrate the great impact of different externality costs, which is illustrated above. For the remaining results, the main difference is in production of ethanol, insulation and flooring, see Figure 15. In the sensitivity with best case environmental impacts for conventional products there is a substantial reduction in GHG emissions primarily due to the reduced emissions from conventional plastics. The share of conventional plastics are the same as in the Industrial Symbiosis scenario, but the GHG emissions and system costs are reduced. There is an increased use of conventional flooring and the forestry residues are diverted to ethanol production. In the slow technology development sensitivity scenario, being unable to use sewage sludge in black soldier fly treatment for insect meal only marginally affects the share of feed being covered by this route. Crop and forestry residues which are used for construction materials are used instead in this scenario to produce plastics.

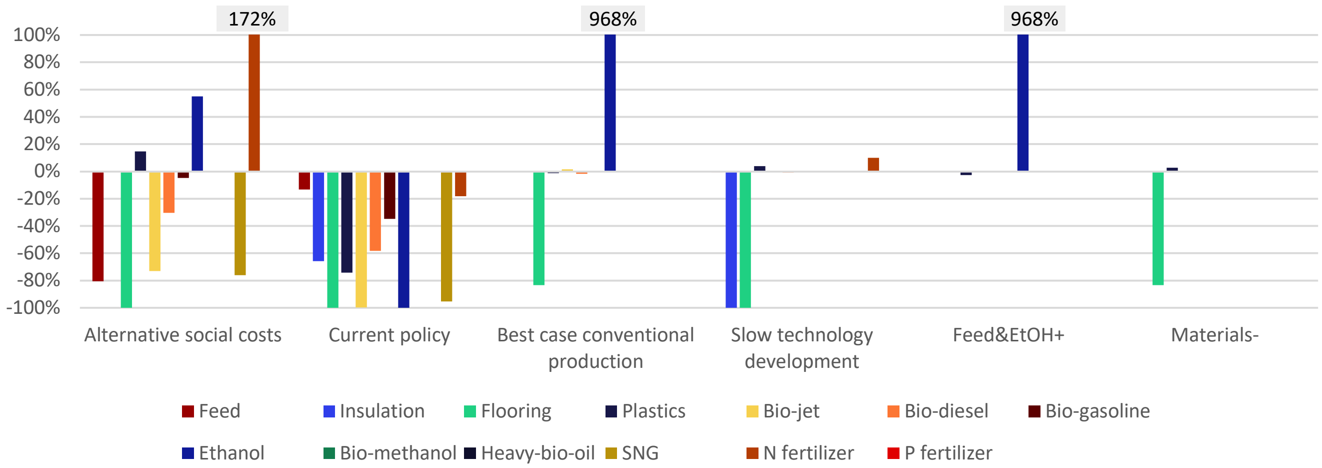

Figure 15: Relative change in demand covered by residuals in sensitivity scenarios compared to the Industrial Symbiosis scenario. For all sensitivity scenarios see Supplementary Information 26.3.

Sensitivities to conventional product prices show a limited impact on demand covered by residuals with a few exceptions, for an overview of results from all sensitivity scenarios see Supplementary Information 26.3. Changes in feed and ethanol prices have no impact on the use of bio-residuals for feed, but with increased conventional prices all ethanol demand is covered by bio-residuals. For conventional material prices, the change of ±50% has no effect on insulation, but reduced prices lead to the flooring going from 100% to 17% of demand being covered by bio-residuals.

Discussion

While this study has illustrated the benefits of utilizing side-streams in an Industrial Symbiosis scenario, it has not addressed issues regarding risk-sharing and cooperation in such partnerships, which could be interesting for further research. Furthermore, costs related to biomass collection follow increasing cost curves in real life, as easily accessible biomass is less expensive to collect than remote resources. In the present study a flat biomass cost is used due to lack of data. With improved data availability, this could be improved by including a cost curve to reflect scarcity pricing.

Previous work has shown that conventional production outperforms biomass gasification when a number of environmental impacts are included and monetized [52]. This stems from the pretreatment of biomass where the catalysts used have great impact on human toxicity [52]. This points to the relevance of including additional impacts, such as human toxicity. The planetary boundary related to novel entities has recently been quantified showing that current levels significantly exceed set boundaries [4]. Novel entities are not considered in this present study and their inclusion would also be highly relevant. This could be accomplished by including indicators regarding novel entities such as heavy metals. In addition to the production of the novel entities, bio-based plastics are used as competitors to fossil plastics. Here processes to produce biodegradable plastic materials could be included to cover plastic demand as the short lifetime of biodegradable plastics would be preferable in a novel entities perspective. The methodology applied is flexible, able to include more options for resource use, to study the applicability of using, for example crop residues to composite materials [53], further use of lignin [54], different feed pathways [55], and fuel production [56].

Conclusion

This study contributes with a system perspective on optimal use of residual biomass by including multiple pathways for use, compared with conventional production to satisfy end-use demands and includes key environmental indicators. In the bioeconomy, resource efficiency is key and this study shows that utilizing side streams has a significant impact on nutrient losses, GHG emissions, PM, and system costs. By quantifying the impacts in a co-optimization between energy and resource use, the results show that when the model is extended to include non-energy use of biomass, many of these options are utilized. This challenges the frequent assumption that all residual biomass would be available for energy uses and suggests that bio resource availability for energy purposes should include considerations for use of biomass in non-energy sectors. When comparing the Multipurpose and Industrial Symbiosis scenarios it is clear that there is value in refining side streams. The Industrial Symbiosis scenario, where side streams can be refined to satisfy fuel and plastics demands, is less costly and associated with fewer emissions than the Multipurpose scenario, which does not include these options. This shows that these options should be included when assessing residual biomass allocation and industrial symbiosis possibilities should be facilitated in society. These scenarios are compared to a third main scenario where the residual biomass is only available for use in the Energy sector. The results show that there is significant added value of using residual biomass in non-energy sectors, pointing to the need to keep a broad scope when assessing resource availability as opposed to assuming all to be available for the energy sector. The results are sensitive to how externalities are priced. However, in all cases of varying pricing levels explored, there are the same trends. As options to use residual biomass expand, so does the value of residual biomass. The results show that using forestry residues has the greatest benefit to society, followed by sewage sludge, animal manure, crop residues, and lastly food waste. This is clear as the demands covered by residual biomass increase and resources ending up in reference use decline as the options for use of residual biomass expand and refining of side streams is included. The methodology presented in this study is flexible and can be used in different countries or at a smaller scale to assess use of residual biomass.

Data availability

For the OptiFlow model please see:
https://github.com/balmorelcommunity/Balmorel/tree/master/base/addons/optiflow/bb4
Input data used in this analysis is available in supplementary information and data for network configuration can be provided upon request.

Author Contributions

Sara Shapiro-Bengtsen: Conceptualization, Methodology, Formal Analysis, Investigation, Validation, Writing – Original Draft, Visualization **Rasmus Bramstoft**: Conceptualization, Methodology, Validation, Data Curation, Writing – Review & Editing **Lars Bregnbæk**: Methodology, Software, Resources **Marie Münster**: Conceptualization, Methodology, Writing – Review & Editing, Supervision

Conflicts of interest

There are no conflicts to declare.

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Abbreviations

CAPEX	Capital expenditures
CH_4	Methane
CO_2	Carbon dioxide
CO_2e	Carbon dioxide equivalents
DF	Diesel
ET	Ethanol
EtOH	Ethanol
FE	Feed
FL	Flooring
GF	Gasoline
GHG	Greenhouse gas
HF	Heavy fuel oil
HTL	Hydrothermal liquefaction
IN	Insulation
JF	Jet fuel
ME	Methanol
MeOH	Methanol
N	Nitrogen
N_2O	Nitrous oxide
NF	Nitrogen fertilizer
NG	Natural gas
O&M	Operating and maintenance
P	Phosphorus
PF	Phosphorus fertilizer
PJ	Petajoule (10^{15} joules)
PL	Plastics
PM2.5	Particulate matter ≤ 2.5 micron
SNG	Synthetic natural gas
Tg	Teragram (10^{12} grams, 1 million metric tonnes)

Nomenclature

$\mathcal{A}$	Areas
$\mathcal{A}_r^{\mathcal{R}}$	Subset of areas in region $r \epsilon \mathcal{R}$
c_g^{CAPEX}	Annualized investment cost of technology, g
$c_{r,r'}^{CAPEX}$	Annualized investment cost of electricity transmission line from r to r'
$c_g^{fxO\&M}$	Fixed operation costs of technology g
$c_g^{vO\&M}$	Variable operation costs of technology g
$d_{r,t}^{dh}$	District heating demand in area a in time-step t
$d_{r,t}^{el}$	Electricity demand in region r in time-step t
$\mathcal{F}$	Flows
$\mathcal{F}^{dh}$	Subset of flows used for heat exchange from or to OptiFlow
$\mathcal{F}^{el}$	Subset of flows used for heat exchange from or to OptiFlow
$\mathcal{F}^{Money}$	Subset of flows used for flow of monetary values from OptiFlow to EDO
$\mathcal{G}$	Technologies
$\mathcal{G}^{dh}$	Subset of technologies that produce district heating
$\mathcal{G}^{dh,Sto}$	Subset of technologies representing storage of district heating
$\mathcal{G}^{dh,VRE}$	Subset of technologies representing VRE technologies for producing district heating
$\mathcal{G}^{el}$	Subset of technologies that produces electricity
$\mathcal{G}^{el,Sto}$	Subset of technologies representing storage of electricity
$\mathcal{G}^{el,VRE}$	Subset of technologies representing VRE technologies for producing electricity
$\mathcal{P}$	Processes or commodity level
$\mathcal{P}^{dh}$	Subset of processes that represents net production or consumption heat in OptiFlow
$\mathcal{P}^{el}$	Subset of processes that represents net production or consumption electricity in OptiFlow
$\mathcal{P}^{Econ}$	Subset of processes that represents the process for economic exchange of monetary values between OptiFlow and EDO
p, p', p''	Processes, used to represent from one process p to another process p' or p''
$p_{a,t,g}$	Commodity level in area a of technology g in time-step t

$p_{a,t,g}^{dh}$	District heating level in area a of technology g in time-step t
$p_{a,t,g}^{dh,toSto}$	Heating level to storage assets in area a of technology g in time-step t
$p_{a,t,g}^{dh,fromSto}$	Heating level from storage assets in area a of technology g in time-step t
$p_{a,t,g}^{dh,curt}$	Production of heat which is curtailed in area a of technology g in time-step t
$p_{a,t,g}^{el}$	Electricity level in area a of technology g in time-step t
$p_{a,t,g}^{el,toSto}$	Electricity level to storage assets in area a of technology g in time-step t
$p_{a,t,g}^{el,fromSto}$	Electricity level from storage assets in area a of technology g in time-step t
$p_{a,t,g}^{el,curt}$	Production of electricity which is curtailed in area a of technology g in time-step t
$p_{a,g}^{ex}$	Existing capacity of technology g in area a
$p_{a,g}^{new}$	Investment in new capacity of technology g in area a
$p_{r,r'}^{tr,new}$	Investment in new electricity transmission capacity between region r and r'
$p_{r,r't}^{tr}$	Export of electricity via transmission in time-step t
$p_{r',r,t}^{tr}$	Import of electricity via transmission in time-step t
$\mathcal{R}$	Regions
$\mathcal{R}_{r,r'}^{exp}$	Subset of regions where region $r\epsilon\mathcal{R}$ can export to
$\mathcal{R}_{r',r}^{imp}$	Subset of regions where region $r\epsilon\mathcal{R}$ can import from
$\mathcal{R}_{a,p,p',f}^{APPF}$	Subset of flows f from process p to process p' in area a
$\mathcal{S}$	Seasons
$\mathcal{T}$	Time-steps in a season
$V_{a,t,p,f}^{B,OptiFlow}$	Net flow f from buffer process $\mathcal{P}^B$ in area a at time-step t
$V_{a,t,p,p',f}$	Flow f from process p to process p' in area a at time-step t
$\mathcal{X}_{a,p}^{AP}$	Endogenously optimized capacity of process p in area a

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