Modelling Renewable Energy Islands

and the Benefits for Energy Planning

Marczinkowski, Hannah Mareike

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MODELLING RENEWABLE ENERGY ISLANDS

AND THE BENEFITS FOR ENERGY PLANNING

BY
HANNAH MAREIKE MARCZINKOWSKI

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AALBORG UNIVERSITY
DENMARK

MODELLING RENEWABLE ENERGY ISLANDS

AND THE BENEFITS FOR ENERGY PLANNING

by

Hannah Mareike Marczinkowski

PhD Thesis

AAU

Knowledge for the World

Knowledge from Islands for Islands and the World

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PhD supervisor: Professor Poul Alberg Østergaard
Aalborg University

Assistant PhD supervisor: Assistant Prof. Søren Roth Djørup
Aalborg University

PhD committee: Professor Anne Merrild Hansen (chairman)
Aalborg University

Professor Erik Olof Ahlgren
Chalmers University of Technology

Professor Henrik Klinge Jacobsen
Technical University of Denmark

PhD Series: Technical Faculty of IT and Design, Aalborg University

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Cover photo: The photo on the cover page shows the German island Föhr – taken by the author born there – as seen from the ferry on a visit half way through the PhD research.

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CV

Hannah Mareike Marczinkowski, born on Föhr, earned the B.Sc. in Environmental Engineering at the University of Applied Sciences (HAW) Hamburg, Germany in 2014 and the M.Sc. in Sustainable Energy Planning and Management at Aalborg University, Denmark in 2016.

In May 2017, Hannah acquired a research assistant position, and in January 2018, she was appointed a PhD stipend on 'Modelling of Smart Renewable Energy Islands' at the Department of Planning, Aalborg University.

From 2017 to 2018, she was involved in the ERA-Net Smart Grids project MATCH: Markets, Actors and Technologies–A comparative study of smart grid solutions, and from 2017 to 2021, she contributed in the Horizon 2020 project SMILE: Smart Island Energy systems– Demonstrating demand response, smart grid functionalities, storage and energy system integration. The participation in both projects resulted in visits to the islands Fur, Hvaler, Samsø, Madeira and Orkney, as well as Sicily, Helgoland, Åland, Shetland and Texel.

Next to the PhD research, Hannah was a volunteer at the PhD Network of Aalborg University (PAU) from August 2018 and at the PhD Association Network of Denmark (PAND) from March 2019, as well as the Sustainable Campus Forum at Aalborg University from March 2020.

Publications during the PhD research period 2018-2021 include five peer-reviewed journal papers and four additional reports in relation to the MATCH and SMILE projects.

Peer-reviewed papers published during the PhD period:

- H. M. Marczinkowski and P. A. Østergaard, "Residential versus communal combination of photovoltaic and battery in smart energy systems," Energy, available 29/03/2018. [1]
- P. A. Østergaard, J. Jantzen, H. M. Marczinkowski, and M. Kristensen, "Business and socioeconomic assessment of introducing heat pumps with heat storage in small-scale district heating systems," Renew. Energy, available 01/03/2019. [2]
- H. M. Marczinkowski and P. A. Østergaard, "Evaluation of electricity storage versus thermal storage as part of two different energy planning approaches for the islands Samsø and Orkney," Energy, available 19/03/2019. [3]
- H. M. Marczinkowski, P. A. Østergaard, and S. R. Djørup, "Transitioning island energy systems—Local conditions, development phases, and renewable energy integration," Energies, available 10/09/2019. [4]

- H. M. Marczinkowski and L. Barros, “Technical Approaches and Institutional Alignment to 100% Renewable Energy System Transition of Madeira Island—Electrification, Smart Energy and the Required Flexible Market Conditions,” Energies, available 27/08/2020. [5]

Other publications during the PhD research:

- H. M. Marczinkowski, “Smart Island Energy Systems (SMILE) Deliverable D8.1: Reference energy systems simulations models of the three pilot islands,” Aalborg University, January 2018. [6]
- H. M. Marczinkowski and P. A. Østergaard, “Markets, actors, technologies: a comparative study of smart grid solutions (MATCH) Deliverable 4.1: Report on energy system analysis,” Aalborg University, August 2018. [7]
- H. M. Marczinkowski, “Smart Island Energy Systems Deliverable (SMILE) D8.2: Short and medium-term scenarios for the three pilot islands,” Aalborg University, December 2018. [8]
- H. M. Marczinkowski, “Smart Island Energy Systems (SMILE) Deliverable D8.4: Energy market analysis,” Aalborg University, drafted for submission 2021. [9]

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Contact:

Rendsburggade 14
9000 Aalborg
Denmark
hmm@plan.aau.dk
hannah.marczinkowski@web.de

PREFACE

I wrote this PhD thesis ‘Modelling Renewable Energy Islands – and the benefits for energy planning’ during my employment at the Sustainable Energy Planning research group of the Department of Planning at Aalborg University from 2018-2021.

The initial aim of the thesis evolved around island research in the field of sustainable energy planning and thereby the challenges and solution for renewable energy on and for islands. With a broad range of answers to the initial idea, the PhD process and I were further influenced by the involvement with the MATCH and SMILE projects, as well as knowledge gathered from other islands and island-like energy systems looking for ‘smart’ solutions. The third target that I developed was the contribution of islands to energy planning and developing the smart energy systems concept.

The combination of island challenges, research and contributions, together with the projects and related publications results in the PhD thesis on hand. The research questions that I settled on address the modelling and scenarios of island energy systems as they are currently and how they might be used in the future. They connect with global trends in energy planning as well as islands’ role as demonstrators. What follows is sharing my understanding of islands as lighthouses, but also as individuals, which is motivated by research and observation on Samsø, Orkney and Madeira, as well as by additional island activities and my personal background. Hence, to be used by both energy planners and islanders, a look beyond the observations is included, which combines the initial ideas of finding solutions for islands as well as finding tools for stakeholders in energy planning and governance.

As a paper-based PhD thesis, my peer-reviewed publications form major parts and are attached in the Appendix. In addition to the Publications [1]–[5], this thesis combines them in a new way by pointing out the PhD process above and the perspectives for energy planners and islanders. Where modelling scenarios with EnergyPLAN forms the major part of the publications, the PhD thesis supplements with additional theoretical reflections, adding qualitative analyses to the quantitative energy system analyses, as well as additional reflections and personal views.

My overall goal is to create awareness and presentation of the different roles of islands in energy planning, done in an illustrative way. It is achieved by a review of modelling with islands and re-evaluating perspectives and approaches towards islands, which not only benefits them but also the world of sustainable energy planning. Both the result and the PhD process are influenced by this world through related views, literature, energy planning approaches, definitions, etc., but emerge as original work.

ACKNOWLEDGEMENTS

Nachdem mein Vater 1986 nach Föhr geschickt wurde und wir vier Geschwister noch dort geboren sind, bleibt uns heute die Inselverbundenheit, das Meer und der Wind.

I would like to express my gratitude to my family, friends, educators and colleagues who have accompanied me until here – I would not have made it without you.

Special thank you for support to my supervisor Poul Alberg Østergaard, who introduced me to the wonderful projects MATCH and especially SMILE. Thank you also, Søren Roth Djørup, for advice and co-supervision, and thanks to the head-quarter, the breakfast club and all office neighbours.

The PhD thesis was funded and greatly supported by the SMILE project[1] and team, and additional appreciation is in order for the research partners and hosts (incl. cats) on Samsø, Orkney and Madeira. Thank you for inviting me into your communities and showing me your lighthouses.

I would also like to acknowledge the impacts on climate change and corona on everyone and the challenges it is causing, but also the potentials it is showing, especially on islands. Still waiting to be able to elaborate on this.

Thanks to everyone who wanted to talk about or visit islands with me, especially in Denmark, where they even have their own letter for island: ø!

Finally, thanks to my (past) self for taking on this challenge, finding inspiration on every island and loving every part of it – I hope the reader enjoys it, too.

There are many stories about climate change and islands. This is mine.

Aalborg, January 2021

Hannah Mareike Marczinkowski

[1] SMart IsLand Energy systems (01/05/2017 - 31/10/2021); Horizon 2020 Grant Agreement No. 731249; EU's research and innovation programme: Secure, Clean and Efficient Energy.

SUMMARY

This PhD thesis, titled 'Modelling Renewable Energy Islands', investigates the role of islands and their models in sustainable energy planning. Resulting from the Paris Agreement, the fight against climate change can be addressed through the uptake of renewable energy sources in a sustainable way by including environmental, social and economic aspects. In order to align this with the decentralisation of the energy supply, islands are to be investigated accordingly as part of global or national energy planning under consideration of their potentials and limitations. While this can be approached through models, exploring island settings and demonstration potentials, further understanding and inclusion of local island energy system aspects are needed. The PhD thesis addresses this under the two-folded perspective of using islands for energy planning as well as islands actively contributing to it. The resulting research questions are addressed throughout the thesis accordingly:

What role can modelling renewable energy islands have in sustainable energy planning?

1. How can modelling *of* islands be used to evaluate renewable energy technologies?
2. Why and how should modelling *on* islands be improved by considering and comparing local conditions?
3. How can contextual and institutional alignment elaborate modelling *from* islands?

In order to answer the research questions, a framework of concepts, theories and methods is defined to guide the following analysis and present the related PhD publications. Thereby, the PhD research is put into conceptual perspectives regarding energy on islands, presenting their potentially significant role in sustainable energy planning. Before the theory of modelling is discussed, two theoretical frameworks are presented to illustrate this role, leading to the methodological framework of the publications made during the PhD research and the analysis of the PhD thesis. In order to answer the research questions, the application of energy system analysis and case studies are further presented, whereby the influence of the modelling tool EnergyPLAN and the case study islands of Samsø, Orkney and Madeira are introduced.

The sub-research questions build on top of one another and are answered in three main sections discussing the different perspectives by emphasising the modelling *of* islands, modelling *on* islands, and the perspectives gained through modelling *from* islands. The sections conclude that modelling in sustainable energy planning should be done *with* islands. These perspectives are supported by the PhD publications, which highlight the role of islands in evaluating renewable energy technology by providing suitable test settings, while also underlining the need for improvements. This is addressed through the inclusion of local perspectives and the consideration and comparison of local conditions on islands. The further alignment with local contexts and institutions, as well as the knowledge to be gained from islands, concludes the various roles of islands and modelling in energy planning.

On reflection, islands present a variety of contributions, which – combined – benefit not only energy planners but also islanders. This is underlined by the discussion of islands in transition theory by assisting innovation at the niche level, contributing to the regime and landscape levels if supported and aligned properly. Furthermore, multi-level governance highlights the potentials from hybrid vertical and horizontal coordination across geographical and governance levels.

In conclusion, modelling renewable energy islands contributes to the understanding and development of sustainable energy planning. This is achieved through coordination and collaboration with islands, acknowledging their quantitative and qualitative inputs, the recognition of island mode and innovation potentials, and the consideration of the limitations. The resulting understanding of islands as lighthouses – despite or due to being on the edge – supports not only energy planners and islanders but also, in turn, the energy transition and the Paris Agreement.

RESUMÉ

Ph.d.-afhandlingen med titlen 'Modelling Renewable Energy Islands' undersøger, hvilken rolle øer og deres modeller spiller inden for bæredygtig energiplanlægning. Som et resultat af Parisaftalen kan kampen mod klimaændringer tackles gennem bæredygtig anvendelse af vedvarende energikilder ud fra miljømæssige, sociale og økonomiske aspekter. For at tilpasse dette til decentraliseringen af energiforsyningen skal øerne undersøges i overensstemmelse hermed inden for rammerne af global eller national energiplanlægning under hensyntagen til deres potentiale og begrænsninger. Selvom dette kan adresseres gennem modeller og udforskning af egnede testmiljøer og demonstrationspotentialer, kræves yderligere inkludering af de lokale aspekter af ø-energisystemer. Afhandlingen beskæftiger sig med det tosidede perspektiv af at udnytte øer til energiplanlægning i modsætning til at lade øer aktivt bidrage hertil. De resulterende forskningsspørgsmål behandles i overensstemmelse hermed:

Hvilken rolle kan modellering af vedvarende energi øer have i bæredygtig energiplanlægning?

1. Hvordan kan modellering af øer bruges til at undersøge teknologier inden for vedvarende energi og tage dem i betragtning?
2. Hvorfor og hvordan skal modellering på øer forbedres ved at sammenligne lokale forhold?
3. Hvordan kan kontekstuel og institutionel tilpasning udvide modellering fra øer?

For at besvare forskningsspørgsmålene er en ramme defineret for indsnævring af de koncepter, teorier og metoder, der styrer den følgende analyse og præsenterer de tilknyttede publikationer. Afhandlingen er konceptualiseret med hensyn til energi på øer og præsenterer deres potentielt vigtige rolle for bæredygtig energiplanlægning. Derudover præsenteres den teoretiske ramme for at illustrere øernes rolle og deres modellering. Dette fører til den metodiske ramme, der bruges både til publikationer og til afhandlingens analyse. For at besvare forskningsspørgsmålene præsenteres anvendelsen af energisystemanalyse og casestudier, hvor indflydelsen fra modelleringssoftwaren EnergyPLAN og øerne Samsø, Orkney og Madeira introduceres.

Underspørgsmålene diskuteres i tre sektioner gennem forskellige perspektiver med vægt på modellering *af* øer, modellering *på* øer og de perspektiver, der opnås ved modellering *fra* øer. Resultatet er, at modellering inden for bæredygtig energiplanlægning skal udføres *med* øer. Disse perspektiver understøttes af publikationerne under ph.d.-afhandlingen, som fremhæver øernes rolle i studiet af vedvarende energiteknologi ved at have passende testmiljøer men også et behov for forbedring. Dette adresseres ved at tage lokale perspektiver og forhold på øer i betragtning, inkludere og sammenligne dem. Derudover udvides kontekstuel og institutionel tilpasning af den viden, der bliver opnået fra øer, og øernes forskellige roller i energiplanlægning udledes.

Øer og modellering af øer tilbyder et væld af muligheder, som ikke kun energiplanlæggere, men også øboere kan drage fordel af. Dette understreges på den ene side af diskussionen om øer i transitions-teorien, idet innovationer på og med øer understøttes, hvilket kan føre til yderligere udvikling af andre områder, hvis de fremlægges og gennemføres korrekt. På den anden side understreger multi-level governance-teorien disse muligheder ved at fremhæve potentialet for samtidig vertikal og horisontal koordination på tværs af geografiske og politiske niveauer.

Afslutningsvis kan det konkluderes, at modellering af vedvarende energi øer bidrager til forståelsen og udviklingen af bæredygtig energiplanlægning. Dette opnås gennem koordinering og samarbejde med øer, anerkendelse af deres kvantitative og kvalitative bidrag, anerkendelse af ø-tilstand og innovationspotentiale, samt hensyntagen til begrænsninger. Den resulterende forståelse af øer som fyrtårne – ikke kun i udkanten, men også som noget oplysende – understøtter ikke kun energiplanlæggere og øboere men også energiomstillingen og Parisaftalen.

ZUSAMMENFASSUNG

Die Doktorarbeit mit dem Titel ‚Modelling Renewable Energy Islands – Modellieren Erneuerbarer-Energie-Inseln' untersucht die Rolle von Inseln und deren Modelle für nachhaltige Energieplanung. Als Folge des Pariser Abkommens kann der Kampf gegen den Klimawandel durch die nachhaltige Nutzung erneuerbarer Energiequellen unter Einbeziehung ökologischer, sozialer und wirtschaftlicher Aspekte angegangen werden. Um dies an die Dezentralisierung der Energieversorgung anzupassen, sind Inseln im Rahmen der globalen oder nationalen Energieplanung unter Berücksichtigung ihrer Potenziale und Grenzen entsprechend zu untersuchen. Während dies durch Modelle und die Erkundungen geeigneter Testumgebungen und Demonstrationspotenzialen angegangen werden kann, ist eine weitere Einbeziehung der lokalen Aspekte von Inselenergiesystemen erforderlich. Die Doktorarbeit befasst sich mit der beidseitigen Perspektive, Inseln für die Energieplanung zu nutzen und Inseln dazu beitragen zu lassen. Die daraus resultierenden Forschungsfragen sind in der Arbeit entsprechend behandelt, wobei die drei untergeordneten Teilforschungsfragen aufeinander aufbauen und zur Hauptfrage beitragen:

Welche Rolle kann das Modellieren Erneuerbarer-Energien-Inseln bei der nachhaltigen Energieplanung haben?

1. Wie kann das Modellieren von Inseln zur Untersuchung von erneuerbaren Energietechnologien genutzt werden?
2. Warum und wie sollte das Modellieren auf Inseln unter Berücksichtigung und den Vergleich lokaler Bedingungen verbessert werden?
3. Wie kann kontextbezogene und institutionelle Ausrichtung das Modellieren durch Inseln ausbauen?

Zur Beantwortung der Forschungsfragen ist ein Rahmen zur Eingrenzung von Konzepten, Theorien und Methoden definiert, der die folgende Analyse leitet und die zugehörigen Publikationen präsentiert. Dabei ist die Doktorarbeit in Bezug auf die Rolle von Inseln für die Energiesysteme der Zukunft konzipiert und als potenziell wichtig für die nachhaltige Energieplanung vorgestellt. Des Weiteren sind die theoretischen Rahmenbedingungen präsentiert, sowie die Rolle von Modellierungen erläutert. Dies führt zu den methodischen Rahmenbedingungen, die sowohl für die Publikationen, als auch für die Analyse der Doktorarbeit angewandt sind. Zur Beantwortung der Forschungsfragen sind daher die Anwendung von Energiesystemanalysen und Fallstudien vorgestellt, wo der Einfluss der Modellierungssoftware EnergyPLAN und der Inseln Samsø, Orkney und Madeira präsentiert ist.

Die Teilforschungsfragen sind in drei Abschnitten durch verschiedene Perspektiven erörtert, mit den Schwerpunkten auf dem Modellieren *von* Inseln, das Modellieren *auf* Inseln, und den Perspektiven, die durch das Modellieren *durch* Inseln gewonnen werden. Das Resultat ist, dass das Modellieren in der nachhaltigen Energieplanung *mit* Inseln durchgeführt werden sollte. Diese Perspektiven sind durch die Publikationen während der Doktorarbeit unterstützt, die die Rolle der Inseln für die Untersuchung von erneuerbaren Energietechnologien hervorheben, indem sie geeignete Testumgebungen bieten, aber auch die Notwendigkeit von Verbesserungen ist hervorgehoben. Diese Verbesserungen sind unter Berücksichtigung, Einbeziehung und Vergleich lokaler Perspektiven und Bedingungen auf Inseln angegangen. Zudem erweitert die Ausrichtung an Kontext und Institutionen das Wissen, welches durch das Analysieren von Inseln gewonnen wird, und schließt die verschiedenen Rollen der Inseln bei der Energieplanung ab.

Reflektierend bieten Inseln und das Modellieren von Inseln eine Vielzahl an Möglichkeiten, von denen nicht nur Energieplaner, sondern auch Inselbewohner profitieren. Dies wird zum einen durch die Diskussion von Inseln in der Transitions-Theorie unterstrichen, indem Innovationen auf und mit Inseln unterstützt werden, die, wenn richtig gefördert und durchgeführt, zur Weiterentwicklung anderer Bereiche führen. Zum anderen unterstreicht Multi-Level-Governance diese Möglichkeiten, indem die Potenziale einer gleichzeitig vertikalen und horizontalen Koordinierung über geografische sowie politische Ebenen hinweg hervorgehoben sind.

Abschließend lässt sich schlussfolgern, dass das Modellierens Erneuerbarer-Energie-Inseln zum Verständnis und zur Entwicklung einer nachhaltigen Energieplanung beiträgt. Dies wird durch die Koordinierung und Zusammenarbeit mit Inseln, die Anerkennung quantitativer und qualitativer Beiträge, die Würdigung des Inselmodus und der Innovationspotenziale, sowie durch die Berücksichtigung von Einschränkungen erreicht. Das daraus resultierende Verständnis von Inseln als Leuchttürmen – nicht nur am Rande der Länder, sondern auch des Neuen – unterstützt nicht nur Energieplanern und Inselbewohnern, sondern auch die Energiewende und das Pariser Abkommen.

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ABBREVIATIONS

AAU	Aalborg University
BESS	Battery energy storage system
cf	confer/compare
EV	Electric vehicle
GW(h)	Gigawatt (-hour)
kW(h)	Kilowatt (-hour)
MATCH	*Markets, Actors and Technology* project
MW(h)	Megawatt (-hour)
PV	Photovoltaic
RE	Renewable energy
SMILE	*SMart IsLand Energy system* project
TES	Thermal energy storage

CHAPTER 1. INTRODUCTION: CLIMATE CHANGE ON THE EDGE

Climate change does not stop at the edges of our countries – it is rather the opposite.

The Paris Agreement signed in 2015 promotes the transition to cleaner energy, lower emissions, and higher efficiencies in the fight against ongoing climate change. The Agreement asks its backers to contribute to limiting the increase of global temperatures this century to 1.5 degrees Celsius compared to pre-industrial levels by reducing greenhouse gas emissions. In this regard, the global guidelines of the Agreement require contributions from each country in the light of their different circumstances. All countries are defining their climate actions accordingly, presenting targets and strategies towards reaching the overarching goal. [10]

One way to mitigate climate change is through the reduction of our high share of and dependence on fossil fuels through the development of sustainable energy. In addition to this transition towards the exploitation of renewable energy resources and the integrating technologies this relies upon, sustainable energy planning should aim to establish the environmentally friendly, economically sound, and socially fair development of the energy sector. For this, central power and energy supply must be coordinated with locally available renewable energy sources, ranging from wind turbines to biomass, solar, and hydro energy [11] while taking local economic and social contexts into consideration. Future energy systems are not only considered to require decentralised energy production, thereby exploiting the specific resources available under different circumstances, but also must include development across energy sectors and borders [12]. Climate change is therefore addressed in the sustainable energy planning approach through both decentralisation and the expansion of renewable energy technology, wherever possible.

As energy transitions require commitment as they become more complex, it might further be required to find new ways to reduce fossil fuel dependence. A major challenge is not just the need for the uptake and integration of renewables but also their transmission from the often remote areas of production to the areas of consumption. Yet these shifts are possible, especially for smaller economies, due to rapid and dynamic ways of adapting their more compact territories [13]. Although it refers specifically to small nations, the same possibilities might exist with islands. With energy often supplied centrally in the past, and future supply becoming decentralised, the solution might lie in local energy supply and system optimisation. This would enable the suggested sector integration through optimisation at a local level [14], [15]. Local energy systems, which provide stability and local development in sustainable terms, should be a common goal in energy transitions; this might be even more relevant in small and remote locations, such as islands, than elsewhere.

In some ways, islands can be challenging to define. While geographical boundaries and sensitive ecosystems are the common norms for islands, further comparisons between islands as well as between islands and mainlands are limited by their individuality. Differences can be found not only in global island comparisons but also within a country or even within a single archipelago, including variations in resources, infrastructure, or demographics. Being secluded does not necessarily differentiate islands from isolated communities or energy systems on the mainland, but being surrounded by water puts them in a simple, yet complex position, not only in terms of energy transitions. This PhD thesis primarily addresses smaller, secluded islands with limited integration in larger energy systems across sectors and borders, as suggested above, without excluding islands of a certain size or population.

Whether as sub-national jurisdictions or island states, thousands of islands host millions of people globally, and they are at the forefront of climate change with predicted rise in sea levels [16]. They are at the edges of our maps as well as of our energy networks and are to follow the same agreements and global trends towards addressing climate change. Yet some differences between the future energy systems of islands and those of mainlands presented above remain. The potential of aligning energy planning with islands also shows in decentralisation, as many resources can be found and explored beyond urban or inland areas, but the ability to expand grids from islands to inland areas is naturally limited.

The location of islands at boundaries of nations and energy networks can lead them to be associated, on the one hand, with limitations, and on the other hand, with being at the outskirts or edges. However, in this thesis, the term ‘edge’ implies not only *limitation* or *outskirt* but also an *advantage* – as in ‘cutting edge’ or *being ready/prepared* as in ‘on the edge’. A visit to the Orkney Islands [17] and the book ‘Energy at the *end* of the world’ [18] highlight this. The book focuses on renewable energy on Orkney and was renamed after initial discussions to present the ‘*edge* of the world’ instead; see Figure 1-1 [19]. This perspective is further explored in this thesis, in addition to the ways in which this can be understood as a potential advantage when considering energy planning and islands in the transition towards cleaner energy.

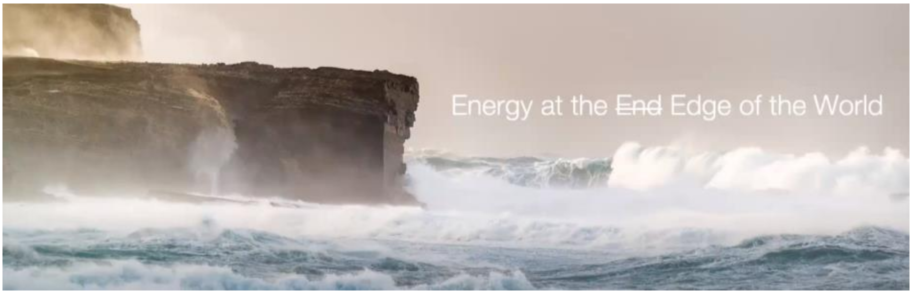


Figure 1-1: Changing perspectives when looking into energy on the Orkney Islands, Scotland [19]

ALIGNING ISLANDS WITH ENERGY PLANNING

While global and national climate actions define the general path for islands to follow, it might not always be realisable at the island level. European and national policies define renewable energy and cross-border interconnection shares for countries as a whole [20] without the much-needed consideration of limitations found in their local municipalities or islands [11]. Likewise, research has been done in cities and on regional or national level, reflecting on how they can follow and contribute to national and global guidelines [21], [22]. This context implies that no one region should be viewed as being above another region but also that resources must be shared horizontally. Highly populated urban areas tend to require more resources than are available locally, while remote areas tend to experience the opposite effect. In general, it has been argued that the different levels should aim at sustaining themselves while playing a part in larger plans, such as cities in a national perspective [22]. The same applies to islands, but to some extent, they might be limited in this regard due to the natural isolation caused by water.

Opportunities on islands to follow global trends, such as renewable energy expansion or cross-border considerations, might be limited due to their natural setting, yet the same guidelines requiring reduction of emissions apply. Furthermore, the effects of climate change can be experienced first and foremost in coastal communities and especially on islands, as sea levels rise and weather extremes can be felt there in a more immediate way [23], [24]. Addressing this reality and the Paris Agreement since 2017, the *Clean Energy for all Europeans package* supports the transition to cleaner energy in various ways and includes a specific initiative for islands: the *Clean Energy for EU Islands* initiative [25]. It suggests that island communities, despite their restrictions, might be the innovation leaders in the clean energy transition for all of Europe by transitioning from high import dependency towards self-sufficiency. The same might apply not only to European islands but also on a broader level when considering islands worldwide.

However, for islands to follow the Paris Agreement and apply similar energy planning developments as their continental counterparts requires more a detailed understanding of ongoing developments, possible challenges, and future opportunities. This PhD thesis addresses an investigation of islands that on the one hand aligns with and learns from the global trends and national targets in energy planning. On the other hand, it looks in the opposite direction of islands as laboratories to contribute to energy planning, as illustrated in Figure 1-2. Where energy planning for islands is done from the continental point of view, island perspectives might also contribute to well-balanced energy planning. Islands have been used to both test and demonstrate ideas on small scale and under isolated conditions. Often this is done for the islands' benefit, but also to evaluate what might work and be replicated elsewhere. This real-life testing of solutions, such as renewable energy technologies, aims to solve challenges specific to islands but also has implications for other regions.

Figure 1-2: Alignment of islands in energy planning, presented through a view of Orkney from the Scottish mainland

The investigation of aligning islands with energy planning practices can be approached through models and modelling. While islands themselves can be considered models of larger (energy) systems, most things can be illustrated in a theoretical way through modelling in island mode. The size of islands and their natural limitations provide an opportunity for testing these practices through observation and evaluation to examine both the alignment of islands with trends and their relevance for other regions. In particular, new technological additions to an energy system, such as renewable energy technologies and their impacts, could be studied through island models, as they provide a natural modelling setting. The right use of models can provide not only details on the object of modelling but also contributes to the Paris Agreement.

The investigations of energy targets for islands as well as testing and learning from islands, however, are often done from a continental point of view, whereby islands are viewer from the standpoint of observers, who more often than not reside in central mainland areas. An example of this is Denmark with its 400 islands, not even counting the autonomous territories of the Faroe Islands and Greenland, which does not consider itself an island nation. Not only in Denmark but also worldwide, islanders present around 10% of the population [16]. This may require them to be acknowledged and better integrated instead of merely looked upon by the mainland.

An example, not only in Denmark, of where the continental viewpoint persists can be found in the research and development done on marine renewable energy. Not only islands but also coastal communities are bound to the oceans, which play a major part in their lives, yet marine energy – both in terms of production and demands – is insignificantly included in energy systems worldwide. Even though these resources have many benefits, they remain largely untapped [26]. Besides fossil fuel extraction and offshore wind, the focus remains on establishing and expanding onshore technologies and supplying demands. Even space research surpasses that of marine – we know more about the surface of Mars than about the largest part of the Earth's surface: our oceans [27], [28]. Even though there are both energy resources and demand in and near the oceans, continental issues and solutions appear easier to grasp than those that are offshore and remote.

To address the acknowledgement and integration of islands better, strategic energy planning raises the issue of energy planning viewpoints and contextual inclusion by suggesting a re-evaluation of coordination needs [11], [29]. Institutional and regulatory framework conditions and central support are lacking, while expectations for local action persist. While this lack of support can be identified between the national and local levels in general, considerations of islands or coastal communities could form yet another specific local level. History indicates that islands are typically colonised and ruled from larger, often continental societies, which tend to know less about specific local conditions and needs [16]. Resulting mainland-based rules and policies, therefore, become the norm for islands, despite their individuality and the fact that they are located at the edge of these lands. This indicates the need for coordination and understanding of islands' local conditions for improved island energy planning.

EXPLORING ENERGY PLANNING THROUGH ISLANDS

Even in Denmark, the neglect islands face is visible at a political level. While the latest climate agreement on energy for 2021-2030 elaborates on the opportunities of artificial 'energy islands' [30], it does little to include actual islands in the national agreement – not as models, nor for testing or acknowledging potential differences [31]. Islands are not even mentioned in the second edition of Renewable Energy Systems [12], which focuses on smart energy planning in Denmark, nor in the Danish Society of Engineers' (IDA) Energy Vision for 2050 [32].

Despite this underrepresentation, the potentials to explore energy through islands are shown in literature. A search of articles available in the ScienceDirect library at the end of 2020 reveals that 13% of the search results for the phrase 'Danish energy system' include 'island', while the same share is only 6% in the non-Danish search. For 'Energy planning', the results are 21% compared to 11%, though the number of results for 'energy planning' includes about one fifth of the literature on 'energy systems'. Both of these searches reveal the role of islands in energy systems and even more in energy planning on both a Danish and international scale, with Denmark surprisingly making up for its lack of island inclusion on a political level through research contributions. [33]

When looking further into the existing 'Danish island energy system' literature, a trend can be noticed towards the use of 'cases', 'models', or 'tests' (97% of search results), as well as 'technology' (70%); this trend supports the claim that islands are often used for testing and modelling technologies. Yet we see less material on the use of 'strategy', 'implementation', 'market', or 'policy' in combination with 'Danish island energy planning' (avg. 61%) or even 'Danish island energy system' (avg. 43%). This indicates a lack in further use of potentials from island energy research and an inappropriate or misaligned role of islands in energy planning. [34]

In contrast to existing island energy literature, the international handbook of island studies [16] emphasises the potential role of islands on the global scale. It suggests ao move away from seeing a world *with* islands to a world *of* islands. Could this suggestion apply to the energy planning world as well? Could Denmark start making energy plans by seeing itself as a country *of* islands – rather than *with* islands – and what could the benefits be for both people on islands and on the mainland?

A potential *light on the Danish horizon* in this regard is the appointment of the Danish renewable energy island in 1997. The goal involved demonstrating a way of becoming 100% self-sufficient within 10 years, and Samsø won the competition by pointing out locally inclusive ways of doing so, including business, municipalities, organisations and citizens. The Minister for Energy and Environment at the time stated, '*Through Samsø, we can create a striking international demonstration project and exhibition window for Danish energy technology*', pointing to it being a 'mini Denmark'. [35]

Despite Samsø reaching this goal and working on various additional projects in the following and up to now, the impact on Denmark remains to be seen. It demonstrated how a community became statistically self-sufficient and reduced energy demands within a short period of time, but it has neither been directly replicated, nor is it referred to in today's politics. Samsø does, however, follow the goals from the EU islands initiative and the European Commission to better include consumers in the energy transition by reaching out to the community [36]. While true replication might never be realised, also the need and approach of self-sufficiency can be discussed, since it currently relies on exporting electricity to compensate for the import of fossil fuels [1]. Models of Samsø have been created over the years, revealing many insights but also an endlessness to both problems and potentials of modelling [37]. However, it remains unanswered how one can or should use this experience in the future – both on islands and elsewhere – or how it relates to the upcoming creation of 'energy islands', which presents the opposite of Samsø's inclusive and local focus.

An elaborate and detailed review of literature regarding the role of islands in the past and future can be found in the publications underlining this PhD thesis, including a closer look at modelling and Samsø [1]–[5]; see Appendices. These five publications further address research gaps in relation to analyses made throughout the doctoral period and in the context of energy planning. Additionally, this PhD thesis addresses the situation presented above and focuses on the two primary areas of interest: how islands align with the trends in energy planning and how islands provide an opportunity for evaluating, comparing, and elaborating models – both for islands themselves and for other geographical regions; and finally, how islands might be the key to the fight against climate change. These areas are addressed through an exploration of energy systems and islands, models and modelling, theories and case studies, as well as a look beyond. The PhD thesis thereby makes use of the underlining Publications [1]–[5] through further elaboration and discussion.

If climate change does not stop at islands, it is where it starts; and so must the fight against it.

1.1. RESEARCH QUESTIONS

The areas of interest presented above lead to the following problem statement and hypotheses: there is a potential misalignment of energy planning understanding and trends with the possibilities – and even more so limitations – presented on islands. The current role of islands and their models for testing energy planning practices must be further assessed and reviewed. Likewise, there is unused potential to learn from modelling with islands that can benefit islands and others. Aligning different perspectives surrounding islands and regarding their innovation potential supports this. Being on the edge might have put them in a difficult position, but islands might bring the cutting edge to energy planning. Considering these aspects more thoroughly can benefit energy planning when facing the ongoing challenges of climate change. It is time to take a closer look at the (cutting) edge, presented through Publications [1]–[5].

With the introduction briefly reviewing the problems and process of implementing renewable energy on islands, the focus of this PhD thesis is the overall contribution that the modelling of renewable energy islands can have for energy planning and transitions to renewable energies on islands and elsewhere. Besides the energy planner viewpoint in this, the islands and islanders' viewpoints are of potential interest. The setting in sustainable energy planning thereby includes geographical context, as well as institutional context including energy systems, markets and policy but also social, economic, and environmental aspects.

In sum, the following main research question focuses on the sustainable energy planners and the different perspectives of island modelling, connecting the PhD publications through the sub-research questions. While the 1st sub-research question aims at to improve modelling islands rather than improving modelling in itself, the 2nd and 3rd sub-research questions are to be understood as building upon one another, as is further elaborated below.

<u>Research Questions:</u>

What role can **modelling renewable energy islands** have in sustainable energy planning?

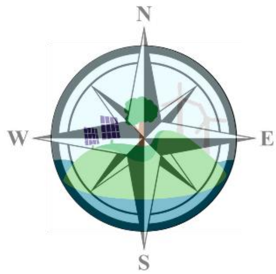
4. How can modelling of islands be used to evaluate renewable energy technologies?
5. Why and how should modelling on islands be improved by considering and comparing local conditions?
6. How can contextual and institutional alignment elaborate modelling from islands?

To clarify the research questions, *modelling renewable energy islands* indicates the complexity of the research, since it can be read as such, but it might wrongly imply that the islands are completely based on renewable energy. The sub-research questions introduce additional perspectives, as it can also be understood as modelling renewable energy *of* islands or specifically *on* islands; which can be further differentiated from modelling and learning *from* islands, or even *with* islands. The answer to these questions might even differ and address different areas of modelling renewable energy islands, which is considered and further discussed throughout the thesis.

The evaluation in the 1st sub-research question implies extracting value about renewable energy technologies through island modelling, the 2nd one relates to the potential reasons and options for improvement through comparison and inclusion of local island conditions. The 3rd sub-research question addresses the alignment or relation of modelling island with the energy planning context by further developing island modelling by coordinating the additional contextual and institutional aspects.

The next section includes these perspectives and indicates the subsequent structure of the thesis to approach and navigate between islands and the role of modelling renewable energy islands. The PhD publications and the research questions are presented according to each other, alongside the required theoretical and methodological framework and the resulting structure of analysis and results.

1.2. STRUCTURE



This thesis is divided into five main chapters, namely, *Introduction*, *Framework*, *Analysis*, *Reflection*, and *Conclusion*. Chapter 1 introduces the problem of climate change and solutions ranging from renewable energy sources to local energy planning, and islands are introduced and presented as a relation worth analysing, presenting the state of the art. The resulting research question and sub-research questions are addressed in the following chapters, as illustrated in Figure 1-3.

In order to do so, the *Framework* of Chapter 2 presents the *Concepts*, *Theories*, and *Methods* that define and are relevant for the subsequent *Analysis*. Section 2.1 on concepts includes a sub-section on *Future Energy Systems* in order to elaborate the use of renewable energy sources as well as sustainable energy planning; a sub-section on *Islands*, where island perspectives, potentials, and limitations are introduced; and a final sub-section on *Energy on Islands*, which discusses the relation of the two previous, as well as different perspectives surrounding energy on islands. Section 2.2 on theories includes the explanation and potential use of *Transition Theory* and *Multi-level Governance* theory with each their relation to models, leading specifically to a sub-section on *Modelling*. Section 2.3 on methods presents sub-sections on *Energy*

System Analysis in order to present the approach to the modelling of island energy systems, and on *Case Studies* presenting the islands Samsø, Orkney, and Madeira. These are elaborated through the related projects, as well as research observations. A summary of the chapter and the use of the case study through the final sub-section on *Research Approach* concludes the framework on which this thesis is based.

Before answering the main research question, the *Analysis* sections in Chapter 3 answer the sub-research questions one by one. Section 3.1 on *Modelling of Islands* explains how renewable energy technologies can be evaluated in island models. In contrast, Section 3.2 on *Modelling on Islands* reflects on the need for and possibility of improvements through considering and comparing the island conditions. Finally, Section 3.3 on *Modelling from Islands* supplies the answer to how contextual and institutional alignment develop and elaborate island models. The first section is supported mainly by PhD Publications [1], [2] and [3], the second section by PhD Publications [3] and [4] and the third primarily by PhD Publication [5], but also builds on top of the others. Besides the analyses of publications in Sub-sections 3.X.1, they are each discussed in theoretical terms of transition theory and multi-level governance for energy planning in Sub-sections 3.X.2.

Reviewing the *Analysis* and the answers to the sub-research questions, the *Reflection* of Chapter 4 presents the answer to the main research question by presenting the roles and benefits of island modelling. For that, Section 4.1 on *Modelling with Islands* summarises and combines the results from the previous chapter. In turn, Section 4.2 on *Sustainable Islands Energy Planning* reflects on the problems and potential solutions presented in the *Introduction* through new perspectives. Finally, Section 4.3 on *Further Perspectives and Research* elaborates the answer to the research question in discussing resulting future roles of islands and island modelling, presenting the final contributions of the PhD thesis.

Finally, Chapter 5 offers a *Conclusion*, after which the bibliography and appendix can be found. The chapter presents the answers to the research questions and clarifies the contributions from the PhD thesis to energy planning by concluding on the role of islands and modelling renewable energy islands.

The *Appendix* includes the peer-reviewed papers published during the PhD research period from 2018 to 2021 [1]–[5]. Their contribution to the thesis, especially in the analysis, but also in the framework and reflection, as well as to the overall structure of the PhD thesis, is shown in Figure 1-3. Other publications from project involvements further support the theoretical and methodological framework, as well as the analyses in the papers. As illustrated by the background image of the *Analysis*, the research visits to islands during the PhD research have had a strong influence on the development of this thesis.

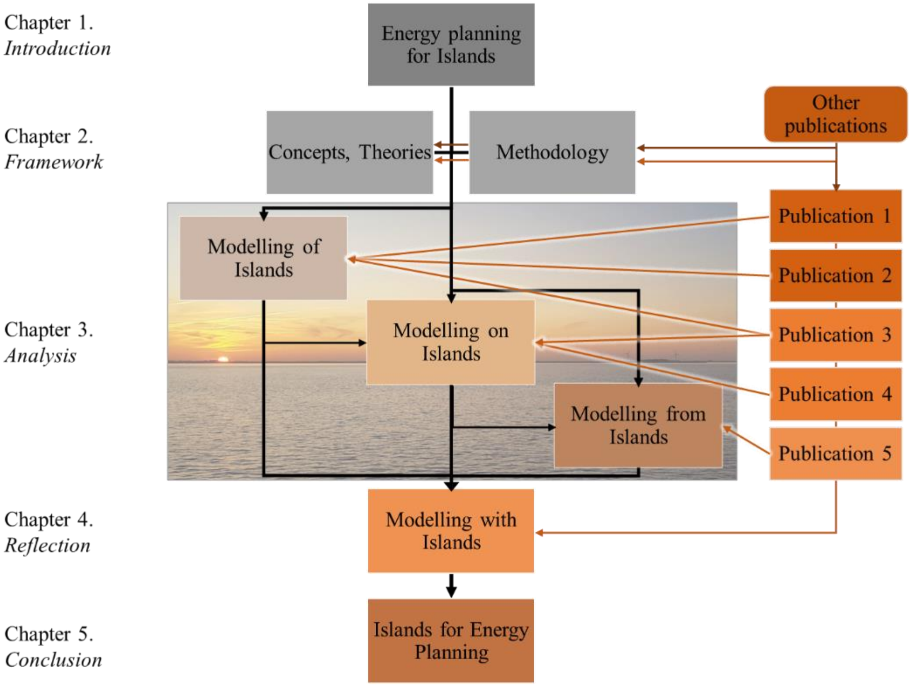


Figure 1-3: Structure and relation of chapters and publications in the PhD thesis of modelling islands

CHAPTER 2. FRAMEWORK: THEORETICAL AND METHODOLOGICAL EDGES

Fighting climate change through a closer look at islands and finding the edges' edge.

This chapter presents the conceptual, theoretical and methodological framework to understand and analyse the situation addressed in the introduction and as pinpointed in the research question 'What role can modelling renewable energy islands have in sustainable energy planning?' Hence, to frame and understand the analysis of this PhD thesis and its conclusions, the following sections present and define the related concepts, theories and methods. Furthermore, in line with the overarching theme of modelling renewable energy islands, their relation to modelling is also addressed.

Section 2.1 presents the concepts of future energy, islands and their combination are. In Section 2.2, the theories of transition, multi-level governance and models are introduced as applied in Chapter 3. Finally, Section 2.3 addresses the methods applied, including the modelling methodology for energy system analysis, the use of case studies, and the resulting approach to the subsequent analysis. Firstly, this underlines the work done in Publications [1]–[5], while secondly, explaining and supplementing these. This chapter thereby not only sets the frame for understanding the analysis and conclusions drawn in the following chapters, but also contextualises and delimits the concepts, theories and methods and their application in this thesis.

2.1. CONCEPTS

The purpose of this section is to present the first part of the framework of this PhD thesis. The key terms and perspectives of future energy systems and energy planning in general are presented, as is the understanding of islands and how those two aspects relate to each other. This section serves to clarify the perspectives and approaches relevant to the analysis and, together with the following sections on theories and methods, presents the process and views of the PhD thesis. The concepts and contexts included in the PhD publications and relevant for understanding the PhD thesis are hereby revisited.

2.1.1. FUTURE ENERGY SYSTEMS

As introduced in Chapter 1, climate change and the Paris Agreement require us to look towards renewable energy technologies and sustainable energy planning. Not only is there a global trend towards the inclusion of decentralised solutions like wind turbines, solar collectors, hydro or biomass energy as resources, but there is also a trend towards ensuring their best combined operation to fulfil all our energy needs. Examining this further, we must address not only electricity production and consumption but also heating, transport and industry. In light of the transition away from large-scale power production using on-demand, simply stored fossil fuels towards decentralised, renewable technologies, the intermittency of the energy production from the latter is a recurring issue. [12]

A resulting future energy system that strives to achieve high renewable energy shares is referred to under the concept of ‘smart energy systems’ [38]. Only by combining all energy sectors can the necessary transition to a 100% renewable energy share be achieved in an efficient way. While countries with abundant hydro or biomass resources have the potential to switch towards a 100% renewable energy supply, this solution does not fit all energy systems. The smart energy system emerges from the idea of combining electricity, heating and gas grids to identify synergies, benefitting not only each sector individually but also the overall energy system. Through the interconnections between sectors that otherwise tend to be handled separately, the intermittency of renewable energy can be addressed more efficiently. This is approached through three main implementation phases, namely: introduction, large-scale integration and 100% renewable energy [4], [12].

Smart energy systems and sector integration can help convert fluctuating electricity production to other energy carriers and use more effective storage while simultaneously addressing demands in heating, transport and industry. This approach is utilised in PhD Publications [1]–[5] through sector-integrating and balancing technological components while considering the effects of these changes on the islands’ energy system. These Components range from PV and battery system combinations [1], heat pump and thermal storages [2] and battery and thermal storages in comparison [3] to a range of smart grid and sector-integrating solutions for transitioning to high renewable energy shares [4] and a 100% renewable energy system [5].

The connections presented in Figure 2-1 illustrate a resulting example of a smart energy system, which explores renewable energy sources and supplies energy demands through cross-sector interconnections. In some places, only certain sources, technologies or demands exist and, therefore alterations are possible. The illustrated smart energy system can be modelled both in island mode and in interconnection with surrounding energy systems. The former modelling mode restricts energy trade to other areas and focuses on self-sufficiency and local system balancing. Even though island mode causes a restriction in terms of electricity transmission, it is also described as informative regarding supply assessment, where balancing of supply and demand must be solved within system boundaries [39]. The island mode is relevant not only for the evaluation of islands but also for modelling in general; see Sub-section 2.2.3. Meanwhile, the interconnection mode introduces the possibility of expansion and cross-border trade, as seen in a typical energy system. It is more appropriate for non-island regions, although submarine transmission lines and trade can also allow this mode to be used for islands.

Figure 2-1: Smart energy system illustration [40]

Besides smart energy systems through sector integration, system expansion across borders is a well-discussed trend [41]. With common energy system targets and collaboration options, the cross-border trading of energy is another solution to local limitations and intermittency. The Nord Pool electricity market and the European trading scheme are examples of setups intended for the optimal coordination between electricity production and consumption units for larger geographical areas. The integration of sectors from a technical perspective has been followed up by proposals to integrate the different energy markets, resulting in the concept of a so-called ‘smart energy market’ [42], which is further discussed in Section 3.3 and Publication [5].

As introduced in Chapter 1, while suggestions of cross-sector and cross-border trade might work for well-connected energy systems like the Danish national grid, remote and outlying regions might be limited in their ability to implement these. Furthermore, the energy planning of future energy systems should not only include geographical and institutional aspects but also incorporate sustainable practices by including local economic, environmental and social aspects [22], [29]. As introduced with the smart energy markets and further detailed in Section 2.3, energy planning is more than technical energy system analysis, as it can also relate to local markets and policy design through institutional alignment. This defines contextual energy planning as it is applied and relevant in the PhD thesis.

This relation is addressed in the research questions, especially the 3rd sub-research question. The integration of sectors and increase of renewable energy share under consideration of the context and local energy systems form the basis of this PhD thesis and are analysed in the associated Publications [1]–[5]. While they are based on the smart energy system sector-integrating approach, appropriate cross-border options suitable for the local conditions of the investigated system are also addressed. However, limitations typical to island energy systems are encountered; these are further discussed in Sub-section 2.1.3.

In order to achieve the targets of the Paris Agreement through smart energy systems on a global scale and to continue developing our understanding of these systems, islands should not be excluded. When the current energy planning is considered as a puzzle to solve, small islands, usually located at the edges of the map, are important pieces, as illustrated in Figure 2-2. They part not only of the Paris Agreement targets but also of our energy systems, whether or not they are directly connected. However, they are also the most difficult to include in the design of strategies and the implementation of the above mentioned trends. While central pieces of the future smart energy system can be easily identified and connected, less attention is given to the areas at the edges of energy systems and maps. At the same time, central regions need to coordinate global agreements and national policies to all local levels, but this coordination is limited if these levels are not fully understood. Nevertheless, additional knowledge can be gained, resources traded and – last but not least – sustainable energy supply achieved across nations and continents in a strategic and contextual way by including islands. This more strategic energy planning is further addressed through multi-level perspectives and governance theories (cf. Section 2.2). Finally, it is applied in the different perspectives discussed in Chapter 3, where Figure 2-2 is further used to clarify and illustrate its sub-sections on modelling islands.

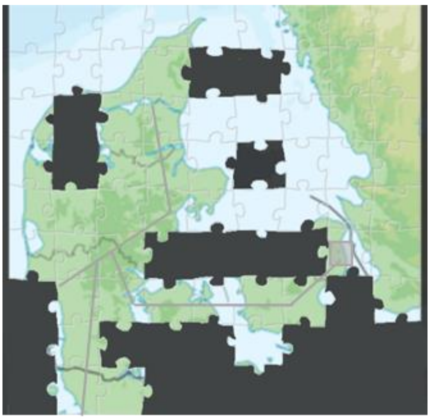


Figure 2-2: Energy planning puzzle metaphor illustrating island context in energy planning

As an illustration of the relevance of context and strategy for future energy systems, Denmark is a good example of an island country that is not considered as such. It may be considered a country *with* islands, rather than *of* islands, as illustrated in Chapter 1, wherein the lack of islands in current and future energy Danish policy is highlighted. Its capital and most populated region is situated on the island of Zealand, and thus more than 60% of Denmark's inhabitants can be considered residents of islands. However, the very well connected islands Zealand, Funen and Vendsyssel are rarely considered islands and are also not addressed in the discussion of small, secluded islands, which are the main focus in this PhD thesis. After removing these islands from the statistics, 470,000 people, or 8% of the population, and 7% of the country's area are still found on small Danish islands [43]. This leads to the next section, wherein the concept of islands is further explored before energy terms are addressed in Sub-section 2.1.3.

2.1.2. ISLANDS

The term island triggers many different associations, making it both easy and difficult to conceptualise. In order to understand the role of islands in the PhD thesis, as well as the perspectives introduced in Chapter 1 and through the research questions, some considerations and definitions are presented, underlining the importance and differences of islands. These are to be considered when modelling and enhance the understanding of the perspectives and related conclusions in the following sections. While islands can be described through facts and figures, experiences and impressions are also included in the following paragraphs to create a common understanding of islands. While many aspects relate to energy on islands, as addressed in detail in the next section, this section focuses on underlining the differences between islands and the mainland, as well as among islands.

When looking at islands from a non-energy perspective, what do we see? Getting on a boat to take the journey to an island obliges us to leave something behind. It may be a car and the connection to the mainland infrastructure, or it may be tasks and worries related to the place we are leaving for a short while. Passing through open waters shows us how we are suddenly cut off and need to reconsider what we might have forgotten, how we need to readjust and when we will return. Nevertheless, the difficulty of getting to such a remote place is quickly forgotten upon arrival, when other impressions take over. We experience a sense of calmness and of getting closer to nature and our surroundings, and this needs to be remembered in this PhD thesis. When arriving in Stromness harbour of Orkney [17], the exclamation of a visitor upon arrival, '*what fresh air!*', led to the thought 'let's keep it that way and make use of it', motivating this PhD research.

Suddenly, the perspective changes from looking *at* the island to being *on* it, requiring a boat rather than a car or train, and to learning *from* and *with* island viewpoints. Yet island communities have survived and succeeded in many ways from adopting and supplying the same standards and demands to having strategic harbours, lighthouses and hubs of innovation of their own [16], [18]. True, they tend to approach things differently, but we come to realise that keeping an island afloat shows strength and suggests that the images of security, calmness and hope prevail. While the edge might have initially been considered remote, now it could be seen as the cutting edge, where something new can be learnt. We begin to feel of the lure of islands, realising, '*They must have an important role to play in our society*' [44]. This perspective is elaborated in Chapter 3 and reflected in Chapter 4.

The situation and understanding of islands vary around the globe, yet similarities exist. While Denmark has around 400 islands, of which 72 are inhabited [43], the EU Island Initiative lists 2700 populated islands across the union [25], and worldwide 80,000 permanently inhabited islands that are home to more than 600 million people [16], highlighting the potential of this PhD thesis. Furthermore, although islands host around 10% of the world's population, they only represent 1.5% of its land surface, yet host 13% of all UNESCO sites. While many of these islands are sub-national jurisdictions, 33 are independent island states [16].

Whether they are part of a larger administrative entity or not, islands can be placed in the same framework. Generally, they are geographically located at the boundaries of nations or continents, surrounded by and often relying on the oceans in one or more ways. Either historically or economically, the connection to on island through water has a visible impact on its infrastructure, tourism and the supply of goods – and recently also on health care and crisis management (cf. Section 4.3 on Covid-19 reflections). Reliance on imports across the water has a major effect on islands, especially in terms of vulnerability and the local economy with its increased prices and more complex logistics. In the context of energy, the surrounded-ness with water isolates islands to some extent, even though bridges and cables might connect them to other lands, whether islands or continents. Further, even if the consciousness of being on an island is not ever-present, the same conclusions might be reached.

Compared with water-surrounded islands, continental and seemingly well-connected regions may also be considered as isolated and their similarity to islands as relevant. Examples include isolated energy systems across the African continent [45], the 68 'energy islands' on the island of Greenland [46] and semi-isolated regions limited through transmission bottlenecks, such as in the north of Germany [47]. Similar to geographical islands surrounded by water, struggles can also be experienced in these areas regarding both exports and imports. Exports of excess local renewable energy to neighbouring regions of demand may be restricted due to transmission limitations. Imports of fuels may be limited across physical borders or remote regions, impacting the availability and options of supply. Even without obvious impacts from their neighbours, every country and region is dependent on others to some extent. While it is not directly addressed as part of the PhD thesis, the isolation on continents can be similar to the isolation found on islands, and these regions can also benefit from the research presented here, as included in the reflections in Chapter 4.

Additionally relevant not only in energy terms, words such as ‘insularity’, ‘limitations’, ‘small’ and ‘remote’ come to mind, indicating the assumed role and limited importance of islands; these words can represent both hindrance and motivation in the context of energy planning. In contrast but also in combination with the other boundaries, the term ‘laboratory’ is also used to describe islands, indicating the potential for experimenting and modelling, as further described in Sections 2.2 and 2.3. Although this term suggests a simplification and a possible up-scaling of local findings for the benefit of others, islands might have more to contribute, since ‘*it would be a far poorer world if islands merely reflected continental goings on at a convenient and manageable scale*’ [16]. This leads to the next section, which helps us determine if this is also true in the context of energy planning.

2.1.3. ENERGY ON ISLANDS

The final concept to be clarified for the understanding of the PhD thesis is Energy on Islands, which combines the sustainable energy planning trends from Sub-section 2.1.1 with the boundaries and potentials of islands from Sub-section 2.1.2. By following the same targets under the Paris Agreement, and thereby also aiming for sustainable energy planning and smart energy systems, this concept addresses islands’ energy supply and demand, however, differences can be expected to other regions.

Islands are presented with particular challenging energy systems due to missing or restricted connections to larger energy grids, making their energy systems more vulnerable and often dependent on imports to supply the demands. Local resources such as biomass tend to be limited, further resulting in energy systems that depend on imports or fluctuating energy production [3]. A comparison to the smart energy system presented in Sub-section 2.1.1 shows that while island energy systems have the same general demands, albeit with often limited gas and industrial sectors, their electricity, heating and transport demands can be larger than those of their continental neighbours [48], [49]. Gas grids are not often found on islands due to the cost and difficulties of connecting to a grid across water, and there is generally little industry in the typically small and remote island energy systems. With exposure to nature and the resulting limits in infrastructure, however, other energy demands can be higher in comparison to the mainland, yet differences exist even between islands [4].

Renewable energy has both obvious potentials and limits in terms of its installation on islands. On the one hand, the high share of wind, sun and hydro resources as well as the remoteness from the national grid and markets support this claim for potentials. On the other hand, the transport and installation of technologies far from the main infrastructure, as well as a less favourable economy, present limits. Nonetheless, decentralisation and the exploration of renewable energy does not stop on islands. As presented in Chapter 1, islands can not only serve as laboratories but also play an innovative role despite their limitations, as suggested in the EU Islands Initiative [25], or even a demonstrative role, like Samsø in Denmark [35].

Before discussing energy differences between islands, the main differences between small and secluded islands – as of focus in this PhD thesis – and the mainland and continental areas are listed as introduced above, describing the typical situation. This highlights their relevance and considerations when modelling renewable energy islands:

- Partly isolated, vulnerable energy systems dependent on imports
- Limited in gas supply and industrial demands
- Higher demand for electricity, heating or marine transport
- Access to resources, yet restricted infrastructure and trade
- Resulting higher energy costs and risk of fuel poverty [17]
- Small, isolated energy systems with potential for representing, testing, demonstrating and innovating

Despite the similarities between them, islands around the world have various experiences and shares of renewable energy. From using only a small share of biomass for heating and cooking to relying heavily on solar, hydro or wind resources for thermal, mechanic and electric uses, islands are very individual, yet the following presents a comparison. An elaborate review of literature on islands' current renewable energy use and future potentials can be found in Publications [1]–[5].

The literature review [1]–[5] shows that most developed countries, and thus their islands, already have large shares of renewable energy and are investigating sector integration and the implementation of smart energy systems on the islands. However, others may still struggle with basic renewable energy introduction. The first typology is often associated with the term 'renewable energy island' or 'smart island' and includes the case studies, so a differentiation with the latter type of island is needed. These different perspectives are important for the PhD thesis to consider when discussing energy on islands, as should yet again be differentiated from artificial 'energy islands' (cf. Chapter 1), as elaborated exemplarily in the following paragraphs.

For many islands, changes in the energy system are complicated due to an existing, well-established fossil fuel-based energy supply and the insecurity that is to be expected with a change of supply [5]. Smart energy systems are far from being introduced in these cases, as economic, geographic or social limitations can complicate even the smallest share of renewable energy, let alone the introduction of sector integration [50]. Nonetheless, less-developed energy islands can learn from the future energy system concept outlined in Sub-section 2.1.1 by avoiding the sector lock-in through the early implementation of the smart energy system concept and from the other information offered in this PhD thesis. While a missing connection to and dependence from the mainland is often the cause for limited development, it can also be the motivation to expand renewable energy shares, pointing to differences even within and across developed countries, such as Denmark or Greece. Where Denmark has all inhabited islands connected to the national grid, yet some islands sticking out in regards to renewable energy use, many Greek islands are not connected with the national energy system, making the development of renewable energy difficult [51].

In contrast to less-developed energy islands, the nomination of the Danish renewable energy island Samsø is an example of a long ongoing island energy transition. It thereby presents the perspective of well-developed energy on islands. Its high-reaching aim was to become 100% self-sufficient in an inclusive way by taking all interest groups into account. Already 10 years after the nomination, Samsø produces a large amount of heat using local biomass and more wind power than can be used locally, making the island statistically self-sufficient. When disabling the offset of wind export with oil imports, more than a 50% renewable energy share is still reached [1]. Samsø won over other Danish islands due to its small size and it thereby being less expensive to realise the aim [35]; however, this also limits the possibilities for testing the smart energy system concept and its replication in other energy systems. Today, as is the case for other developed energy islands, Samsø is still struggling with advanced technological solutions aimed at further sector integration and 'smartening' the already highly renewable island.

As presented in Chapter 1, current energy policies are also looking into artificial 'energy islands', illustrating yet another perspective of Energy on Islands. With the current political targets to reduce carbon emissions, the further deployment of renewables – especially offshore wind – is foreseen in Denmark, as are power-to-X technologies, both of which are to be supported through the establishment of these energy islands [31]. Foreseen for offshore placement in both the North and Baltic Seas, these energy islands would be able to utilise considerable wind resources and unused marine areas, similar to those existing islands naturally have access to. While such energy islands would not supply island communities, their featured meaning and potential could nonetheless underline the importance of this PhD thesis, as is reflected on in Section 4.3.

Energy on Islands is a wide-reaching area with many implications and perspectives that are relevant to this PhD thesis. However, the islands addressed in this thesis, as further introduced case studies in Sub-section 2.3.2, present mainly the second typology of islands that are highly developed in terms of renewable energy. This limits the attention area in the thesis of modelling renewable energy to those islands which already possess a certain renewable share and which are now targeting the next necessary smart steps. However, the PhD thesis furthermore shows the importance of and for all islands. While they are not addressed in detail in Publications [1–5] or in

Chapter 3, islands with limited renewable energy can still contribute to and benefit from the reflections in Chapter 4. Testing and exploring renewable energy on islands in the hope of reaching global targets on a local scale or to demonstrate solutions for the benefit of others bring us to the next section. The theories present the potential role of islands in the transition to and governance of renewable energy systems and climate change response through modelling.

2.2. THEORIES

Following the concepts addressed above, the theoretical framework presents theories underlining energy planning and modelling in the transition to renewable energy on islands as applied in this PhD thesis. Therefore, transition theory and the potential role of islands within it are explained, as are the perspectives of multi-level governance for strategic energy planning, as suggested in Section 2.1. Both support answering the sub-research questions by addressing different contextual levels of energy planning in Chapter 3, where they add theoretical discussions to the review of the modelling done in Publications [1]–[5]. The final sub-section on the theoretical aspects of modelling returns us to the main research question, ‘What role modelling renewable energy islands can have in sustainable energy planning’, before looking into the related methods in Section 2.3.

2.2.1. TRANSITION THEORY

The presentation of energy planning trends and islands in Chapter 1 and Section 2.1 leads to the consideration of islands as representing a certain niche in energy planning research with a potential impact on a larger scale. A way to illustrate this is shown in Figure 2-2 (cf. Section 2.1, p. 16), highlighting how island perspectives can be important pieces of the energy transition puzzle by illuminating areas of the energy transition, not only in Denmark but also globally. Transition theory and its multi-level perspective can further explain this relationship and support the strategic influence of islands in various areas, including energy planning and governance. Hence, the theory is applied to illustrate the PhD research and place it into a theoretical framework, which adds new perspectives to the analysis of the PhD publications. The underlying processes referred to in this theory that are happening across the globe have a common denominator in societal changes, such as climate change requiring action in energy planning, leading to socio-technical transitions [52].

There are three interacting levels in the dynamical structure supporting this theory. These are niches, where innovations and learning take place, regimes, where well-established and more stable conditions exist, and socio-technical landscapes, where the wider context is shaped and defined. The levels each have an impact on the others; see also Figure 2-3 [52]. While the context is mainly understood as institutional, it can also be considered in other terms, as many influences can be included, which further relates to multi-level governance in the next sub-section. Hence, the dynamic structure allows for a controlled environment but also gives certain freedom for experimenting within the multi-level perspectives.

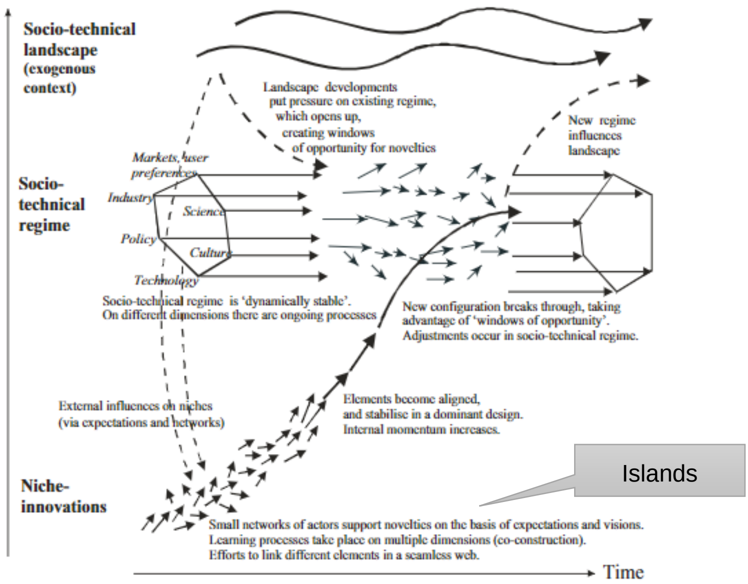


Figure 2-3: Multi-level perspectives [52] and islands as a part of niche innovations

The ongoing socio-economic transition discussed in this PhD thesis is the change from fossil fuels to renewable energy, ranging from changes in technology and science to changes in policy, industry, markets and culture. Even when discussing a change in only one of these areas, such as a new technology, additional changes in the other areas can be observed. This can be conceptualised through the regime level in multi-level perspectives of transition theory, where the impact of climate change through the landscape and the modelling of renewable energy islands at the niche level can be discussed.

Niches of technological innovation can be seen in various, but often small and secluded places, since enclosed environments provide suitable conditions to study. With islands having potential for experimenting and modelling, niche innovations can be explored in transparent and controlled island settings. The transition to renewables and the potential role of islands therefore present a potential window of opportunity for novelties [52], [53]. However, the success of an innovation in making it first onto the regime level and then into the landscape depends on the existing context found in the respective island or its surrounding. While the landscape can be expected to be similar across different regions defined by dominant structures, the regime level can vary even within a country or archipelago. With landscapes presenting well-established and far-reaching understandings, innovations have a long and difficult path to making an impact and may even result in different outcomes in different settings [54]. The success of innovation requires a full understanding of potentials at niche level and the impact on others, as well as the of targets and practices on regime and landscape level influencing niches. Hence, innovation needs to be aligned and stabilised. The consideration of local conditions in niche innovation, ranging from societal to environmental and economic aspects, addresses this understanding of local context and sustainability. Despite their individuality, islands are likely to succeed in the push for socio-technical transition, as they are '*seriously engaging society based on place specific issues*' [55].

The fact that islands present good test settings is addressed in Section 3.1, which focuses on the influences of landscape and regime on niches and islands. Hence, in Section 3.2, the potential of islands as niches for innovation is elaborated and discussed before Section 3.3 addresses the potential influence of islands on other levels. For that, Figure 2-3 is adapted and applied throughout Chapter 3 to illustrate the different approaches to innovation through island modelling.

Additionally, a new understanding of islands itself can be considered an example of innovation. This understanding could influence the role of islands in energy planning and the impact of this on other areas. After investigating islands as a setting for technological innovation, this PhD thesis highlights the additional role of the island-continental relationship in Chapter 4. The framing of concepts in Section 2.1 represents the first step, and the theoretical framework is a second. Finally, after the influence of islands in energy transitions through modelling is shown in Publications [1]–[5] and in the theoretical discussions, transition theory can be further combined on an institutional level with multi-level governance.

While transition theory is hereby investigated through the new perspectives of and through islands, multi-level governance helps further understand their potential role from the institutional perspective. After illustrating the levels of governance in relation to islands and the insights gained from modelling them, a new qualitative understanding of transition theory can be achieved in which islands impact the existing socio-technical relations, illustrating the role of modelling renewable energy islands in sustainable energy planning.

2.2.2. MULTI-LEVEL GOVERNANCE

The importance of strategic energy planning results from the need for central coordination in combination with decentralised technologies and action, which leads to the outlook into governance in energy planning. The already established need to re-evaluate the coordination between different institutional levels to enable local experimentation and strategic energy planning might yet require additional consideration in regards to islands [11], [29]. Where transition theory frames the different levels of influence in innovation, multi-level governance allows for a qualitative analysis of governance.

The coordination and actions of different governmental levels and non-governmental actors can be illustrated through multi-level governance, as is addressed in the field of energy planning in this PhD thesis. The theory discusses the coordination both vertically from global to local levels and horizontally across different areas and sectors in each of the vertical ones. Similar to the levels in transition theory, the lower levels are usually characterised by less power and outreach, while the upper levels demonstrate influence and coverage. The PhD thesis discusses this in Chapter 3 by evaluating the modelling done and the goals achieved for the energy transition towards renewable energy.

In multi-level governance, influences on policy actions are mainly categorised in three approaches under vertical coordination. First, the top-down approach indicates local responsibilities led from global or national level. Second, the bottom-up approach initiates at the local level, aiming to influence the higher ones. Third, a hybrid approach includes the coordinating features of both in parallel, whereby the top-down and bottom-up approaches take place at the same time, yet often without proper coordination between them. All of these approaches can be seen in energy planning, although a tendency for top-down governance through central power and coordination prevails. This can be due to, for example, the prevailing national central electricity production and planning or EU influences on local energy planning through directives and initiatives. This top-down perspective leads to the consideration of models as tools for testing with decisions made at the top levels. Yet, the potential of local bottom-up action has also been stressed, and it has been suggested that the central government should have a more reflexive and communicative role in decentralised developments [56], providing the right framework for bottom-up action to contribute and coordinate appropriately [11]. These options are discussed in the light of islands being considered as the bottom and edges of the energy transition puzzle.

With history showing foreign island colonisation and continental influence [16], parallels be can found here with the top-down perspective, encompassing classical vertical coordination even to the edges of the lands. However, various governmental levels below the national ones are crucial for the implementation of policies due to different resources and capacities at the different jurisdictional levels and a requirement for strong horizontal coordination [57]. Yet municipalities, for example, are still the ones '*voluntarily responsible for developing strategic energy plans*' [29]. Hence, the involvement of local aspects in energy planning could be elaborated and include not only local conditions but also consumers and their residents from small communities.

Local and transnational networks can be important for success within European governance systems as they may either foster or prevent actions at the different jurisdictional levels [58]. Recognising and upscaling local models and actions can thereby help to reach the Paris Agreement targets by also improving the vertical multi-level governance through bottom-up approaches. Not only is the role of local institutions in the fight against climate change through sustainable energy planning recognised, but there is also the need for support from overarching governments [29].

In the comparison of the different aspects of multi-level governance, Figure 2-4 emerges. Through transition theory, islands can be considered local niches with currently little power or influence, following national top-down advice. This happens in parallel across the globe or within the EU, with the same guidelines at the top level influencing development on lower levels vertically and in various, often insufficiently coordinated ways. Hence, the implementation and action taking place on islands can vary substantially depending on the conditions of islands (cf. Sub-section 2.1.2). In contrast, bottom-up or horizontal coordination are seen less often, despite the demonstrated relevance and the importance of niches in transition theory.

This gap is further addressed throughout this PhD thesis, especially through the qualitative combination of Publications [1]–[5] in Chapter 3, as it aligns the various contextual aspects of sustainable energy planning. Hereby, the top-down perspective is emphasised in Section 3.1, where island perspectives are only included to a limited extent, while Section 3.2 focuses on the horizontal level and Section 3.3 explores the potential of a bottom-up perspective through islands. The perspectives, hence, are combined with the puzzle illustration of Figure 2-2 (cf. page 16) and illustrated with the same colours in the corresponding figures in Chapter 3 to contribute to the understanding of islands in energy transitions.

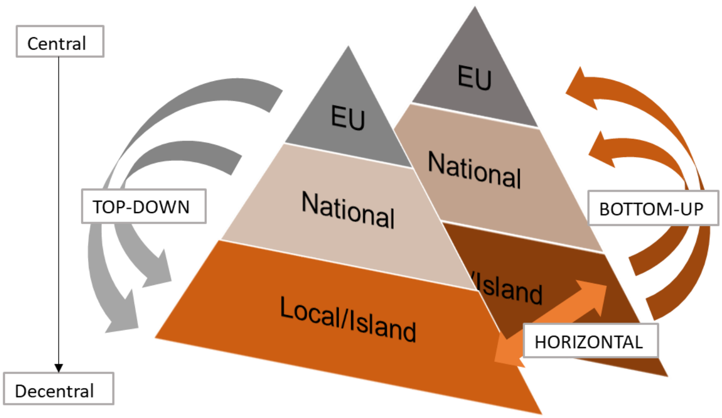


Figure 2-4: Vertical (top-down or bottom-up) and horizontal coordination in multi-level governance including the island level

2.2.3. MODELLING

Whether focusing on energy systems or islands, transitions or governance, modelling combines the trends and concerns above presented by contributing to niche innovation or governance decision-making in both quantitative and qualitative ways. The title of the PhD thesis suggests an emphasis on *modelling* when looking at renewable energy and islands, and the potential of island models for energy planning was introduced in Chapter 1. Furthermore, the perspectives from Sub-section 2.1.2 suggest different ways of looking at modelling islands. This section, therefore, presents the theory and understanding of modelling used in this PhD thesis before delving into modelling as a method for energy system analysis and energy planning of islands, as presented in Section 2.3.

The introduction to smart energy systems, the individuality of islands, and their role in theory and innovation justify the use of models in this PhD thesis. The term ‘model’ refers to both something ideal to look up to and something used for experimentation and replication elsewhere. The latter was initially intended in this thesis, while the former appears with increasing frequency throughout the research on this topic. Besides the potential of innovation in transition theory, the need for experimentation has also been mentioned in the literature, where local experiments are suggested and enabled through modelling, leading to the development of new understandings [59]. As presented previously, island settings permit transparent and accessible forms of modelling wherein lessons can be tested and learned.

In order to experiment with and evaluate the possibilities offered by a smart energy system, as suggested in Sub-section 2.1.1, a suitable theoretical model is needed. Figure 2-5 presents such a model, which is based on the smart energy system and energy flows illustrated in Figure 2-1. The purpose is to show a simplified, modelled version of an energy system to test and model technological changes under monitored conditions. Hence, compared with Figure 2-1, the theoretical model is streamlined and more elementary, providing greater better transparency of what is included and how it is connected in the energy system model.

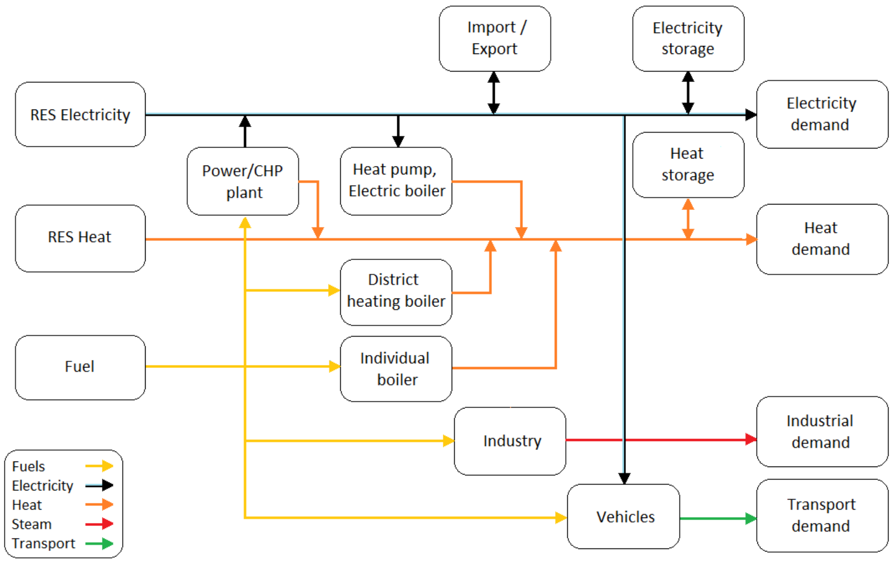


Figure 2-5: Simplified, theoretical smart energy system model

The simulation of situations or energy systems digitally through a model ideally results in a digital twin in which to test hypotheses and, hence, supports answering the research questions. The digital twin is a model that virtually represents all relevant energy system aspects and simulates their behaviour. Modelling also contributes to transition theory and multi-level governance through its potential role in these theories, when considering the purpose it serves and the understanding it provides in terms of both innovation and the contextual manner of island-continent governance relations. Most importantly, and similar to the perspective change mentioned before, the rational *for* the models might not be the same as the outcomes resulting *from* them (cf. Section 1.1); this dynamic is discussed in the course of Chapter 3.

In transition theory, the landscape demands innovation through niches and a change in regimes, which can be illustrated through modelling. The implementation of novel ideas like smart energy systems can be approached through modelling by showing the possibilities and limitations. This is often done in island mode or other controlled settings, which creates an understanding of niche innovations. Choosing the limits and inputs of a model enables the researcher to set selected modelling conditions. Creating models in island mode or testing technology in an island setting allows for a certain predictability and establishes boundaries for the model, which increases transparency and the potential for learning.

The use of models has also been seen from a critical point of view, ranging from technical limitations to impracticalities. While the first argument emphasises the limits of digitalisation, the simplification of models and their lack of completeness compared to the complexity and contexts of reality, the latter refers to the practical use of models. The potential that they may be misunderstood, undervalued or deemed irrelevant for various reasons limits the use of models and advises caution, for example when presenting them to municipal stakeholders [60] or when seeking optimal solutions [61]. A solution to this is a better understanding of models, which also contributes to niche innovation in transition theory through choice awareness [12]. In that way, models and niches may create an awareness of choices by demonstrating alternatives.

In addition to the general theoretical viewpoints in modelling that must be considered to understand the PhD thesis, there are two modelling types to discuss in the context of energy transition: optimisation and simulation. Both have been described and compared in this field as they aim to assist the planning and implementation processes of the energy transition. They are differentiated by their endogenous versus exogenous characteristics, as well as their computed versus user-chosen inputs to the model, respectively. Unlike optimisation, where the solution is predefined, simulation models the various consequences of different additions to the system, resulting in user-specified – thereby controlled – scenario making. Examples of optimisation models include Homer or Balmorel, while simulation models include energyPRO and EnergyPLAN. [61]

In order to choose simulation modelling over optimisation modelling for this thesis, an understanding of both the potentials and the limitations of user-specified simulation models was needed. Simulation makes the results more comprehensible and retraceable, yet its recommendations may not be as well-supported as results from an optimisation model due to the assumptions involved and the uncertainty as to whether the exogenously defined energy systems are optimal. Hence, simulations can be understood as descriptive rather than prescriptive. Decisions must be made consciously and potentially in dialogue with stakeholders, which makes the modelling process with simulation models more complicated, yet also more inclusive and contextual. The relevance of simulation is further established by addressing the innovative aspect of islands as niches. Finally, as optimisation also has weaknesses, such as assumptions, simplifications and less inclusivity, simulation can be considered the most suitable for testing, learning and debating possible future scenarios under the aim of this PhD thesis.

To answer the remaining parts of the research questions, the final aspect of modelling, already introduced in Chapter 1, is the replication of its findings; this is not strictly part of the modelling process, but it is one of the reasons for modelling in the first place [59]. This relates to Figure 1-2 (cf. page 4) and the relationship between islands and energy planning as well as the potential of models. In particular, the potential of islands as laboratories and for up-scaling illustrates this, even though doubts exist as well [16]. In order to evaluate the influence of top-level governance and regimes or landscapes in the multi-level perspective of transition theory, the innovation processes staged with island models must be understood and be able to reach further. Through this understanding, they might be seen not solely as places for experimentations but rather as offering a valuable contribution to energy planning. This shift in perspective is analysed in Chapter 3, especially in Section 3.3, and reflected in Section 4.1.

The role of modelling renewable energy islands is further discussed in the energy system analysis and case studies this PhD thesis makes use of, presented in Section 2.3, as well as in the following analysis. This aims to indicate what works under which conditions and how to replicate what works in an island model elsewhere. When looking at modelling in theory, it is relevant which tool serves the purpose, even though the theory might not imply that it is the case. With the aims and limitations of this PhD thesis in mind, the selection and relevance of the tool in addition to other methodological considerations are presented in the following.

2.3. METHODS

The use of island models and case studies is useful to understand how islands can not only achieve but also contribute to the understanding of the transition to renewable energy systems, either as testing grounds for innovation or governance showcases. With the concepts and theoretical framework presented in Section 2.2, much can be learned from the practice with islands, depending on the methodology behind it and its application. The following presents the requirements, options and consequences of the use of models as implemented in Publications [1]–[5] and analysed in Chapter 3. The energy system analysis tool EnergyPLAN and the three case studies Samsø, Orkney and Madeira are therefore addressed in detail. Connecting the theoretical aspects of modelling with the methods clarifies the practices relevant to understanding the approach and results of this PhD thesis, enabling the research questions to be answered and concluding this chapter.

2.3.1. ENERGY SYSTEM ANALYSIS

In order to evaluate the use of renewable energy on islands, the trends presented in Sub-section 2.1.1 need to be modelled, including smart energy systems and their characteristics, as a part of energy planning. A modelling tool is required for such an evaluation, thereby supporting the approach of the 1st sub-research question. Cross-sector options are part of the characteristics, as are the prioritisation of renewable resources and the options for balancing them. Unlike other geographical regions, islands are more often than not restricted in their electricity or gas trading options, so simulations of island mode is another necessity for the modelling tool. Furthermore, a simulation tool is the preferred option to establish a controlled island setting for testing and evaluating technological components, scenarios and contextual considerations.

As is presented through the choices made in PhD Publications [1]–[5], wherein more details are given, EnergyPLAN is a suitable modelling tool for smart energy systems and the corresponding technological evaluations. The modelling tool is developed by Aalborg University [40], [62] and the versions 12.5-15 correspond to and were applied in the PhD research. The modelling is thereby defined by the inputs and choices made, resulting in a controlled testing environment, although the interpretation beyond is up to the modeller. With the potential limitations presented above, including simplifications and simulations, the use of EnergyPLAN is further elaborated and discussed in the context of the PhD thesis in Chapters 3. Publication [4] presents its basics, while especially Chapter 4 reflects on its results.

'*The EnergyPLAN model can simulate the electricity, heating, cooling, industry, and transport sectors of an energy system on an hourly basis over a one-year time horizon, and can be used on various geographic levels and sizes of energy systems. Hence, it can be adjusted to specific locations and years by applying the respective data, such as projections to 2030. It simulates the mix of technologies in the whole system by identifying and exploiting synergies across the sectors. It is able to model fluctuating energy sources, and simulates their effects on the rest of the energy system. […]*

EnergyPLAN's simulation strategy is either technical or economic. While the economic strategy focuses on the most economically feasible operation of the energy production units based on exogenously given market data, the technical strategy focuses on primary energy supply (PES) and hourly system balance. […] Especially relevant for this study, EnergyPLAN may simulate island mode, allowing for an analysis irrespective of interconnections. Any export or import is therefore not evaluated further in terms of fuel consumption or related emissions avoided through export and caused by import.' [4, pp. 3–4]

The application of EnergyPLAN throughout this PhD thesis is reflected in the corresponding publications. Details on the inputs, for example, for the Samsø energy system model, can be found in [6], including hourly distribution curves and the impact of weather data. While technical simulations are applied in PhD Publications [1], [3]-[5], Publication [2] uses the economic simulation strategy. Besides the user-specific scenario creation discussed in 2.2.3, the simulation strategies applied in the analyses of the PhD thesis prioritise hourly system balance and renewable energy sources over fossil fuels in the case of the former, while market economic feasibility influences the results of the latter. Both strategies, however, present optimally operating energy production and conversion technologies.

More specifically regarding the publications, [1] shows how technologies can be modelled and analysed, whereby EnergyPLAN is '*chosen for the simulation of PV* *and battery systems [...] to investigate the more physical import/export response to systems changes*' [1, p. 4]. In [2], the tool is applied '*to perform the holistic systems analyses and the business economic optimisation*' [2, p. 2]. And thirdly, '*EnergyPLAN is able to analyse all energy sectors with all inputs and outputs of the energy system, including balancing and storage options*', which enables the analysis in Publication [3], where '*a small BESS is added to the EnergyPLAN reference models*' [3, pp. 5–6].

In [4], the possibility of scenario creation is utilised, where '*scenarios are created under consideration of the current energy system, as well as the planned actions in the upcoming 5–15 years*' [4, p. 5]. Finally, the '*option in EnergyPLAN to run serial calculations facilitates the elaboration of sensitivity analyses*' in [5, p. 6]. Additionally, the transition to 100% renewable energy share can be modelled, and this is also used for policy design through an institutional analysis [5]. Also applicable to all publications is the time perspective in the scenarios. While some of the time frames in these scenarios are not specified, they relate to short-term [1]–[3], medium-term [4] and long-term [5] changes in the energy system model, depending on the extent of technological changes and the local conditions. Thereby, the context of the energy system is taken into account to various extents; see Sub-section 2.3.2 for details on the case studies, which are elaborated in Chapter 3.

As shown in Figure 2-6, EnergyPLAN can represent any energy system, such as that illustrated in Figure 2-1 and Figure 2-5. The modelling interface presents the typical energy system flowchart and the many modelling options possible in EnergyPLAN. As discussed in Sub-section 2.1.1, some aspects might not be found in certain energy systems, such as islands, so Figure 2-6 should be adjusted accordingly. Additionally, a certain level of detail is lost due to the aggregation of energy units in EnergyPLAN, adding to the limitations of modelling in general. While island mode modelling is possible, it can present possible mainland-island bottlenecks, although internal bottlenecks cannot be represented. While Danish islands currently do not have bottleneck issues [63], they can be found across the Orkney Islands [64], [17].

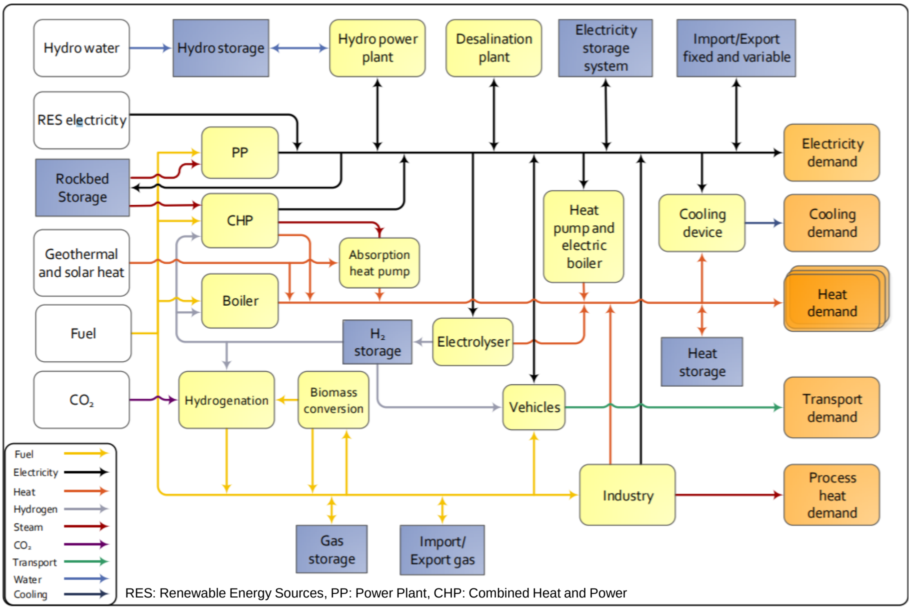


Figure 2-6: Energy system model as illustrated in the interface of EnergyPLAN vers. 15 [40], [62]

Even though it is not further elaborated, the modelling tool energyPRO also needs to be mentioned. EnergyPRO is a non-aggregated economic analysis tool that is mainly used for business models in heating assessments [65]. A model made in energyPRO contributes to Publication [2] through the specific technological evaluation of heat pumps in a district heating system. The different contributions of the co-authors to this section, as well as the focus on the reasons presented for using EnergyPLAN, exclude energyPRO from further exploration in this thesis and thereby also from further explanation. While energyPRO is aimed at business economic assessments, EnergyPLAN aims at socio-economic and contextual assessments and is, therefore, the focus of the following analysis.

Besides incorporating sustainable energy resources and the technical simulation strategy to address the efficient use of renewable energy, socio-economic costs including investments and operation costs are also analysed with EnergyPLAN. Furthermore, environmental considerations can be reflected in its inclusion of CO_2 emissions, of which a reduction directly addresses the Paris Agreement. Finally, in addition to including social aspects in the modelling, EnergyPLAN enables individual units to be tested, including at household levels, such as individual boilers or vehicles. [62]

It is further suggested in [61] that modelling of technical scenarios is not the final step in energy planning and that additional steps can be considered, for example, the use of the results and the related development of possible implementation strategies across different institutions. The purpose of modelling is to also highlight certain aspects of reality and '*to assist in the design, planning and implementation of future energy systems*' [61] through energy market and policy design, which is addressed in this PhD thesis. While modelling renewable energy islands suggest a mere technical focus, as is also addressed in Section 3.1 and in Publications [1]–[3], the discussion of the implementation is included in the later sections and Publications [4], [5]. Modelling thereby connects to the theories through technical innovation and institutional governance.

For the energy market analysis that follows the scenario modelling, a three-phase analytical process is used. While '*Phase 1 presents technical scenarios, […] Phase 2 identifies the institutional context and shows the existing barriers and benefits [and] Phase 3 leads to new recommendations or concrete design proposals*' [5, p. 7], [56]. This process applied and discussed in Section 3.3, particularly to address the 3rd sub-research question. The technical energy system analysis, and partly the implementation, is illustrated through case studies, which are presented in the following sub-section.

2.3.2. CASE STUDIES

Case studies are used to test theories in relation to technological modelling. If a theory is validated through case studies, the reader may draw conclusions for other cases, as is intended in this PhD thesis. While this process documents particular situations in specific contexts, it can be a methodology '*to understand how [technologies] were being implemented, why they had positive effects in some regions of the country and not others, and what the outcomes meant in different […] contexts*' [66]. Building on this definition, the following addresses the concrete case studies that the PhD research revolves around.

The discussion of modelling renewable energy islands requires models to work with; hence, the use of case studies is discussed for that purpose. Whether they truly represent the terms associated with islands given in the sections above, such as models, laboratories, testing grounds or showcases, is discussed in Chapter 4. While case studies potentially enable generalisation, a strategic selection of each case is recommended. This contributes qualitative insights, whereby a large number of samples result in quantitative data. Although there is value in a carefully selected individual case, a larger number of case studies should bring additional value. [67]

Furthermore, different types of cases exist, and those applied in this PhD thesis are understood as critical cases with '*strategic importance in relation to the general problem*' [67]. The answers to the research questions are therefore sought through three islands, with consideration given to both their individual and common values.

The case studies whose energy systems have been analysed are briefly introduced and discussed alongside their role in the corresponding Horizon 2020 Smart Island Energy system (SMILE) [68] project. This PhD thesis closely relates to SMILE and the preselected case studies, though a discussion thereof and research beyond the project definition is sought in light of the overarching role of modelling renewable energy islands (cf. Sub-section 2.3.3 and the following chapters).

The SMILE project involves a number of partners in investigating three preselected cases, namely Samsø in Denmark, Orkney[2] in the United Kingdom and Madeira[3] in Portugal, and their ways of becoming carbon-neutral through renewable energy and smart technology demonstration. Differing in their location, size and population, these islands represent a selection of geographical edges suitable for the study and comparison of technological and social interaction with '*important energy challenges common to several locations in Europe, on islands as on mainland*' [68].

'*While Samsø has been undergoing a decade-long transition from nearly zero to a high RE share after winning a competition of being Denmark's officially designated RE island* [69]*, it has, however, not solved the full energy system integration. The Orkney Isles are characterized by a large number of wind turbines and offshore energy production testing facilities, but suffer from fuel poverty and curtailment* [70]*. Madeira lies far off the European continent and stands out in European terms with great solar potential, while having to balance their energy system and grid stability autonomously* [71]*. These islands are therefore good case studies with challenges, as well as potentials, for the evaluation of RE integration in the transition to 100% RE.*' [4, p. 2]

Even though the local conditions on these islands differ widely, the SMILE project covers similar technical and non-technical solutions, such as demand response, smart grid functionalities, storage, and energy system integration. The specific solutions include – in line with the transition to a high renewable energy share – so-called smart technologies, such as battery electricity storage systems (BESS), power-to-heat, power-to-fuel, electric vehicles (EVs), electricity storage onboard boats, aggregator approach to demand side management (DSM), and predictive algorithms. Within the framework of the SMILE project, the aim[4] is to analyse and present the case study islands' energy systems as well as the impacts, strategies and market designs associated with the project. The main objective is to investigate potential development pathways towards high renewable energy shares for the three case study islands. Through assessment of the energy system impacts and potential pathways, replication

[2] This refers to the Orkney archipelago, or the Orkney Islands, which include around 70 islands.
[3] This refers to Madeira Island, not the archipelago, which includes 3 islands.
[4] SMILE Work package 8: Impact analyses - Energy system impacts, energy strategies and energy markets design [6], [8], [9], [68].

potentials are explored. SMILE thereby supports answering the research questions of the PhD thesis by addressing the role islands can have for sustainable energy planning. [6], [68]

In relation to the main objectives, the respective deliverables are the development of reference energy system models [6] as well as short- and medium-term scenarios for the three case studies [8]. The case study of Samsø is further made use of in the MATCH project[5], in which additional perspectives of Samsø are addressed [7]. Finally, the SMILE deliverable on energy market design for the case studies [9] concludes the reports that involve the cases and support the PhD thesis. In parallel with those reports, the publications made during the PhD research are based on related research for Samsø [1], [2] and Orkney [3], on all three cases [4], and especially for Madeira [5].

Publication [5] elaborates on the role and boundaries using case studies for innovation: '*The case study to test this novelty aims at looking at an existing energy system and its current technologies and market, and how it can be optimized to reach a 100% RE share. […] While [the introduction] presents the complexity of energy planning approaches, these are further complicated through geographical and economic boundaries. The selected choice of technical approaches would result in a variety of options and outcomes. Therefore, the following presents the introduction of the scenario development for the case study […], which is to test these approaches under its unique boundaries, for the reader to draw the consequences for other cases.*' [5, pp. 3–4]

Contrary to the often-considered use of a singular case study for experimentation, this research presents the advantage of several islands, which facilitates a comparison, such as in Publications [3] and [4]. However, the consideration of the contextual details of a singular case study also helps conclusions to be drawn by including and understanding local specifics. These aspects are relevant to answering the 2nd sub-research question.

In conclusion, case studies support modelling under certain conditions by providing living laboratories. While the SMILE project is aimed at replication and knowledge that may be important for many European locations, the project is also limited by its fixed objectives, choice of technologies and preselected case studies. Why and how the PhD research is making use of the project to evaluate island modelling through the three case studies as well as addressing solutions beyond this is elaborated in Sub-section 2.3.3. Further details regarding observations of the case studies and related field research are presented in the following paragraphs.

[5] MATCH Work package 4: Energy system analysis - a comparative study of smart grid solutions and new forms of relations between energy producers and consumers [7].

CASE STUDY AND FIELD RESEARCH OBSERVATIONS

The SMILE project not only provides targets for the case study islands, and thus a framework to be investigated, but also offers the possibility for additional observations during collaboration with the project partners and from field research. This is used to support the PhD research and analyses in both the PhD publications and in Chapters 3 and 4. In order to clarify this approach, the research and relevant influence on the case studies are presented and the validity is discussed.

Since case studies are context-dependent, the level of researcher involvement and the resulting subjectivity are important. While a high level of personal interaction can result in subjectivity that influences the choices in modelling, making the research potentially unsuitable for scientific argumentation, however, placement within the context of a case study creates a better position from which to understand it. This common misunderstanding about case studies is revised in literature: '*The case study contains no greater bias toward verification of the researcher's preconceived notions than other methods of inquiry*' [67]. Additionally, the subjectivity emerging from the close relation to the case studies positively influences the motivation and ambitions of the PhD research. However, the theoretical and methodological framework of this chapter is pursued, which results in the research maintaining objectivity in its use of case studies and related research observations.

The case studies, as well as the collaborators of each island, are mentioned in Table 2-1, including the period and form of interaction. Furthermore, other island perspectives are gained through collaboration with one island, such as the discussion about Fur that results from the work with Samsø, which in turn influences Publication [1]. In the observation from research on and around Orkney, additional insights from Shetland are included as well which support the Orkney perspectives in this thesis.

While some observations solely impact the respective publications, others support and complement each other, thereby not only providing quantification and validity to the PhD publications and thesis but also supporting the analysis qualitatively. Some details can be found in Publications [1]–[5], while others are documented in notebooks and correspondences collected over the period of the PhD research. Overall, the use of these case studies and research observations is done consciously to maintain an adequate level of objectivity as further discussed in Sub-section 2.3.3.

Table 2-1: Observations of case studies and collaborations

Case study	Collaborators	Period of close collaboration	Types of observation and research	Reference
Samsø/ Denmark	Samsø Energy Academy, Samsø municipality	12-14/04/2018, 01-03/04/2019	Data, discussions, Danish island observations	[37]
Orkney/ Scotland	Community Energy Scotland, European Marine Energy Centre, Orkney Council, Shetland Council	26/08-30/11/2019	Data, discussions, interviews, field trips, site visits, observations	[17]
Madeira	Madeira Interactive Technologies Institute, Empresa de Eletricidade da Madeira	02/02-18/02/2019	Data, discussions, site visits, research collaboration [5], observations	[72]

In additional to the three main case study islands and respective research observations, the German islands Föhr and Helgoland are also relevant [73]. Even though they do not represent a specific case study in the following analysis, the PhD research is closely connected to and influenced by observation on both islands before and during the PhD research, which offers additional supportive insights. This additional exploration of non-SMILE islands is motivational and inspirational when addressing modelling islands and finding the role modelling plays in sustainable energy planning, thereby supplementing the case study observations in Table 2-1.

Together with the scientific approach of the theoretical and methodological framework, the observations of case studies and their neighbour regions or islands supplement the PhD research with qualitative data and insights, providing validity. The observations are mainly used in supportive and elaborating arguments throughout the PhD thesis, while some of the limitations and the overall approach are presented in the following.

2.3.3. RESEARCH APPROACH

To summarise and validate the concepts, theories and presented methods so far, this section concludes with the approaches taken and the application of the framework in the PhD thesis. As presented in Chapter 1, the role of islands is potentially larger than previously assumed, and the theoretical and methodological framework and tools can be used to give this a deeper consideration. While neither an evaluation of the 80,000 global islands, nor the 2700 European or 72 Danish ones is possible, the framework conditions established in the previous sections nonetheless permit this to some extent in the following chapters of the PhD thesis. This section thereby presents how the framework conditions influence and apply to the analysis in Chapter 3 and the reflection in Chapter 4.

Based on the targets of the Paris Agreement, the two main trends addressed in the PhD thesis are sustainable energy planning and smart energy systems. These are defined by contextual considerations and sector integration. Whether through the evaluation of the necessary renewable energy technologies or the consideration of the local context, islands may present suitable places for experimenting and learning. However, theories suggest a strategic alignment of innovation and governance across all areas and levels. The resulting methodology for modelling renewable energy islands includes energy system analysis and case studies.

The case studies, however, as defined through SMILE [68], show misalignment with the choice of technologies and the approaches used within them. This is highlighted in the 3rd Publication: '*In the SMILE project, the focus lies on the electricity sector. To form [smart energy systems], however, the transition of islands should entail the integration of all energy sectors – electricity, heating, cooling, industry and transport, specifically making use of the access to the [local renewable energy sources]*' [3, p. 1]. Thereby, additional technological solutions besides the ones suggested by SMILE are included in the research conducted, such as thermal energy storage (TES) besides BESS (cf. Sub-section 2.3.2).

Going beyond the initial intention in SMILE is also addressed in the 4th Publication, whereby '*sector integration […] is therefore included in the scenario design, which goes beyond the idea of SMILE. […] the SMILE project somewhat predefines the scenarios, yet they are further dependent on the local conditions and demands*' [4, pp. 5–6]. Hence, the scenarios made for the case studies are adjusted according to the local possibilities rather than merely following the continental viewpoint, as introduced in Chapter 1.

The selection of Samsø, Orkney and Madeira as case studies further limits the conclusions to be drawn, since they might represent a certain edge and category of islands that differs from others. Being involved in not only the SMILE project but also having experience in other innovative projects and showing a prior willingness to experiment, the three case studies must be counted among the 'smart islands' as defined in Sub-section 2.1.3, Furthermore, they must also be considered as particularly curious and engaging ones, which cannot be expected in other places [59]. Hence, in contrast to others, Samsø, Orkney and Madeira might already be branded as 'renewable islands' and thus may not represent islands globally [55].

Therefore, the PhD thesis addresses the potentials and limits of modelling renewable energy for islands through energy system analysis and the case studies, as evaluated in Publications [1]–[5], as well as beyond. The thesis thereby presents the cutting edges of research from the PhD period through perspectives from certain edges of the world. The following generalisation and combination with transition theory and governance adds new perspectives to the areas of investigation. Through additional reflections through the theories presented and relations drawn from the problem statement, the PhD thesis aims beyond the knowledge gathered from – and relevant for – the case study islands. This is supported by the research observations during the PhD period.

The PhD thesis, therefore, reflects on the quantitative as well as the qualitative values of the island models. The analysis of the case studies under these conditions, as well as the replication potential, is addressed specifically in Chapter 3. The implications and new understandings of modelling renewable energy islands are drawn out in Chapter 4, highlighting how quantitative research can lead to qualitative conclusions.

This relationship between the following sections in Chapters 3 and 4 and the PhD publications is also illustrated in Figure 1-3 (cf. page 11) and further elaborated in Table 2-2. While the concepts of Section 2.1 and the theories of Section 2.2 can be found in each of the subsequent sections, the different aspects of transition theory and multi-level governance are especially addressed in the theoretical Sub-sections 3.X.2, which follow the respective analyses of Publications [1]–[5] in Sub-sections 3.X.1. Furthermore, the subsequent Sections 3.1, 3.2 and 3.3, all make use of the same energy system analysis methodology, while the selection of case studies varies. Section 4.1 presents the first reflective section of Chapter 4 and summarises and concludes the research steps and questions, while Sections 4.2 and 4.3 finalise the reflections and the role of islands in sustainable energy planning with resulting research opportunities.

Table 2-2: Research steps and relations to publications, theories and questions

Section	Research steps	Publications (3.X.1)	Theoretical aspects (3.X.2)	(Sub-)Research question 'focus'
3.1	Modelling of islands	[1], [2], [3]	Top-level influences	Using islands to 'evaluate renewable energy technologies'
3.2	Modelling on islands	([1], [2]) [3], [4]	Niche and horizontal views	Improving island models by 'considering and comparing local conditions'
3.3	Modelling from islands	([1]-[4]) [5]	Bottom-level influences	Elaborating 'contextual and institutional alignment' for island modelling
4.1	Modelling with islands	([1]-[5]) (beyond)	Coordination, generalisation of the above	Combination of the above regarding modelling renewable energy islands
4.2 and 4.3	Reflections on the above and conclusions on 'the role of modelling islands in sustainable energy planning' with resulting perspectives and research beyond			

CHAPTER 3. ANALYSIS: CUTTING EDGES OF MODELLING

Modelling islands, cutting-edge research, and the edge towards new understandings.

After presenting the framework for modelling renewable energy islands, this chapter approaches the research question 'What role can modelling renewable energy islands have in sustainable energy planning?' This is done in three steps, taking into account the corresponding publications during the PhD thesis, as explained in Sections 1.2 and 2.3. Hence, the 1st, 2nd and 3rd sub-research questions are addressed in the following order and sections:

3.1. How can modelling of islands be used to evaluate renewable energy technologies?
3.2. Why and how should modelling on islands be improved by considering and comparing local conditions?
3.3. How can contextual and institutional alignment elaborate modelling from islands?

These questions are addressed separately in relation to the Publications [1]–[5], which chronologically follow the research questions, i.e. the early publications support the first questions and so forth. Sections 3.1, 3.2 (cf. page 52) and 3.3 (cf. page 63) additionally pick up the perspectives introduced in Section 1.2 that can be associated with islands: perspectives *of* or *to* islands, perspectives *on* islands and, finally, perspectives and learnings *from* islands.

To answer the corresponding sub-research questions, as well as the main research question, the respective first sub-sections in Sections 3.1, 3.2 and 3.3 review the publications, while the second sub-sections put them into a theoretical perspective. Chapter 2 thereby contributes not only to the first sub-sections through the concept, theories and methods used in the publications, but also to the second sub-sections by putting them into the new context of transition theory and multi-level governance to add theoretical and qualitative perspectives. The analysis and results are reflected in Chapter 4, which summarises and combines the results presented here.

3.1. MODELLING *OF* ISLANDS

In order to investigate how islands can be used to test and evaluate renewable energy technologies, this section discusses mainly Publications [1] and [2], but also parts of [3], which links it to Section 3.2. This is done in Sub-section 3.1.1 through a closer look at the modelling done, the reasons for it and the immediate results achieved. Meanwhile, theoretical interpretation beyond the modelling is presented in Sub-section 3.1.2. For this, transition theory is discussed through the impact of landscapes and regimes on niches as well as top-down action on other levels in multi-level governance.

3.1.1. EVALUATING RENEWABLE ENERGY TECHNOLOGIES

The first publications in the PhD research start by addressing global or European targets and trends, stating '*Energy systems worldwide are facing an energy transition*' in [2] and '*Europe has ambitious energy targets*' [1]. They then outline the resulting need for the modelling of novel technologies under consideration of the concept of smart energy systems. This places the focus from the beginning on central perspectives and on islands being used as case studies for this evaluation.

Despite the wide-reaching targets, the technologies are tested in an island setting, either because the island is known for '*testing and demonstrating sustainable energy solutions*' [1, p. 1] or because it is '*the site for many energy innovations*' [2, p. 2]. The island characteristics of natural water borders and the easy traceability of imports, exports and local energy system details make islands a suitable setting for evaluating technologies. Based on the concepts and the theoretical approach to modelling from Chapter 2, island energy systems can be modelled as other energy systems, with the island setting offering a potential benefit for modelling. The resulting representation in flowchart models illustrates the technological system constellations and their evaluation in a simplified way. The EnergyPLAN modelling done in [1] and [2] is also based on this. The impact this has on the results is discussed after the presentation of the analyses in the light of evaluating technologies and thereby addressing the 1st sub-research question.

EVALUATING PV AND BATTERIES

In "*Residential versus communal combination of photovoltaic and battery in smart energy systems*" [1], different combinations of PV and electricity storage are tested to evaluate their performance in the residential sector of the Samsø energy system. Therefore, in addition to the simple energy system model from Figure 2-5 (cf. page 28), which forms the basis for the energy system analysis, the consumer level is also presented in the flowchart model of Figure 3-1. Contrarily, technological details, which are deemed irrelevant in this analysis, are excluded in the model to focus on the test at hand. The Danish island Samsø is chosen as the test site for the analysis, making use of the island setting and contributing to the discussion of communal or individual technologies and involvements of consumers. However, despite being part of MATCH [7], the consumer involvement is limited.

Within the smart energy system framework, the publication addresses two potential ways to balance the fluctuating electricity production from PV panels. One scenario is direct storage at each household production side via individual batteries, and the other scenario describes a communal battery shared by many households. The technological capacities are thereby adjusted for either typical residential installations of 4-6 kW for PV panels and 0-10 kWh for each household battery or for the same capacity but accumulated communal battery scenario (cf. [1], Tab. 2).

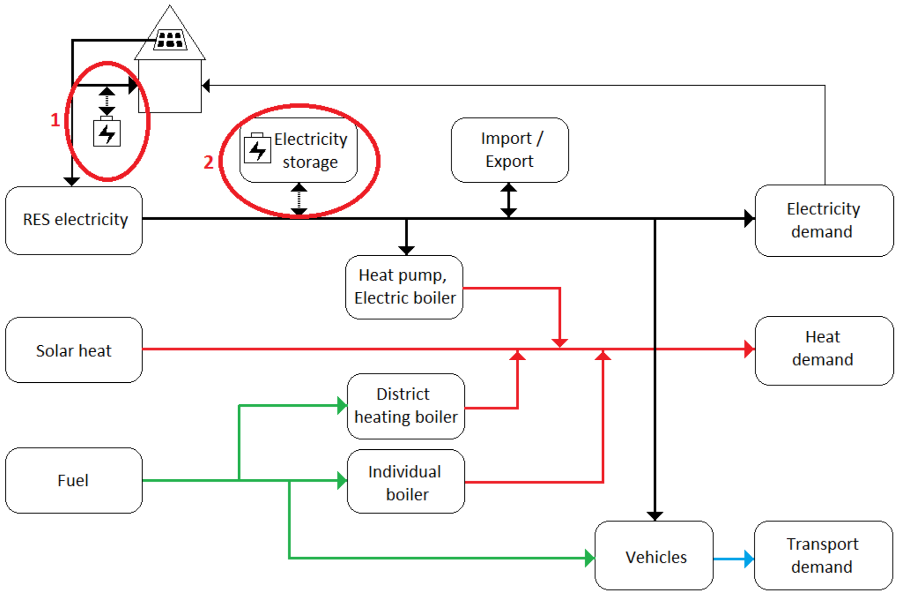


Figure 3-1: Energy system model of Samsø for evaluating PV and batteries [1, Fig. 1]

Even though Figure 3-1 shows that this analysis affects only a small part of the energy system, the connections to the overall energy system indicate potentially wide-reaching impacts, which are evaluated in EnergyPLAN. These are of significance for the island setting and have impacts on the local energy system balance, even though one of the approaches seemingly only addresses residents. The alternative of consumer solutions further addresses the issue presented in Chapter 1 regarding centralised versus decentralised planning and optimisation [14]. The research thereby contributes to the scientific literature by pointing out whether there is, and how to approach the potential for, local optimisation within an energy system. An additional way of looking at it could be to consider the household focus in an island (-within-an-island) perspective, thereby indicating the impacts on other areas, similar to how islands impact other islands and/or the mainland.

One of the key results of the analysis in [1] is illustrated in Figure 3-2, where the top graphs show the impacts of the residential battery and the bottom ones show the impact of the communal battery on the whole island's. While the first interacts only with the residential demand, and thereby depends solely on PV production, the latter is influenced by the whole island's electricity demand as well as its PV, and also wind, power production. The communal solution, with the influence of wind power, significantly impacts the utilisation of the battery, while the residential solution only depends on solar radiation and household demands. [1]

Without a clear preference in the analysis, the importance of both renewable energy and storage technology in general is shown. Both scenarios result in similar increased renewable energy shares of around 2% to 70% and reduced CO_2 emissions of 27% each. While the electricity export also increases the same (13%) for both batteries, the import is reduced almost two-fold with the communal solution. This is explained by having the same additional PV capacities in both set-ups, but the only the perspective with the communal batteries adds a significant new balancing option to the reference system. (cf. [1], Tab. 3)

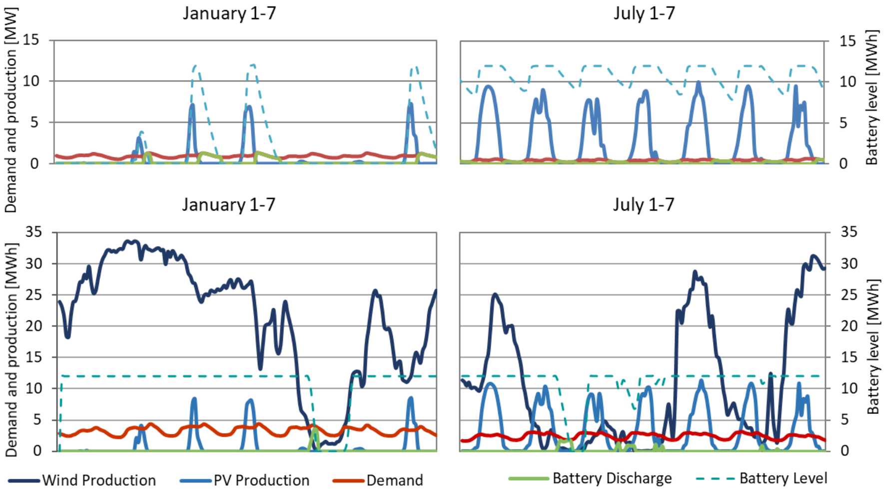


Figure 3-2: Renewable energy production, demand and battery behaviour for the residential (top) and communal (bottom) perspectives [1, Fig. 9]

Through Figure 3-2 we gain a further understanding of island perspective and island mode, since the residential set-up can be understood as an island-like set-up within the island of Samsø. Creating borders, theoretical, electrical or otherwise, results in different results and impacts on the surroundings. As an example, the battery charging and discharging – and thereby the assessment of the technology – differs considerably in the presented publication. For example, the residential solution leads to a constant loss of energy due to self-discharging instead of exporting during hours of high PV production. '*The resulting constant loss of electricity might make the residential solutions less favourable compared to communal battery solutions*' – or more generally, the result makes the island-like solution less favourable compared to the communal, more contextual solution. Contrarily, considering and modelling the contextual and wider impacts makes the communal solution inadequate, cf. '*a large utilization of wind power would make the selected battery size insufficient*' [1, p. 8].

Hence, depending on the perspective, the best combination of components depends on the context, as illustrated through the island perspectives and the effects on the remaining energy system.

Another aspect the publication illustrates is the potential of decentralisation, and thereby the possible increase of local consumer engagement, by choosing the residential combination of PV and battery. '*Compared to residential batteries, communal batteries result in less customer involvement'* [1, p. 8] due to less interaction and the benefits from the communal battery; hence, the communal solution limits the potential of local energy planning, even though a certain degree of localness is addressed. This is potentially in conflict with not only an inclusive study of markets, actors and technologies in MATCH [7], but also the European Commission's goal of putting the consumer at the centre of the energy transition [36] and adds to the understanding of strategic local energy planning (cf. Section 2.2).

EVALUATING HEAT PUMPS AND STORAGES

Using Samsø to test and model technological approaches towards decentralisation or higher renewable energy shares allows some assumptions to be made, for example for replication on other islands and sites concerning the advantages of residential and communal PV-battery solutions. The same applies to the analysis made in the 2nd PhD publication, where the district heating of Samsø is investigated through the same energy system model. The investigation "*Business and socioeconomic assessment of introducing heat pumps with heat storage in small-scale district heating systems*" [2] includes the integration of fluctuating renewable energy into the heating sector and addressing the potentially unsustainable use of biomass. This is done by modelling a potential switch to heat pumps, illustrating the role of power-to-heat and heat storages for small-scale district heating. While the business economic assessment only looks into one district heating plant[6], the socioeconomic assessment addresses the whole island's district heating plants to illustrate potential impacts on the island's energy system.

Supporting reasons for the evaluation include large amounts of fluctuating renewable electricity, a high share of biomass used in heating and the potential to use the latter as a future transport fuel. While this is the current situation on Samsø, similar situations can be found around the world regarding high wind fluctuations or controversial use of biomass, both presently and in the future. While converting some of the fluctuating electricity production into thermal storage, which is more effective than potential export or curtailment, addresses an element in the smart energy system concept, this is primarily aimed at the heating sector. The modelling shows how the

6 Modelled with energyPRO and excluded from further evaluation; see the limitations in Sub-section 2.3.1.

integration of local renewable energy into the heating sector has a positive impact in regards to the concerns raised with the use of biomass. [2]

Similar to Figure 3-1, Figure 3-3 also presents the model set-up used in the analysis. Despite being the same case study energy system, this figure shows the differences a simple model like Samsø's can have. While the first model includes individual boilers and batteries, the model depicted in Figure 3-3 includes industry. It shows the different perspectives the modellers have and the potential limits in presenting a full smart energy system that includes all sectors. Therefore, the statement '*it will be a clear demonstration of the benefits of the sector integration through the smart energy approach*' [2, p. 6] should be read with that potential limit in mind.

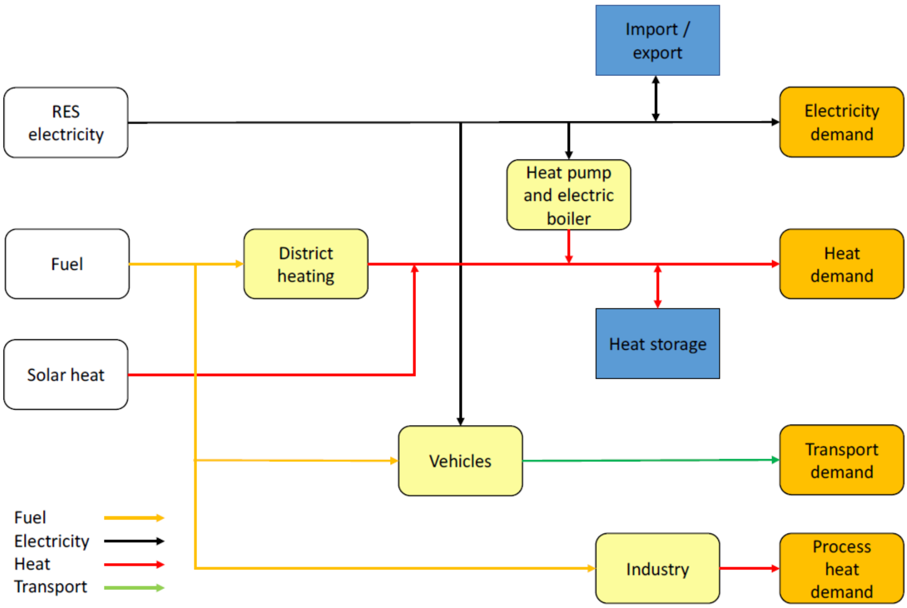


Figure 3-3: Energy system model of Samsø for evaluating heat pumps and storage [2, Fig. 1]

The results in [2] indicate the socio-economic feasibility of implementing heat pumps in district heating to reduce the export of local electricity by 7% and free up biomass resources. To make even better use of the fluctuations through the heat pump, thermal storage is added to the model; see the options in Figure 3-4. While no specific capacity is recommended in the EnergyPLAN analysis of the island, a balance of cost and benefit for the whole system is suggested. While smaller storage capacities yield better cost-benefits results, the largest capacity would lead to an additional reduction of electricity export of 8%, which increases costs by 10% due to the simplified linear cost development assumption in EnergyPLAN. [2]

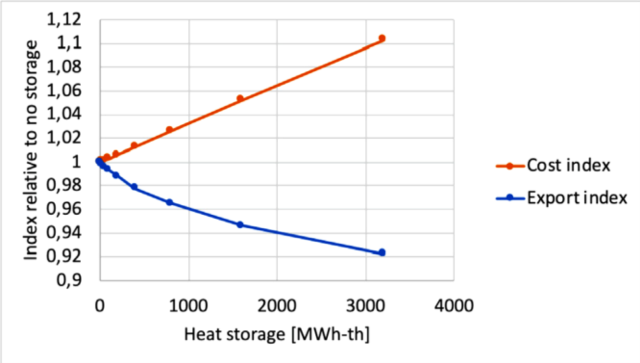


Figure 3-4: Options and resulting costs of heat storage size for Samsø [2, Fig. 6]

The analysis in [2] shows that adding a heat pump and thermal storage can be attractive for islands, both with limited options to trade renewable electricity as well as a with restricted use of biomass. However, the business economic assessment including the electricity market shows a different tendency due to limited feasibility, potentially hindering this development. It should, therefore, be clarified that the results of modelling depend on the modelling set-up. For example, '*Current political negotiations aim to reduce the levy on electricity for heating purposes gradually over three years starting in 2018, however this has not been considered, but may eventually improve the feasibility*' [2, p. 7]. Hence, the conclusions for potential replication by others must be read as such, including the dependence on the set-up. While this is true for any other research done in a specific setting, the following goes a step further.

EVALUATING ELECTRICITY AND THERMAL STORAGE

The publication "*Evaluation of electricity storage versus thermal storage as part of two different energy planning approaches for the islands Samsø and Orkney*" [3] takes modelling of an island a step further by modelling the same technological approach for two islands. Narrowing in on the technology focus of SMILE and its case studies, this publication presents the investigation into thermal energy and electricity storage for two of the SMILE islands. The publication stresses that one of the main requirements of fluctuating renewable energy production is balance; therefore, two balancing options are presented and analysed. The first is electricity storage, or battery energy storage systems (BESS), and the second is thermal energy storage (TES), which is enabled through power-to-heat technology and district heating. While the first option responds mainly to the activities of the SMILE project, the second one is more within the framework of a smart energy system.

The modelling is done on the islands of Samsø and Orkney, and Figure 3-5 illustrates both in the flowchart set-up, showing their similarities with each other and with the models used in the previous two publications. The main difference to Samsø is that district heating is not found in the reference energy system of Orkney, while a larger industry and a power plant is. Figure 3-5 shows the simplified relationship between tested storages and the respective energy systems, either through direct connection with the electricity grid or through heat pumps or electric boilers with thermal grids for electricity and thermal storage, respectively. The model thereby includes all sectors and compares especially the heating and electricity sectors, yet examines both within island mode and making use of the island setting. [3]

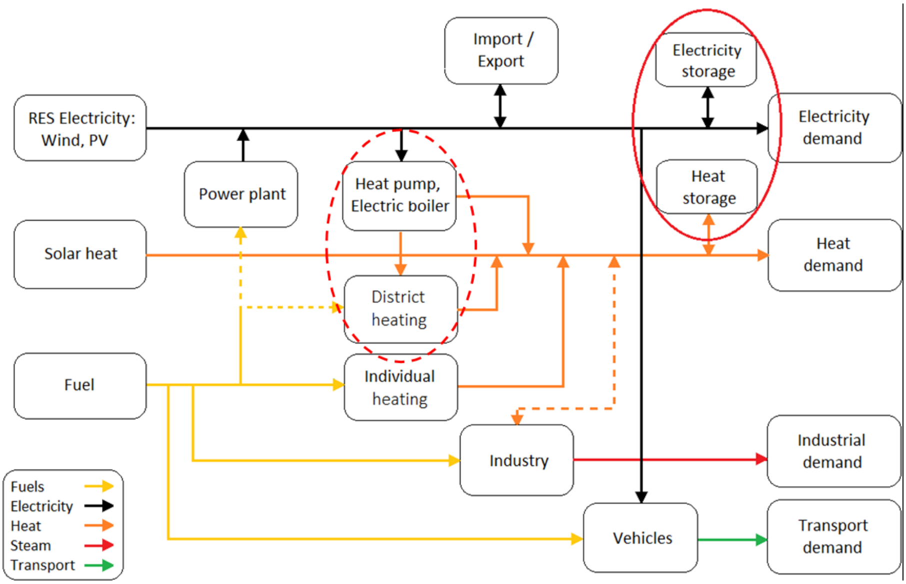


Figure 3-5: Energy system model of Samsø and Orkney for evaluating storages [3, Fig. 2]

Despite the small differences between Samsø and Orkney, Figure 3-5 shows the similarities in their energy systems. The modelling done using their energy system models includes the same battery and thermal storage capacities as well as the option of using heat pumps and biomass for the heat production in the respective district heating plants. Hence, an analysis and addition of district heating is performed for Orkney. Due to the similarities of the islands and the approaches for each, the results support each other, showing the benefit of sector integration through the use of power-to-heat and thermal storage in district heating. Without affecting the import of electricity, thermal storages reduce the export by up to 10%, while costs are reduced by 1-3%. Electricity storage reduces the import, but increase the costs with similar or worse effects on the export (cf. [3], Tab. 3).

Overall, Publications [1]–[3] illustrate the potential role of modelling islands for evaluating technologies through the use of models, thereby answering the 1st sub-research question. In particular, the island setting provides a simplified yet transparent modelling context that is suitable for the evaluation of renewable energy technologies.

This is shown through an evaluation of PV and batteries on the consumer side of the energy system in [1], heat pumps and thermal storages in district heating in [2], and comparing electricity with thermal storage in [3].

The impact, implications and further understanding derived from the modelling of islands are further explained and evaluated in the following. The transition and governance theories' perspectives thereby add discussions relevant also for Sections 3.2 and 3.3.

3.1.2. LANDSCAPE INFLUENCES AND TOP-DOWN GOVERNANCE

Transition theory implies the influence of socio-technical landscapes on both the established regimes and niches of innovation [52] in which islands might be situated, as introduced in Section 2.2 and Figure 2-3 (cf. page 23). Considering islands as places for innovation and learning entails that landscapes and regimes with their respective stakeholders want to make use of islands and influence the innovation. This can be done to achieve knowledge through evaluating renewable energy technologies, as done in the previous section and Publications [1]–[3].

With climate change defined as a socio-technical transition, the landscape's visions and pressure as well as the expectations from the regime in terms of innovation require interaction with the islands to address it. The influence of landscape and regime is illustrated in Figure 3-6, which shows their top-down impact on islands through the use of island models. By testing a technology on an island, innovation and learning can take place in a test setting, as presented in the previous sub-section, but under the influence of the different levels and areas.

Modelling islands enables both a transition in controlled settings with clearly defined boundaries and a transparent way of tracing effects in the energy system. With naturally resulting small-scale tests, complexity and contextual distractions are limited, yet the results are easily traceable. Often, islands thereby seem to represent larger energy systems in a compact way. The potential for up-scaling or replication thus becomes a possibility, which addresses the visions for innovation on the landscape level. As presented in Sub-section 2.2.1 and Figure 2-3, only if the innovation is stable and aligned can adjustments be made accordingly at the regime level. However, as illustrated in Figure 3-6, the influence of islands on other levels is not yet shown as the limits from higher levels restrict any further impact. This is elaborated in Section 3.2 and 3.3.

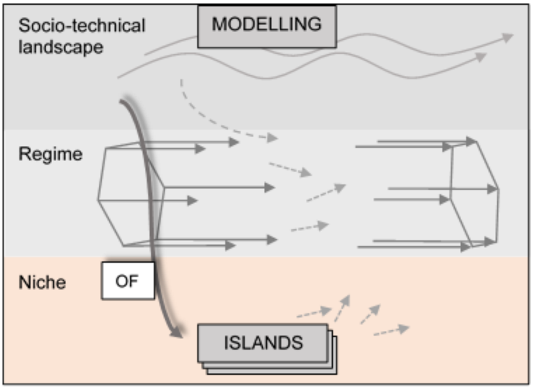


Figure 3-6: Modelling of islands in transition theory – the influence of landscape and regime

This top-down influence of landscape and regime can be related to multi-level governance, as introduced in Sub-section 2.2.2. The literature review in Publications [1] and [2] started from a general, global or European perspective, which reflects the top-to-bottom arguments presented here. Islands, on the contrary, are only mentioned in the 8th and 3rd paragraphs, respectively.

As Figure 3-7 shows, this influence can be illustrated in a geographical context. Islands are defined as bottom-level in the governmental hierarchy or as edge pieces in the puzzle of energy planning. With decisions taken and coordination often happening on the central level, non-central regions have to adjust accordingly. Political targets, also regarding energy planning, are defined in the national directives and initiatives to be implemented regionally. With early electricity and fuel markets organised centrally, this was justified in the past; however, it should be elaborated, as is done in the following sections.

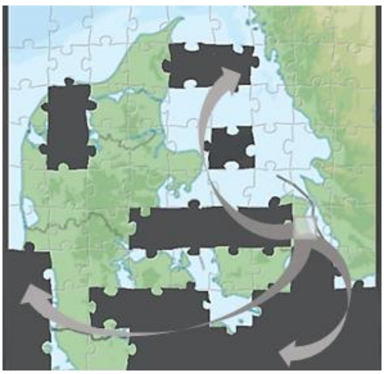


Figure 3-7: Modelling of islands – seen from the top-down perspective, illustrated as the influence from Copenhagen on the Danish islands

Figure 3-7 illustrates the top-down governance from a Danish perspective, with Copenhagen presenting the central entity that directs and coordinates the islands in Denmark, illustrated as missing pieces of the puzzle. This is supported by the experience of Orkney and Shetland, which must follow decisions from central places like Edinburgh and London [17]. These capitals, however, are not aware of the situations and abilities in implementing the directives and decisions on the edges of their countries, supporting the illustrated gaps in the puzzle of energy planning.

As transition theory and the top-down influence already illustrate, certain limitations are encountered when evaluating renewable energy technologies through modelling of islands. Even though the modelling of islands has some benefits, such as small test settings, their replicability regarding innovations that have an impact on the existing regime or for returning knowledge to the top level is limited. On the one hand, this is due to the technical limitations that both the modelling itself (cf. Sub-section 2.2.3) and the methods (cf. Section 2.3) have, but on the other hand, it is also due to additional aspects, which are described in the following paragraphs.

While the evaluation of renewable energy technologies usually relates to trends that are established for the country as a whole or for well-interconnected energy systems, testing on islands or in an island setting might not be suitable since these do not represent typical energy systems or because the modeller's outside perspective does not reflect those of the island. At the same time, results obtained in an island setting might not be relevant in the context of other settings. This is introduced through the different perspectives of islands in energy planning in Chapter 1, Figure 1-2 (cf. page 4), and is further raised in Section 3.2, where the replication is also addressed.

Nonetheless, the analysis of evaluating technologies through modelling of islands as well as the role and influence in transition theory and governance answer the 1st sub-research question. This is illustrated by the potential and perspectives for other energy systems and levels by providing a test setting and transparency. Furthermore, it gives a first impression of what role the modelling renewable energy islands could have in sustainable energy planning. As suggested in the previous chapters, the role in experimentation is shown, yet further steps are possible, as explored in the following sections.

The remaining limitation, where modelling *of* islands is usually done from an outside view, limits the learning as well as the replication. This is, therefore, discussed in the next section by addressing the issues of renewable energy modelling on islands as well as its replicability. For that, the comparability of island models as well as local energy system understanding are investigated. The aim thereby is to better address transition theory's level of the niches, as this is where the innovation is expected to happen and where the international and national directives and initiatives are to be implemented. Hence, the next section turns to modelling *on* islands.

Figure 3-8: View of Samsø and the ferry that takes us there, seen from the mainland

3.2. MODELLING *ON* ISLANDS

After examining the reasons for and possible results from modelling *of* islands, this section looks at the perspective of modelling *on* islands and answers the 2nd sub-research question 'Why and how modelling on islands should be improved by considering and comparing local conditions'. This section, therefore, builds upon the learnings and limits from Section 3.1 by continuing the discussion of the use and understanding of renewable energy island modelling.

References to Publications [1] and [2] pick up aspects from the investigation in the previous section and support the need to improve modelling in this section. In turn, Publications [3] and [4] are evaluated to address this through the comparisons between islands as well as the local conditions to gain a further understanding of island models and their potentials, as discussed in Chapter 2. Therefore, the following addresses the replication and interpretation potential of the models, before elaborating this in the theoretical context of local niche innovation and horizontal governance.

By modelling *on* islands, aspects that are typical for islands and not as significant or obvious in other settings are taken into consideration to improve the understanding of island settings. As introduced in Sub-section 2.1.2, islands are unlike other areas due to their geographical setting, demography or perspectives. This also applies to energy on islands (cf. Sub-section 2.1.3) in terms of local resources, infrastructure and demands. However, while islands have worse conditions in some aspects, they may have better ones in others. For example, islands may not have heavy industry, yet may have much tourism; they need boats, while others have better rail and road infrastructure; and while there are water borders, there are no physical borders. Hence, in regards to the generalisation for replication, islands are just as special as other areas, yet more predictable in many ways. A generalisation is therefore difficult; nevertheless, it is attempted and brought to attention in the following through comparison and inclusion.

3.2.1. COMPARING AND INCLUDING LOCAL CONDITIONS

While Publications [1] and [2] start off with global or European perspectives, the literature reviews in Publications [3] and [4] address the importance of the islands by starting off with their individuality, rather than a trend observed in global or national energy planning. ‘*Islands present special energy systems*’ [3] and ‘*Islands’ energy systems are like most other […] However, they are under more pressure*’ [4] highlight a new perspective, which supports the analysis in this section. Analysing the potential of recognising islands’ individuality through a comparison and inclusion of their conditions addresses the issue of the limited usability of island modelling and its replicability. The issue is first elaborated and then addressed in the following.

REASON FOR IMPROVEMENT

As presented in Sections 2.2 and 2.3, by their very nature, models are meant to be understood in a limited way, used mainly for representing and simplifying. This includes the natural limitations of data, with information on subjects ranging from technology and consumer behaviour to weather. Even for well-documented and tested islands, like Samsø, any model will have deviations from reality. Based on data that are often built on national statistics and need to be adjusted to the island or based on local data that might be outdated or selective, the model of an island’s energy system will never fully represent reality. Furthermore, based on theories, estimates or measurements, depicting and replicating the energy system of any future becomes limited. This is related to both the impact from, as well as the subsequent result for, the outside world, namely, that models tend to be made externally and often for the external use. The result is a theoretical and simplified model which – usually – suits the modeller rather than the island under investigation.

The modelling tool for energy system analysis as introduced in Section 2.3 is also expected to simplify things. Limitations are found not only in the tool itself, but also externally. The internal limitation refers to EnergyPLAN’s aggregated method of operating, overlooking potential transmission or internal bottlenecks, which are especially common to islands, as well as intra-hour or technical issues that exist in reality yet not in the models presented here. An example is the operation of the local battery storage, whereby ‘*EnergyPLAN will rather import electricity than store it at a loss*’ [1, p. 8], even though this might reflect neither the reality nor the needs of the local community and energy system limits, such as bottlenecks. The external limitations include the issue of limited or incorrect inputs, which puts pressure on the one responsible for choosing the data and modelling criteria. As mentioned before, if not being from the island in question, this responsibility can be difficult to fulfil by the modeller. This brings us to the overarching point that EnergyPLAN is technically sufficient within its own limits in finding suitable scenarios even though it is perhaps realistically insufficient for modelling and replicating real system operations.

While EnergyPLAN's simulation strategies can be either technically or market-economically optimal, neither way is specifically suited for an island setting, nor can they take local conditions into account optimally, though the technical simulation performs the best representation. Hence, the results should be understood as such and the conclusions should be drawn carefully, unlike, for example, in Publication 2, where it is stated '*If the electricity export is decreased by means of thermal storage, it will be a clear demonstration of the benefits of the sector integration through the smart energy approach*' [2, p. 6]. Instead, the replication value might be limited to this model, and a comparison with other scenarios or energy systems and the inclusion of perspectives on islands would address the limitations.

In addition to the limitations presented, one must ask the question: If all decisions in the model are made for the purpose of modelling a particular island, where is the potential for demonstrating and replicating with other islands or for up-scaling? At the same time, could some aspects in [1]–[3] not have been modelled in other, non-island settings? While many potentials can be identified when modelling renewable energy islands, including global trends, technologies or other combinations, some of these might potentially not be designed for island testing. More often than not, the island setting complicates their validation for other areas to use. Before diving further into the replication potential and contextual consideration, the use of islands as case studies must be understood as such: mere case studies under the boundaries that we set (cf. Sub-section 2.3.2).

COMPARING ISLAND ENERGY SYSTEMS

Overall, and despite the limitations outlined above, the replication options vary across the research presented so far. Where Publication [1] has some general solutions for energy systems, it does not include clear recommendations for replication, focusing rather on the comparison of technologies for the system at hand: Samsø. However, the potentials and limits are shown in regards to island-within-island/system tests, which is presented in Section 3.1. Similar in Publication [2], the analysis of only one island shows a restricted result. This influences the replicability by illustrating a specific constellation, which should be kept in mind. '*Using the island Samsø as a case, this article has demonstrated [the importance of] utilising wind power locally and free biomass resources for other purposes [since] importing and exporting large amounts of electricity is not an example that can be followed*' [2, p. 10]. This illustrates the requirements for Samsø, which may or may not be found elsewhere, such as limited biomass and excess wind energy.

Publication [3] already introduced an evaluation of renewable energy technologies for two islands, making the conclusions and learnings less restricted. The Sankey diagrams in Figure 3-9 illustrate the additional value of including and comparing two islands, as well as the presentation of the energy system. The Sankey diagram presents the same energy system model as in the previous sections, but permits a more detailed representation of the quantities of energy inputs and outputs. Furthermore illustrated, by evaluating storages, the publication addresses the local conditions of these islands, specifically the fluctuating surplus electricity production, but also the need for sector integration. The importance of island mode and local energy system optimisation is thereby demonstrated. Where cross-border energy system optimisation might be an option in non-island energy planning (cf. Section 2.1), it is limited in island energy systems.

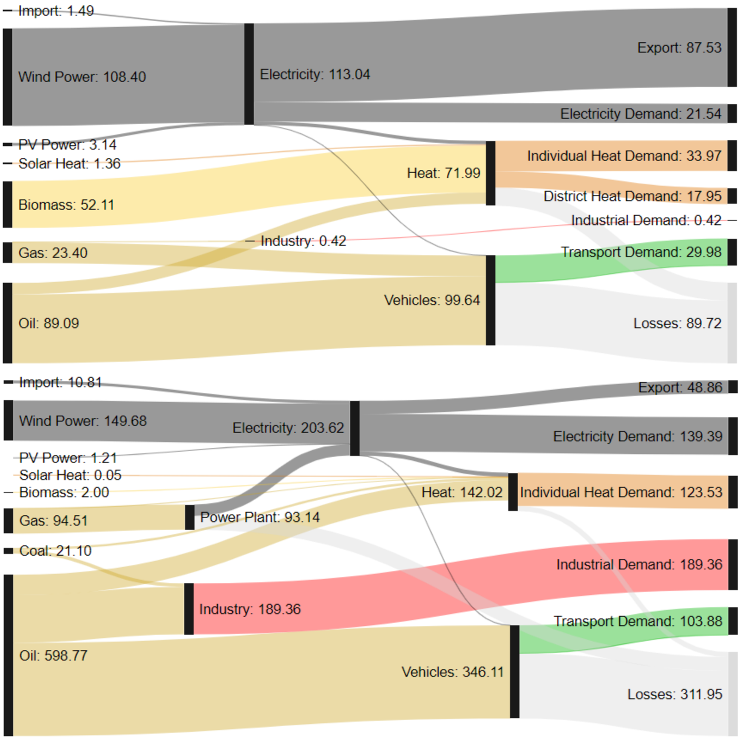


Figure 3-9: Sankey diagrams of the reference energy system models of Samsø (top) and Orkney (bottom) (in GWh/year) [3, Fig. 3]

Hence, unlike Publications [1] and [2], which could have been more or less evaluated elsewhere, except for the advantages from the island test setting, the technologies and solutions included in Publication [3] are especially important to islands. By including local conditions, such as the specific resources, demands and issues, the modelling done in [3] already includes some technical and social aspects of the local energy system. Before elaborating on the aspects and importance of the local conditions with Publication [4], comparisons are also important, which are possible in Figure 3-9. In contrast to the simplified energy system models used in the PhD publications so far, Figure 3-9 enables the comparison of seemingly similar island energy system models, where both the approach suggested through SMILE but also aspects beyond (cf. Subsection 2.3.2) are addressed.

Contrary to [1] and [2], which only evaluated one island each to draw conclusions, the comparison of two islands in Publication [3] further allows for additional conclusions in regards to replicability. The study was first carried out for Samsø and later extended to Orkney to elaborate the preliminary results, eventually supporting them with the same tendencies. While this is already introduced in Publication [3], the comparison of the two case studies of Samsø and Orkney shows the possible variations in implementing the same technologies in different places and under different conditions. Despite having some similarities between the islands, as well as between the results, the local conditions further underline their individualities: '*Orkney, on the contrary, […] contributes to the evaluation […] with its different context, while otherwise seeming similar to Samsø*' [3, p. 3].

The evaluation in [3] concludes that local energy system optimisation is especially important due to the limits that are present on both islands, such as transmission limitations or resulting curtailment. While the modelling is aimed especially at islands, the importance of local conditions, sector integration and increased self-sufficiency is also highlighted for other energy systems. It shows how modelling on islands, by comparing and considering the local conditions, can result in more contextually inclusive results that are better applicable not only to the islands under investigation but also to neighbouring and other energy systems, as suggested in Chapter 1 [11], [22]. The publication comes to the following conclusion: '*For the future energy systems […], local renewable resources should generally be strategically utilized and sector-integration made to the best extent possible*' [3, p. 9].

While the comparison of Samsø with Orkney already allows more extensive conclusions to be drawn by involving an additional energy system and including aspects beyond the SMILE ones, there is room for further improvement. This emphasises the gap and the potential for a further comparison between and consideration of the context and local conditions: '*While the same tendency can be assumed for other places, a further study of other islands and energy system configurations is suggested*' [3, p. 9].

This comparison of similar technologies and energy planning procedures with other energy systems and the inclusion of local conditions for each island shows the potential of improving the use of modelling renewable energy islands. In order to further align this with the limitations of the research conducted in [1]–[3], a further comparison of islands under consideration of common renewable energy targets, yet also of their individual local conditions, is required, thereby answering part of the 2nd sub-research question.

IMPORTANCE OF LOCAL CONDITIONS

The 4th Publication "*Transitioning island energy systems—Local conditions, development phases, and renewable energy integration*" [4] further addresses this need for comparison as well as the inclusion of local conditions. It discusses the gap of energy modelling done in a contextual way, since '*[technologies] have mainly been considered individually and in limited contexts […] they have not been studied as part of a holistic island energy system transition process considering and comparing local conditions' impacts*' [4, p. 3]. The role of case studies, as introduced in Sub-section 2.3.2, further supports the importance of the research conducted: '*The study and presentation of the case studies' complex energy systems and the alignment, as well as distinction of the transition of three similar yet individual islands, further address the research gap.*' [4, p. 3]

Therefore, the scenarios are co-created with the input from locals involved on the respective islands [17], [37], [72], besides following the SMILE guidelines. For clarification, the inputs on and importance of local conditions vary between the islands, but generally, and as presented before, local conditions encompass local resources, demands and limits, mainly referring to the energy systems. Furthermore, they range from weather, geography, infrastructure, economy, and politics to location and national context as these have an impact on the current and future energy systems as well.

Relating to the alignment with local conditions, the transition to a smart energy system, as introduced in Section 2.1, mentions three phases which support renewable energy integration. These phases are presented in Publication [4], which puts the three island case studies into perspective in Figure 3-10. Unlike the previously addressed Publications [1]–[3], the 4th Publication presents a complete picture of the transitions to high renewable energy shares by various islands, based on several technological approaches. Hence, it illustrates the alignment of current situations in the local energy systems with the energy technology requirements and the overarching target of increased renewable energy share.

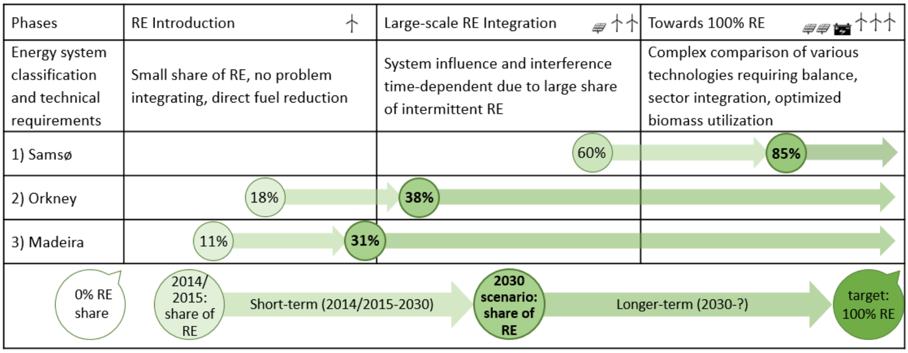


Figure 3-10: The island case studies in the transition towards 100% renewable energy (RE) in three phases [4, Fig. graphical abstract, online]

The different technological components and scenarios of the SMILE case study islands Samsø, Orkney and Madeira put the transition to renewable energy into an elaborated context to better understand the limits and potentials on a global scale. This is further shown in Figure 3-11, where the different energy system models and energy flows are illustrated in detailed Sankey diagrams for each of the islands' reference and future scenarios. Thereby, the individuality of the three islands is highlighted, while the flowchart models, such as Figure 3-5, focus on their similarities.

As can be seen in Figure 3-11, while Samsø and Orkney have the potential to import energy through transmission cables, a comparison to a fully isolated energy system is possible through the case study of Madeira. Furthermore, while Samsø and Orkney have more significant heat demands, Orkney and Madeira have noteworthy industrial demands, although only Orkney has marine industry and Madeira relies heavily on its power plant. The Sankey diagrams show the different amounts of renewable energy produced and the required fuels, the conversion technologies and the resulting demands, as well as losses. Figure 3-11 thereby presents the different conditions on the case study islands and their transitions to higher renewable energy shares [4].

The presentation of the upper graphs builds upon aspects of [3] and the reference years 2014/2015, as further detailed in [6]. The medium-term scenarios of 2030 of the case studies (indicated by the lower (b) graphs in Figure 3-11) show the transitions indicated in Figure 3-10. While the islands test different technologies and have individual possibilities and demands, some similarities can be identified. In the transitions presented in Publication [4], each island shows a decrease in fossil fuel use and losses, while renewable energy contributions, efficiencies and electrification increase. Hence, Figure 3-11 shows the transitioning to renewable energy for different islands, taking local conditions into account.

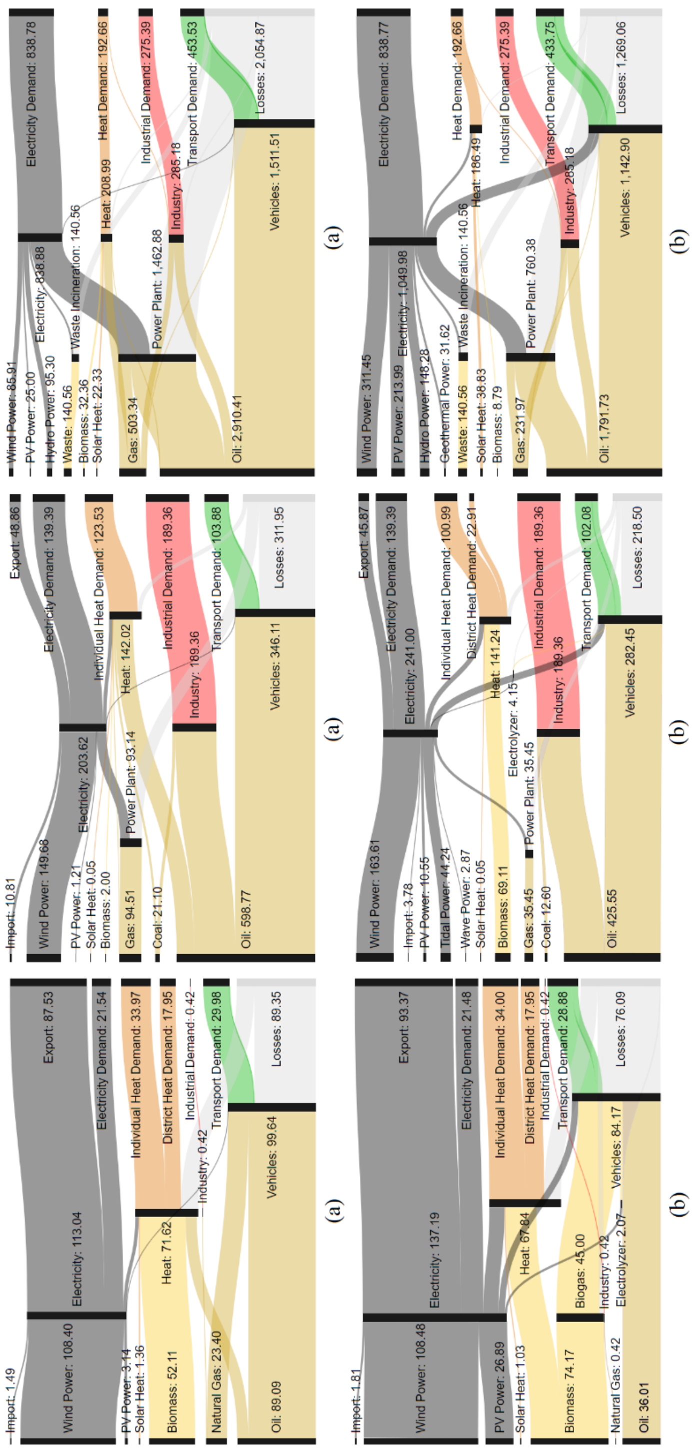


Figure 3-11: Sankey diagrams of the energy system models of Samsø, Orkney and Madeira; (a) refers to reference energy systems of 2014/2015 and (b) refers to 2030 (in GWh/year) [4, Figs. 1, 2 and 3]

Comparing different islands and their energy system conditions, for example by looking at Figure 3-11, provides better understanding of the similarities and individualities, which can contribute to sustainable energy planning not just for islands. Finding transcending solutions for islands is difficult, but it can be concluded that with '*islands being potential representatives of bigger energy systems, the results can be transferred to other systems as well. However, individual variations are also to be expected'* [4, p. 16]. It proposes that the main difference is not the interconnectedness, as one might expect, but the context: '*While an interconnection can ease the transition, balancing and integrating technologies are even more important, as well as the local conditions*' [4, p. 16].

Compared to Section 3.1, the elaboration on the local conditions enables a better evaluation and understanding in the field of modelling renewable energy islands. By changing the perspective towards islands to include the limits, needs and potentials *on* islands, the modelling (*of* islands) can be improved, as further illustrated by applying theoretical perspectives (cf. Sub-sections 3.1.2 and 3.2.2). Not only are the results more elaborate, thereby improving their learning potential and replicability, but also knowledge about islands is gained. Unlike the trends of future energy systems illustrated in Sub-section 2.1.1, where expansion across sectors as well as borders is suggested, the importance of local optimisation indicates a higher need for self-sufficiency on islands than is usually targeted elsewhere. The presented new understanding of islands is also reflected in transitions theory's niche innovations and results in highlighting the potentials of horizontal governance, which is done in the following.

3.2.2. NICHE INNOVATION AND HORIZONTAL GOVERNANCE

This section continues the discussion from Sub-section 3.1.2 and examines the influence of the landscape and regime on niche innovation and top-down governance. This is done by elaborating on the arguments presented in the previous section, which pointed to the potential for improvements in both regards through the comparison and consideration of local similarities and individualities.

Not only is the test setting at the niche level improved by including local conditions, but also the potential for up-scaling or replication is made more transparent through comparisons of islands in renewable energy modelling. This elaborates on the potentials as seen through transition theory and as illustrated in Figure 3-12. The previous discussion in Sub-section 3.1.2 defined islands as suitable testing grounds due to the natural and controllable setting, albeit from the outside perspective through modelling *of* islands without considering much of their individuality. It is, therefore, suggested to elaborate the understanding of these niches to make better use of and have a higher impact on the other levels to better contribute to the fight against climate change. This also represents modelling *on* islands.

The consideration of the local conditions and the comparison improve the niche innovation by elaborating the reasons and results of the research conducted there. Even though windows of opportunities are not yet apparent regarding the influence on the regime or landscape level (cf. Section 2.2), this local perspective can still be seen as a window of opportunity for islands, which develops into potential for others, as is further discussed in Section 3.3. Understanding the test setting and conditions elaborates and strengthens the value of the innovations happening there. This contributes to the general understanding of sustainable energy planning by including the local social, environmental and economic aspects of each island in the transition to renewable energy. While the modelling *of* islands mostly contributes quantitatively, modelling *on* islands adds further qualitative insights to make niche innovation more tangible. Hence, the arrows in the dynamic structure of socio-technical transitions still do not indicate the impacts from islands on other levels, but shows stabilisation on the niche level for possible future impact. The relevance and influence of this is discussed in Section 3.3 and in the corresponding figure.

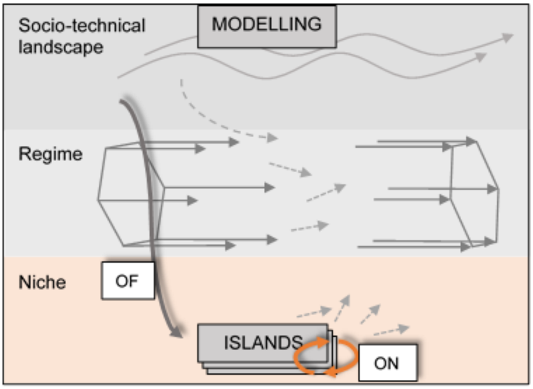


Figure 3-12: Modelling on islands in transition theory – the importance of niche coordination

The knowledge transfer that can improve the understanding of transitions also contributes to the understanding of governance. Where Section 3.1 stressed the influence of top-down governance, the publications discussed in this section add a different angle. The literature review in Publications [1] and [2] started with global and European targets, but Publication [3] and [4] start with ‘*islands*’. Not only do strengthened local levels stabilise the higher levels but also the horizontal coordination in particular improves (cf. Sub-section 2.2.2). Showing similarities and individualities makes replicability more transparent as the limits and possibilities are easier to identify and circumvent or include. The coordination between islands, as illustrated in Figure 3-13, underlines this importance, since much can be learned on the horizontal level before it can be transferred to vertical governance. For example, the coordination of island solutions helps shed light on the benefits for others, as

SMILE does across three islands before drawing conclusions [68]. Even though some trends, policies or initiatives are coordinated from a central level to the local levels, decentralised alignment and horizontal coordination is important to achieve these.

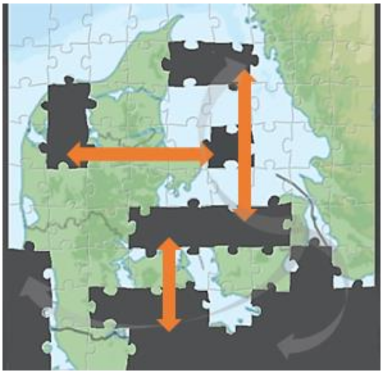


Figure 3-13: Modelling on islands – with a horizontal perspective, illustrated as influence and cooperation between islands in addition to central coordination

Besides the importance of self-sufficiency, which is highlighted for islands by the analysis in this section, the term cross-border energy planning can be re-evaluated. While there are limited options for the physical cross-border trading of electricity and goods, the trading of knowledge across borders and seas becomes increasingly important for islands and faces fewer challenges while having global potential. The subsequent benefits for island modelling are discussed through Publications [3] and [4] and support the suggested focus on the horizontal level. How this benefits the other levels is further discussed in the final part of analysing island modelling in Section 3.3.

The conclusions drawn in the 3rd Publication emphasise the strategic local use of renewable energy for the '*future energy systems of islands'* [3, p. 9], eventually also supporting and benefitting the future of all energy systems. This section thus not only answers the 2nd sub-research question 'How comparing and considering local conditions can improve modelling on islands', but also underlines the benefit of modelling renewable energy islands for sustainable energy planning in general.

Finally, after taking the local context into account, which includes not only geographical differences but also social, environmental and economic ones, the institutional context and further use of the scenarios for policy design are mentioned in [4], leading to the next and final section in this chapter, Section 3.3. Where the previous Publications [1]–[4] focused on the technical explorative step into renewable energy for islands, the relevance of subsequent steps towards institutional alignment is introduced. '*Subsequent steps assess what is required to implement the technical solutions […], possibly the adaption of policies, regulations and business economic* *framework conditions to advance technically and socio-economically favorable solutions*' [4, p. 3].

To be able to analyse the final aspects in answering the main research question 'What role modelling renewable energy islands can have in sustainable energy planning' an examination beyond the technical scenarios is made in the following section and through the final PhD publication. After answering the 1st and 2nd sub-research questions by pointing out islands' potential for use in evaluating renewable energy technologies, albeit in need of further improvement through considering comparisons and local conditions, the 3rd sub-research question considers the final elaboration of island modelling. This, on the one hand, closes the chapter on modelling islands, yet, on the other hand, opens up the discussion for reflections and further research in Chapter 4.

Figure 3-14: View from Madeira of local wind and PV power production

3.3. MODELLING *FROM* ISLANDS

Where Section 3.1 found islands to be optimal for evaluating technologies in the transition to renewable energy, some limits were also encountered, which were addressed in Section 3.2 by including comparisons and local conditions of island energy systems. This was illustrated by how the perspectives were improved for transition theory and governance in energy planning, yet this can be further improved by examining energy system analysis beyond the technical aspects. Therefore, this section addresses how we make use of the learnings so far by including the island context more strategically and aligning the energy system analysis with institutional aspects. It thereby addresses the 3rd sub-research question 'How contextual and institutional alignment can elaborate the use of modelling from islands'.

This section presents the value of islands introduced in previous sections and elaborates it by modelling *from* islands, indicating the learnings to be gained from there and through local perspectives. The context is explained in the first sub-section, including a closer look at Publication [5], before it is illustrated through advances in transition theory and energy planning governance in the second sub-section. By combining Section 3.3 with the previous as well as following sections, it concludes the main research question 'What role modelling renewable energy islands can have in sustainable energy planning', which is further reflected in Chapter 4.

3.3.1. CONTEXTUAL AND INSTITUTIONAL ALIGNMENT

Contrary to the literature reviews in [1] and [2], which had a broad contextual introduction, and in [3] and [4], which had a strict island focus, PhD Publication [5] includes '*Energy systems, both large and small [… for a] well-planned transition to 100%*' renewable energy, indicating a comprehensive approach to sustainable energy planning at last. While the island test setting was illustrated in the first two PhD publications and the importance of local conditions was presented through the other two, the strategic use and combination of both is applied in the final publication of the thesis. It hereby illustrates how to use the knowledge of what works, what does not and what should be considered by applying contextual and institutional alignment.

CONTEXT AND INSTITUTIONS

The 5th PhD publication "*Technical Approaches and Institutional Alignment [for the] 100% Renewable Energy System Transition of Madeira Island—Electrification, Smart Energy and the Required Flexible Market Conditions*" [5] starts off with the same intention as the preceding Publications [1]–[3], namely, evaluating technologies or scenarios on islands. However, despite the same aim of increasing the renewable energy share in an island energy system, the 5th Publication is further trying to find a contextual understanding and solutions that can be made replicable for other energy systems to realise the technical aim. Therefore, it follows the suggestion made at the end of Section 3.2, referring to subsequent steps to look into the implementation '*to advance technically and socio-economically favorable solutions*' [4, p. 3]. Hence, when thinking about the illustration options for the energy system (cf. Figure 2-5 or Figure 3-9), certain technical aspects are usually under focus. Contrarily, in the following, additional contextual areas of concern are included that were previously overlooked or disregarded.

The contexts referred to in this thesis include not only the geographical and sustainability context but also the institutional (cf. Sub-section 2.3.1). Where Publications [1]–[4] already include local geography, resulting demands and resources as well as some location-specific needs, a more strategic alignment with local institutions is needed. Similar to Publication [2], which benefitted from local island co-authors on the team who contributed with inside knowledge instead of relying on an outsider's view, Publication [5] is also written in collaboration with a local stakeholder, influencing the quality of the data and analysis.

The contextual and institutional alignment aims at strategic, local energy planning, as already pointed out in [3], where the energy transition is suggested to align with local resources and market establishment: '*With an increase in [renewable] power generation in remote areas and limited transmission capacity* [63],[64], *all of these island systems are vulnerable to security of supply. They should therefore aim at integrating their local resources and establishing better local markets to secure the optimal integration of fluctuating [renewable energy] [15]'* [3, p. 2].

Hence, this section addresses the institutional as well as the technical complexity in the energy transition, as introduced in Section 2.3, with additional steps in the energy system analysis [61] and as illustrated through Figure 3-15. '*In relation to the technical changes between the sectors and technologies, also the market setup changes accordingly, indicating where requirements in the market are shifting and need to be supported*' [5, p. 7]. The changes are shown from a simple energy system scenario (0) to two scenarios with high renewable energy shares through electrification (1.X) and through a smart energy system approach (2.X), as is analysed in [5]. This increase in complexity not only technically but institutionally also reflects the idea of smart energy markets, as introduced in Section 2.3.

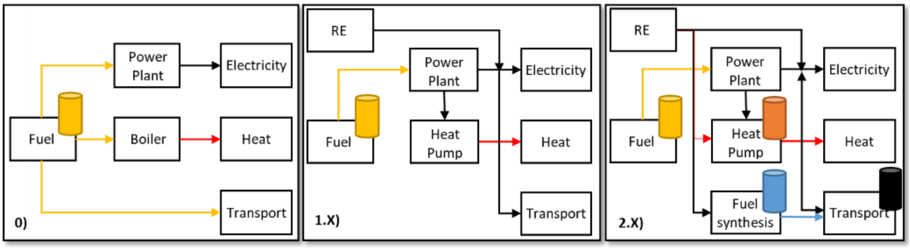


Figure 3-15: Energy system models of scenarios with increasing renewable energy (RE) and complexity (barrels indicating storage options) [5, Fig. 2]

The hypothesis is that the higher model complexity also increases its usability, as it reflects more of the local context and thereby allows for the modelling of higher renewable energy shares without losing credibility. Hence, instead of comparing different energy systems, the emphasis is put on the elaborated inclusion of local conditions. It entails not only a sensitivity study of renewable energy capacity according to local requirements but also the strategic alignment of the local market possibilities. This supports the model of a 100% renewable energy system that can be fully self-sufficient. Even though full self-sufficiency is not as important in most other energy systems, it illustrates a self-sufficient energy system that can be replicated in other energy systems by taking their conditions into account.

Unlike Publications [1]–[4], Publication [5] investigates not a single technology or technological combination but rather the full transition to 100% renewable energy across the energy system. The model presents a completely isolated energy system transitioning from an 11% to a 100% renewable energy share. The technological transition is based on the smart energy systems approach to 100% renewable energy solutions [12] and is compared to a less integrated electrification. It thereby connects to Publication [4] and Figure 3-10 (cf. page 58) in regards to the classification and requirements of highly renewable energy systems, indicating higher complexity and the need for alignment.

The resulting step-by-step approach makes it easy to show and follow the impacts of each step, as outlined in Figure 3-16, where the institutional alignment is illustrated as a research gap. Especially the isolated state of the Madeira energy system allows for a reflection of the technical smart energy system approach and the increased requirement for self-sufficiency and contextual alignment.

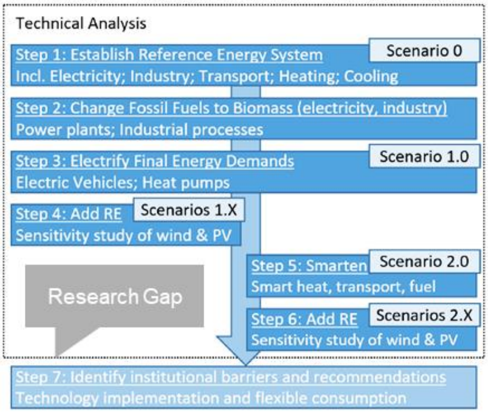


Figure 3-16: Technical and subsequent institutional analysis, addressing a research gap [5, Fig. 1]

Further highlighted in the publication is the importance of optimising the local energy system, which supports both the technical and institutional transition to a 100% renewable energy system. All steps presented in Figure 3-16 take local conditions into account, especially Steps 4 and 6. Here, a sensitivity study of additional wind and solar power capacity is made, taking local potentials and limitations into consideration, and giving options '*depending on local requirements and wishes*' [5, p. 10], such as land, biomass and economic availability, as viewed from the island.

LOCAL MARKET ALIGNMENT

Compared to [1]-[4], the research in [5] is taken a step further by the closer look at the modelling made in EnergyPLAN. The technical simulation strategy of EnergyPLAN is used (cf. Sub-section 2.3.1), which models the energy system according to the technical possibilities: When there is renewable energy production, especially excess production beyond the normal electricity demands, all flexible demands are engaged, such as synthetic fuel production or power-to-heat with balance achieved through thermal storage. This is contrary to reality, where the system might not be operating in such a balanced way, since the production and consumption side do not align as well due to the limited availability and flexibility of technologies and demands.

This smart way of aligning fluctuating production and usually inflexible demands is addressed by discussing the options on the demand side through market alignment. These suggested institutional changes aim to increase end-user flexibility to better implement the variable renewable energy production from wind and PV: '*While [the technical analysis] is modeled optimally in EnergyPLAN, incentives, regulations and/or market redesign are required for implementation*' [5, p. 13].

While the market analysis in Step 7, Figure 3-16, focuses on design proposals for a local smart energy market, based on the identified institutional barriers, a first basic sub-step is required beforehand to allow this. The requirement is '*a flexible and dynamic energy market, where the fluctuating [renewable energy] production is in the centre. To allow for a dynamic market, the first step is the uptake of suitable technologies on the demand side*' [5, p. 15]. Hence, the technologies required for a more flexible energy system are needed. As a second sub-step, since many of the technologies convert electricity to other forms of energy, the institutional analysis and recommendations focus at making the electricity market more dynamic in the following pages of the publication.

The result of the market analysis is illustrated in Figure 3-17, showing the current tariff options and the suggested redesign. The current ones, however, do not include renewable shares and hence do not support the smart energy market approach, where energy is traded according to the increasing production of fluctuating energy. The designed tariffs A and B are subject to hourly renewable electricity production (Tariff B) as well as typical demand (Tariff A), illustrated through the data applied in the EnergyPLAN model of Madeira's energy system [5]. This redesign of the electricity market shown in Figure 3-17 aims at the better integration of fluctuating renewable electricity by incentivising electricity consumption during certain hours. While this is based on forecasts and modelling, further consideration for its introduction is recommended, such as the discussion of a suitable day-ahead or live-feedback mechanism.

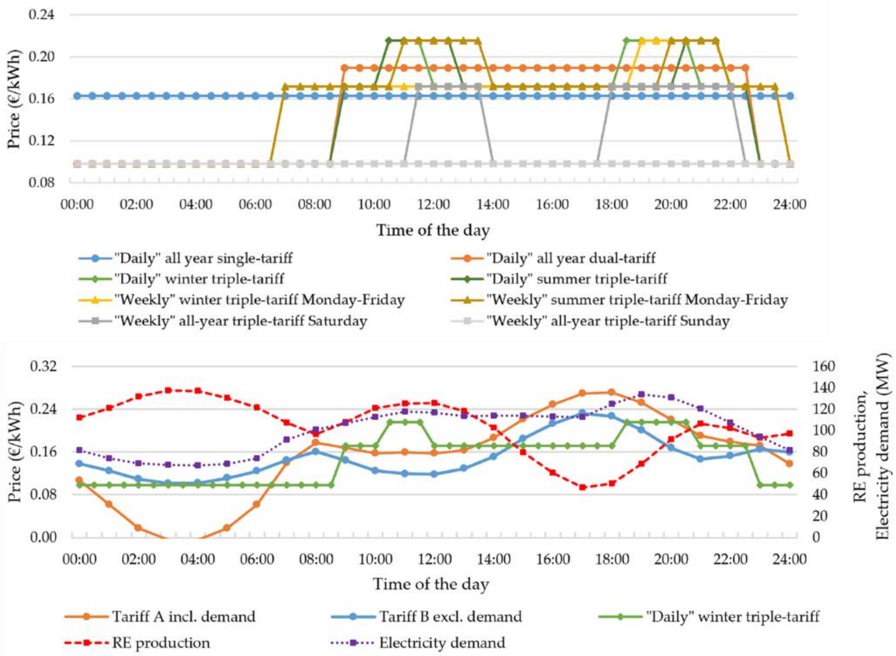


Figure 3-17: Electricity tariff options on Madeira (2020, top) and the combination of renewable energy (RE) production, electricity demand and resulting proposal for dynamic tariffs (bottom) [5, Figs. 7, 8]

When critically reviewing the redesign of the energy market, the focus on the electricity sector misses out on the suggestions made for a smart energy market, wherein also the heat and fuel markets should be better integrated if possible [42]. Contrary to the widely accepted importance of the electricity sector in the Madeira energy system, the heat and gas network are energy-wise less significant (cf. Figure 3-11), which led to their disregard in the market analysis [5]. If district heating or other fuels were to play a larger role in the (Madeira) energy system, then their market conditions should also be further discussed. If fuels were to be included in a sector-integrated smart energy market, the price of oil, for example, could be made to better reflect real costs, such as higher ones when renewable energy is available. Alternatively, and more relevant to the presented case, any electricity used specifically for heating and transport could be weighted differently in the electricity market, for example, using further incentives for electric heating or more dynamic charging incentives for electric vehicles. This shows that despite the island setting, modelling can become very complex when trying to consider the full context, while isolation from certain areas in the energy context makes energy modelling easier.

Nonetheless, taking into account the local context to the best extent possible shows the local potentials and limitations in the best possible way and the most true to reality.

For Madeira, the on-site geography and infrastructure influence the possibilities and acceptance of EVs, yet it is the EV users who are most relevant as they drive, charge and pay for the EV [5]. Hence, the subsequent discussion of the dynamic energy market results in a focus on the demand side as '*the importance of consumer involvement and demand response becomes evident*' [5, p. 17].

Further replicability is highlighted, yet with caution. Publication [5] concludes that the context has an influence on the results' relevance, illustrating their usability only to those for whom the situation applies. '*The presented research can be replicated in other energy systems and become most relevant for those with sensitive or limited infrastructure'*. However, when taking into account the context in the replication, the use of island modelling '*can also be relevant for those systems that aim for higher self-sufficiency and more independence even when being well-connected*' [5, p. 18].

ELABORATION OF MODELLING

Finally, the potential influence and knowledge that can be gained from islands is presented through the contextual approach: *'the complexity of energy system planning [...] is evident and the need for alignment of technical and institutional analyses presented through the perspective of islands*' [5, p. 18]. This research elaborates not only on the potentials beyond evaluating renewable energy technologies, but also on the learning potentials from further research in that direction and the learnings *from* islands. This answers the 3rd sub-research question by showing how contextual and institutional alignment with the previously presented aspects of modelling elaborate and further develop the modelling of islands, before we move beyond this edge of research.

In sum, even if an analysis or island model is only aimed at a technological test, additional contextual and institutional considerations should be kept in mind, which includes the understanding of local individualities and similarities, to find transparency for replication. One must contemplate the implementation and realisation of often ambitious models and their true relevance for the island or place in question. This elaborates from the claim to consider local conditions, not only technically, and supports the replication opportunities of island modelling.

How this final analytical sub-section contributes to the main research question is summarised in Chapter 4, along with the further research and learning opportunities that emerge when looking at the options and learnings *from* islands. Before that, however, the potentials are put into a theoretical perspective, illustrating island innovation through niche influence and bottom-up governance.

3.3.2. NICHE INFLUENCE AND BOTTOM-UP GOVERNANCE

After establishing the perspectives and potentials of the modelling *of* islands in Section 3.1 and modelling *on* islands in Section 3.2, this sub-section continues the discussion by adding the potentials and learnings of modelling *from* islands, as seen through transition theory and multi-level governance.

Unlike in Publications [1]–[4], both the critical assessment of the technical simulation strategy in EnergyPLAN and the required institutional analysis in Publication [5] exceed the initial idea of evaluating or comparing a technology in an island setting, which forms the beginning of the analysis of modelling energy islands in Chapter 3. Instead, it introduces additional aspects not always taken into consideration in the previously prioritised top-down perspective and makes use of the horizontal perspective.

Transition theory entails the idea that the landscape and regime levels, each with their own objectives, want to experiment with niche technologies or create innovation through niches. Yet, the landscape and regime levels limit this development at the same time due to path dependencies and the insufficient understanding and support of the niches. At the same time, the niche level innovations need to include the conditions surrounding the innovation and the impact of the individuality of and similarities with other niches and niche technologies to increase the chances of their usability in the future. Replicability and up-scaling are otherwise difficult. Hence, proper niche innovation benefits not only islands by being better understood and supported but also others, who benefit from the replication and knowledge gained. With the additional consideration of contextual, strategic and institutional alignment for a better understanding of the modelling done in the niche, the knowledge that can be gained from there increases in quality and challenges the path dependency and influence of higher levels.

The results of this additional aspect in transition theory are windows of opportunities that have an impact beyond islands or niches, with an influence also on existing regimes and landscape, adjusting them accordingly; see Figure 3-18. Hence, the learnings from islands result in new configurations and understandings of the energy transition, including changes to the areas represented by the hexagon. With changes in even only one area, like technology or markets, the whole regime is affected, and this demonstrates the importance of alignment. While this might have a direct impact, mostly in the respective island and surroundings, it can also influence others when done right, representing the difficulties of niche innovation presented in Section 2.2. Hence, the responsibility is not only with the niches but also with the upper levels and their support, as multi-level governance further clarifies.

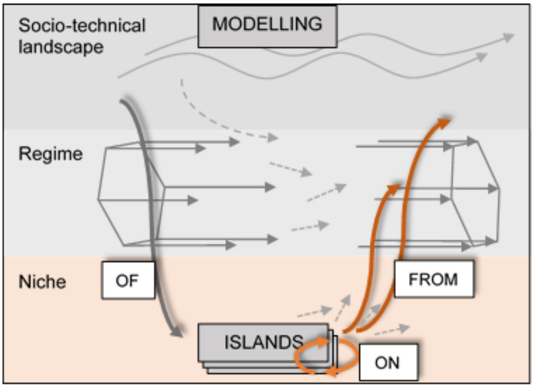


Figure 3-18: Modelling from islands in transition theory – the influence and opportunity of niche innovation

Besides the perspectives presented in the previous sections, the addition of contextual and institutional alignment emphasises the individuality of islands and local experimentation. At the same time, similarities can be pointed out while taking the context into account. The cooperation among '*Energy systems, both large and small [… for a] well-planned transition to 100%*', introduced through [5], also highlights the potentials in energy governance. Even though the analysis only reflects one island at the bottom level of the vertical hierarchy, strategic knowledge can be gained, especially when additional qualitative studies like this are combined, as suggested in Section 3.2, through a comparison. The resulting influence from the bottom-up is illustrated in Figure 3-19. It presents the great learning possibilities that can emerge from the differences and ideas on the islands and which are developed constantly in energy systems around the world. The possible influence and knowledge from the bottom up support the development of both local and global energy systems and trends, both technically and institutionally.

Besides the potentials offered by horizontal collaboration across islands, qualitative insights also contribute to vertical collaboration. Even though cross-border improvements are not always possible physically, the cooperation and theoretical understanding across borders help in shaping the right policies. Also, self-sufficiency is more relevant to islands, yet the potentials shown can also create benefits in other energy systems.

Figure 3-19: Modelling from islands – with the bottom-up perspective, illustrated as the influence from Danish islands on Copenhagen

As already elaborated in the previous sub-section, the complexity of sustainable energy system planning becomes evident but is furthermore also supported from the different perspectives *of*, *on* and *from* islands. This is illustrated both through the niche innovation and influence on existing regimes and landscapes and the qualitative bottom-up insights into multi-level governance understanding.

This section concludes the analysis of modelling, which is supported by the cutting edge of modelling in the PhD publications, as illustrated in Figure 1-3 (cf. page 11). The following chapter reflects on the individual contributions and answers to the sub-research questions and thereby answers the main research question 'What role can modelling renewable energy islands have in sustainable energy planning?'

The reflections in Chapter 4 take a look beyond modelling *on the edge* and the potential influence of islands in energy planning through an exploration of the other potentials that this PhD thesis indicates. In the future, we might consider what the islands really have and need before deciding on the technology that is to be tested and potentially implemented there, as well as how this can be achieved. The recognition of islands and their role in energy planning, policy and global development through understanding and learning from them in new possible ways should also be recalled. This is further elaborated in Section 4.1, before a review reflecting key areas of sustainable energy planning in island context in Section 4.2. This supports current, as well as future research by adding new perspectives and brings us back to the need to conduct research that is often off the radar of continental research, such as developing a clear understanding of marine energy or 'energy islands', which is addressed in Section 4.3.

CHAPTER 4. REFLECTION: ROLES OF EDGES AND BEYOND

Reflecting on cutting-edge research and building resilience against climate change.

To provide a final answer to the research question 'What role modelling renewable energy islands can have in sustainable energy planning', this chapter is split into three sections. It presents a reflection on the research on the edge presented in Chapter 3, in regards to sustainable energy planning, and for further perspectives and research. While Section 4.1 thereby mainly summarises, Section 4.2 reviews and Section 4.3 expands on the resulting role of modelling islands in sustainable energy planning.

This chapter discusses the role of islands at the edges of maps and systems, and takes a look beyond to explore the benefits that can be found there for both islanders and others. It thereby represents the explorative chapter of the PhD thesis, discussing the potentials supported by the analysis, the publications and the case studies, as well as the discussing resulting learnings and possibilities beyond.

4.1. MODELLING *WITH* ISLANDS

The previous chapter illustrated the potentials from the modelling *of* islands in a quantitative and exploratory way as well as the contributions from comparative modelling *on* islands and, finally, how qualitative knowledge *from* islands be can elaborated through this. In the following, I reflect that modelling *with* islands summarises this, thereby benefitting not only island energy systems but also global energy planning and related institutions. This is presented by discussing the modelling potentials of islands based on the analysis made in Chapter 3 and finalising the theoretical context by concluding on the transition theory and multi-level governance perspectives. The resulting Figures 4-2 and 4-3 illustrate this combination of perspectives after reviewing the individual perspectives from Sections 3.1, 3.2 and 3.3. The results of both research and innovation, explained and supported by theory, influence and enable Sections 4.2 and 4.3.

Section 3.1 illustrates how islands are suitable for evaluating renewable energy technologies for various reasons, yet there are also limitations. The setting of islands simplifies the often complex energy system research through their natural borders, small scales and transparency. Modelling renewable energy for islands not only addresses the need for decentralisation and local energy transition by evaluating technologies [1]–[3], but it also provides information for other areas, on both national and global scale. However, replicability is critical, and the context of an island test setting usually shapes and defines the modelling and results; thus, island models are very location-specific and this requires special attention. The perspective of the modelling *of* islands explains this situation, as guidance and initiatives normally follow top-down processes aiming to experiment with and implement renewable energy technology locally, yet from a central viewpoint. The innovation potential is thereby limited, as illustrated by the multi-level perspective in transition theory, where landscapes overshadow niche innovation, and as shown through weaknesses in central governance without the often-claimed local coordination. While experimenting, testing and evaluating renewable technologies on islands still provide quantitative feedback, the suitability of the respective technologies for islands, and vice versa, must be considered; hence, more qualitative discussions are sought.

Section 3.2 builds upon the knowledge from Section 3.1 and improves the modelling potential through its acknowledgement and additional inclusion of island conditions. Hereby, replicability, which was previously limited by location-specific island models, can be addressed by comparing several case studies, and the quality of modelling further improves by considering local conditions on islands [3], [4]. This introduces an additional understanding of how decentralisation can become more effective and how cross-border coordination in energy planning can be not only technical but also procedural and collaborative. The section thereby illustrates how local conditions help understand and utilise what the island models are theoretically intended for, namely to test and show how decentralisation can be achieved and replicated. By modelling *on* islands, niche innovations become more explorative and competitive, while horizontal alignment strengthens vertical governance. Additionally, local coordination helps islanders and others at the bottom level in terms of energy governance. The learnings from collaboration and coordination on islands support sustainable energy planning with qualitative inputs. Also, the knowledge of the individuality and similarities between energy systems indicates that solutions to energy transitions are neither simple nor singular but depend on the context, as addressed in Section 3.3.

Section 3.3 includes insights from the modelling *of* islands, as well as perspectives *on* islands, and thereby presents how to make modelling work *from* and through islands (cf. Figure 3-18, p. 71), adding the final aspect from the PhD publications to the islands' role in sustainable energy planning. The strategic context consideration is proven to be most helpful, whereby not only technical and local aspects but also institutional alignment with energy markets and policy gain importance for local energy system planning [5]. The complexity should be balanced with the simplicity of modelling. Yet new qualitative knowledge can be best achieved by including most aspects, bringing the models to the highest level of quality and usability. While replication also becomes more complex, understanding certain aspects of individuality and transcendent solutions suitable for many islands offers a new way to use the learnings. In particular, self-sufficiency is a potential that should be explored not only in the context of islands but also to help other energy systems understand the value of local energy system optimisation. The resulting bottom-up influence from niche innovation and through vertical governance presents islands and their models with a wide-reaching impact and higher power than is initially attributed to them. The learnings from islands can thereby influence existing understandings and institutions on national and global levels and reconfigure current regimes and landscapes. Thus, giving this power to islands through bottom-up action and coordination benefits not only islands locally but also central stakeholders through the knowledge gained and actions accomplished in a decentralised manner. This is further addressed in Sections 4.2 and 4.3.

Sections 3.1 to 3.3 and the corresponding publications increase the complexity of island modelling, and so other qualities also increase relatively: the value of self-sufficiency, local focus, sector integration, CO_2 emission reductions, and renewable energy shares. While self-sufficiency is addressed only to a limited extent in the early PhD publications, as shown in Section 3.1, it significantly shapes the publications in Section 3.2, and especially in Section 3.3. As also presented in Chapter 3, the initial focus is global or European in the first two publications, while the focus in the later publications is directed more directly toward the local islands and their conditions. Also, sector integration is not addressed much in the early publications and Section 3.1, where the analyses focus rather on certain technologies; however, it gains more attention in the following publications and sections. The final section of Chapter 3 presents a technically and institutionally feasible fully-renewable energy system, taking all sectors into account. This reflects in the CO_2 emission reductions, which are highest in the later publications, compared to earlier ones; cf. 27% in [1], 66% in [4], and 98% in [5]. Finally, an increase in the renewable energy share by 1.6-2.3%-points is demonstrated in the early analyses [1], [3], and 25%-points [4] and 89%-points in the later analyses [5]. Figure 4-1 illustrates this relative share or difference of the qualities of sustainable energy planning increasing throughout the sections in Chapter 3. While it illustrates overall enhancements throughout the sections, it is further indicating areas for improvement, even in the modelling done in Section 3.3.

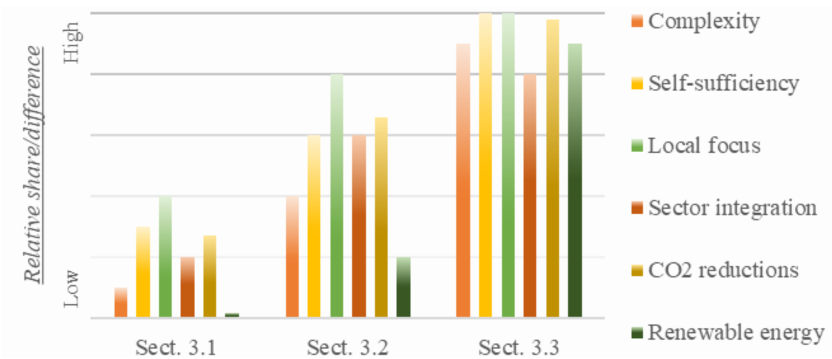


Figure 4-1: Relative increase of complexity and content throughout the analysis in Chapter 3

Despite the increased complexity and various additional perspectives of modelling renewable energy islands, I conclude that modelling should be done *with* islands as it provides qualitative value on top of quantitative data. For that, the other perspectives *of*, *on* and *from* islands and the overall learnings are acknowledged, combined and included. Both quantitative experiments and qualitative knowledge on and from islands can influence and offer a benefit on the global scale. While some individuality must be recognised, similarities also support the understanding and help identify transcendent recommendations from the modelling. By doing so, the need for self-sufficiency as well as cross-border collaboration, either technically or theoretically, can be evaluated accordingly; see the next sections. Furthermore, the resulting CO_2 reductions in Figure 4-1 directly address the Paris Agreement and the fight against climate change. Concluding, islands in the context of modelling can be seen as lighthouses rather than laboratories [17] by including the above-mentioned aspects and acknowledging their importance in the transition rather than merely for their capacity for experimentation.

When put into the context of transition theory, Figure 4-2 emerges, including the theoretical reflections on modelling *with* islands. Existing socio-technical landscapes and regimes require and influence niche innovation, however, enabling the additional local inclusion and strengthening of the innovation can benefit them in return through qualitative learnings on and from islands. The opportunities offered by modelling with islands result in knowledge and adjustments for landscapes and regimes, which finally enables the transition towards future energy systems that combat climate change. Therefore, the adjusted levels from this point onward indicate a better inclusion of islands with increased influence and understanding on the landscape and regime levels, as well as an impact on future niche innovations to come. Through Figure 4-2, islands are presented as niches for innovation, but also the support, understanding and learning of islands transform the multi-level perspective of the energy transition. Where control from higher levels once prevailed, the importance of supporting guidance and freedom is now presented.

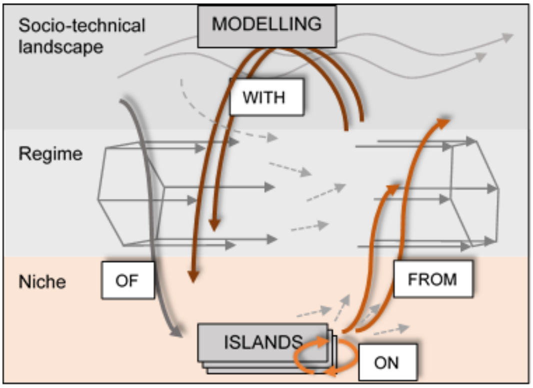


Figure 4-2: Modelling with islands in transition theory – transformed understanding on all levels

The summary of the multi-level governance perspectives throughout Chapter 3 results in Figure 4-3, which combines all levels and directions of vertical and horizontal influence, as explained and suggested in Section 2.2 and Figure 2-4 (cf. page 26). After presenting the options and relevance of each of these separately in Sections 3.1, 3.2 and 3.3, the alignment and combination of all are highlighted here. Instead of one-sided influence, a combination of top-down coordination, horizontal alignment and bottom-up action is suggested. This hybrid governance aligns with the requirement of central coordination and decentralised action in strategic energy planning by addressing the similarities and differences, allowing for a better understanding of the results when working with islands in terms of tests, demonstrations and innovation. Finally, this combination and inclusion of perspectives result in the edges of the map becoming more transparent as we come to understand islands and their role better. Solving the puzzle of sustainable energy system planning can thus come within reach.

Figure 4-3: Modelling with islands – through acknowledging multiple perspectives in multi-level governance, leading to solving puzzles and to more transparency

While Figure 4-3 and the corresponding previous perspectives of the puzzle focus on Denmark as an example, the same might be found globally. The knowledge flows between Copenhagen and the Danish islands, can also be found on the European scale, either through coordination via nations or directly to the islands (cf. Figure 2-4), as initiated by the *Clean Energy for EU Island initiative*. Furthermore, even without central coordination, cross-border collaboration between islands can contribute to research and solutions in relation to the Paris Agreement by working together globally and finding transcendent solutions despite local individualities. With replication and up-scaling in their respective countries, this acknowledgement of and collaboration between islands has wide-reaching impacts. Accepting the role that islands could and should play locally, nationally or globally highlights their contribution and benefit to sustainable energy planning, as is further discussed next.

4.2. SUSTAINABLE ISLANDS ENERGY PLANNING

In this section, the impacts of the analysis and the theoretical conceptualisation are further discussed in light of the problem statement and the state of the art from Chapter 1. It, therefore, addresses the issues raised in regards to sustainable energy planning and the alignment with islands. Specifically, reflections concerning island energy planning are introduced following the potentials of modelling with islands as pointed out in the previous section, resulting in the update of Figure 1-2 to Figure 4-4.

In light of the impending task of reducing fossil fuel demands and increasing sustainable energy shares, islands are not to be overlooked or disregarded as they play an important role in decentralisation. The contribution from each country to the Paris Agreement in light of their circumstances, hence, should be inclusive of their islands and perspectives. This also aligns with the centralised-decentralised coordination of locally available renewable energy sources and includes the environmental, economic and social aspects found locally. By combining the options of both cross-sector and cross-border optimisation in a new way and by acknowledging the local needs and limits, islands can not only contribute quantitatively but can add new qualitative knowledge to sustainable energy planning. Especially when taking considering their differences from and similarities with the mainland, both in their nature and institutional aspects, the understanding of context contributes beyond technical optimisation towards institutional areas. By providing a good setting for experimentation, islands further light the way for new forms of cooperation and collaboration across the complex contextual areas of energy planning. This is based on Section 4.1 and elaborated below.

Island modelling addresses the geographical context not only by aligning the available resources with demands in other locations, but especially by including the remote areas of consumption at the edges of our energy networks. This makes islands a rather central piece in the energy system, despite being far from political centres. Differences between islands and mainlands still need to be acknowledged, such as limited gas availability and industrial energy demands, but also additional demands and resources of islands. If modelling is done *with* islands, it addresses these areas of concern and limits the continental view towards them, creating a more inclusive and strategic island-mainland relation. Being located *on the edges* finally benefits both island and general energy planning.

While still offering great potential as models and for the modelling of global or national energy planning trends and technologies, islands' representation in energy planning and energy system literature might become more inclusive and valued, as indicated by the change from the modelling *of* islands to *with* islands. This is not to be confused with the perspective towards islands both in Denmark, with its many islands, and worldwide. Here, the targeted inclusive view [16] may change from a country/world *with* islands to a place *of* islands, also or especially in sustainable energy planning.

Therefore, not only the Danish island of Samsø but also other island examples may continue to be a light on the horizon in terms of experimentation and demonstration. However, further acknowledgement of the context of, and strategic energy planning for, islands, including Samsø, is required. The context must include the geographical aspects influencing the demands and resources locally, the sustainable inclusion of society, environment and economic options, and the institutional context, which entails the right level of recognition and inclusion in governance. Where models of current and short-term scenarios should include the latest data to the best extent possible, also challenges and changes, for example in demographics, should be included in future scenarios [37]. This can be summarised as a new way of strategic contextual energy planning that is especially relevant to islands, although others may also benefit from the approach through new understanding.

While the PhD thesis demonstrates the importance of contexts and of inputs from islanders, the output and understanding of the island models are just as relevant for islanders as well as for others. As touched upon by the limitations in modelling (cf. Sub-section 2.3.3) and the related contextual and institutional alignment (cf. Section 3.3), the translation from technical models to new knowledge and understanding by energy planners or the local communities and the resulting concrete local action suitable for islands is highlighted. Samsø, as an example, already bases its municipal plans on the models done of its energy system, which provide expert documents that lend credibility and direction to local actions [37]. This suggestion to improve the use of island models should be kept in mind when modelling in sustainable energy planning.

The use of islands as case studies in past and future energy planning research can be considered. On the one hand, they remain places for testing and experimenting, yet in a different way and with a new understanding. It should be considered that some things cannot be tested on islands and some things cannot be replicated from islands. Where islands were once considered models of larger energy systems or showcases of renewable energy technologies, they can now also be seen as lighthouses, showing the way at the edges of our countries. They might be the first to be hit by storms and climate change, but they can also become frontrunners and demonstrators of innovation. However, this requires the inclusion of contextual and strategic energy planning, under consideration of their individualities.

Case studies still need to be considered as introduced in Section 2.3, where a generalisation as well as quantitative and qualitative insights were presented as targets for case study research. While the work with renewable energy islands as lighthouses provides these quantitative and qualitative insights, the generalisation and a common solution for islands cannot be presented. Although Samsø, Orkney, Madeira, and others provide insight, they do not represent global perspectives, or even Danish, Scottish or Portuguese ones, completely. However, they do provide, along with the energy system analysis of, and the scenario work with, their different energy systems, three valuable perspectives *on* and *from* islands and within their limitations.

In relation to the use of islands as case studies and in contrast to Section 2.1, where islands are generally referred to as limited, a better use in sustainable island energy planning requires a reflection of these limitations. Besides reflecting some aspects of energy systems at a manageable scale, their differences not only advise caution during replication but also show new and resilient ways of doing things. With over 80,000 islands – and therefore perspectives – worldwide, islands appear to play a significant role in our society (cf. Section 2.1). Instead of simply serving as test-beds to be exploited, islands might actually '*lend credibility to innovation activities*' [55], where limitations result in resilience.

Self-sufficiency and optimisation in island mode bear relevance for every energy system, as discussed in the previous sections, even when there are good trading options. Hence, it can be related to islands or island-like isolations on continents, as found across Africa or Greenland, and to well-connected energy systems. A reliance on opportunities for export during times with excess local production and for import to supply insufficient local means is worth reconsidering. While trade and collaboration across borders have benefits and some fluctuating renewable energy can be well balanced that way, this might be something to limit, not only in remote or isolated areas. This would reduce dependency on others while strengthening the local energy system. Hence, this PhD thesis suggests the reconsideration of every energy system in terms of island-ness. Where solutions have to be found within system boundaries [39], the island mode is showing to be relevant also for countries such as

Denmark, where high shares of fluctuating electricity production might need to be addressed locally as an alternative to trade. In a future of many countries with highly fluctuating production or limited local fuel reserves, trade might not always be suitable and island mode optimisation could be an advantage, also globally.

Islands thereby expand the understanding of future energy systems and energy planning by defining limits and understanding. Where smart energy systems, sector integration and expansion may be the norm, islands encounter challenges or limited possibilities. Renewable energy technologies, for example, might be very suitable for islands, yet the transport and installation locally can be difficult due to remoteness and geographical boundaries. Also, the usually simple trade of products or electricity is hindered compared to other smart energy systems. However, taking the findings from this PhD thesis into account addresses and overcomes these challenges. The transition to renewable energy can thereby be assisted, and global trends can be replicated on islands.

In parallel to the options for energy planning on islands, islands can contribute to energy planning in general and to other non-islanded energy system settings. Concluding, Figure 1-2 from Chapter 1 can be updated to Figure 4-4. From previously seeing either the influence of energy planning on islands or the use of islands in energy planning, the coordination and collaboration of the two is now stressed. To elaborate, instead of using islands quantitatively for modelling with an outsider's view, the islands' qualitative contribution is recognised, which results in better coordination and collaboration between modeller, islander, and decision-maker. It also depicts the hybrid vertical governance, which is suggested in Section 2.2 but is often neglected in current energy planning, as discussed in previous sections and through theoretical reflections, especially in Section 4.1. Through the adjustments in Figure 4-4, the importance of coordination, not only between Orkney and Scotland but also globally, is introduced, as are potential new areas of research, as further addressed in Section 4.3.

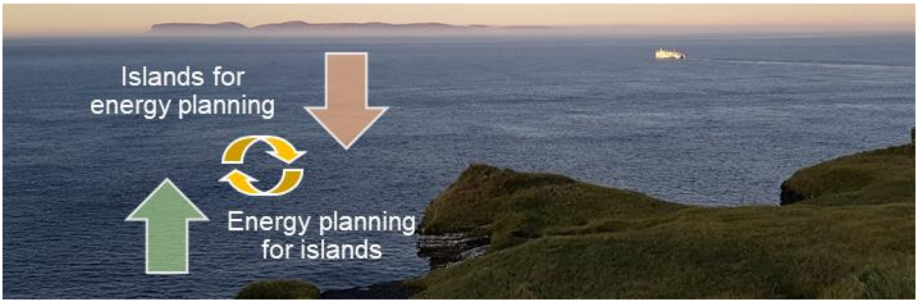


Figure 4-4: The role of modelling islands presented through adapted alignment in energy planning with an increased focus on contextual coordination

In summary, the following points contribute to the understanding of sustainable island energy planning, which further influences the next section:

- The inclusive coordination and collaboration of islands, taking local views, conditions and resources into account
- Acknowledgement of the quantitative and qualitative potentials of island test settings and island modes on a global scale
- Recognition of the self-sufficiency, innovation and lighthouse potentials
- Consideration of the limits in representation, infrastructure and island-suitability

Finally, the benefit for energy planners and both local and global audiences is given, although even more so for islanders. The acknowledgement and inclusion of all relevant contextual aspects provide better integration, more influence and the recognition of being more than simply models or laboratories, i.e. lighthouses. Thereby, islands contribute to the Paris Agreement and the fight against climate change by being more than test sites and playing a valuable role in solving the puzzle of energy planning.

The remaining concerns from Chapter 1 and the issue regarding the role of edges and islands in sustainable energy planning are discussed in the next section. Relating to topics introduced but also beyond these, Section 4.3 includes further perspectives and research opportunities on the aspects of island mode, energy islands, marine energy, island representation in politics, and latest developments concerning both island sustainability and island energy research.

4.3. FURTHER PERSPECTIVES AND RESEARCH

Following the summary of the analysis and publications, as well as reflections on sustainable energy planning, this section identifies, explores and discussed resulting new perspectives and avenues for further research based on the previous chapters. It is based on the previous reflections and addresses additional possibilities from and beyond island modelling. It thereby tackles the research gaps from Publications [1]–[5] and builds upon the theoretical and qualitative aspects provided in the previous chapters. With the PhD research returning from the edge with a new understanding and the acknowledgement of islands and their differences to other areas in energy planning, the following takes a closer look at the remaining gaps, which can be addressed both now and in the future. Islands are thereby put in relation to the future of energy planning, energy policies, energy islands and marine research, presenting both an exploratory and critical part of the PhD thesis as it goes beyond the analysis and publications. Thereby, it contributes to the role and inclusion of islands to the fight against climate change.

Even though islands are often understood as being limited, they are presented as lighthouses in this PhD thesis to enlighten and inspire innovation and hope. However, this also puts them in the spotlight for being at the front, even though they are usually less included in energy planning. This must change if it is those communities who are to show the way. While taken individually, islands do not have a large impact, but together, they do. With 10% of the Earth's population [16], they have a potentially large impact, yet they also need to be supported. Islands have shown to be more vulnerable due to being located on the edge and exposed to its remoteness (cf. Section 2.1), but they can also contribute significantly when strengthened and – contrarily – thus become the leading edge [18]. We want to continue having islands not only for recreational purposes but also for their resources and knowledge, for example regarding resilience or the marine environment. These potentials of islands are highlighted by considering modelling *with* islands, which is further reflected in the following for inclusion in future energy planning and research.

As presented in the previous sections, the right level of self-sufficiency and cross-border collaboration must be found in every energy system and should be included in further research, making better use of the learnings from island modelling. Whether technically possible or not, the theoretical collaboration across borders through the exchange of knowledge should gain more attention, as benefits can be found beyond the technical ones. Besides the new understanding of cross-border energy planning, self-sufficiency can also be attributed higher importance; see also the previous sections. Whether aiming for higher security of supply or strengthening the local energy system and community, the PhD thesis suggests that local self-sufficiency and resilience play a bigger part in future strategic energy planning.

The importance of self-sufficiency and resilience has also been highlighted in recent events with the barriers to international trade and reliance thrown up by the Covid-19[7] situation. This suggests that local resilience is important, especially, but not exclusively, for islands. While many areas of concern can be mentioned in this regard, energy planning and the importance of local energy system optimisation is one of them, ranging from optimising the current situations to future ones where more remote work may be seen on islands [74]–[76]. With local economies weakened by the situation, which has already hit weak economies, such as those found on many islands, especially hard, priorities change and the importance of self-sufficiency increases. When modelling with islands by including their local conditions as well as institutions, islands can be strengthened and security in the energy sector be provided, which seems especially important in this context. The energy sector, hence, should be strengthened through the expansion of local renewable energy production. This may

[7] The corona-virus detected in 2019 influenced research both globally and in this PhD.

result in the reduction of the imports and the dependence on others, thereby strengthening local communities in a sustainable way.

In one way, modelling with islands shows not only the importance of self-sufficiency for islands but also how this can be approached and benefit energy planning in general. Hence, the relevance of island mode and islanded operations could be elaborated in the future, also for energy markets and policy design. The current discrepancy between a capital and its islands is presented through multi-level governance and the example of the Danish puzzle metaphor (cf. Figure 3-7, p. 50) or Orkney's reliance on London and Edinburgh (cf. Section 3.1). As the perspectives of islands in transition theory and multi-level governance show, the need for experimentation and innovation can be best fulfilled by central coordination and collaboration between different institutional levels. As Chapter 3 further shows, contextual inclusion provides qualitative feedback with a potentially positive impact on energy transitions and energy planning, contributing to energy policy design; however, more research is required. Input to solutions for optimal decentralisation must also be found in a decentralised manner and, hence, the knowledge from the most remote places needs to be included to redesign energy markets and policy accordingly. Likewise, the understanding and presentation of islands as lighthouses, rather than as laboratories, can support this in future energy policy. Concrete research could be aimed at the island mode in energy policy, such as finding deviating policies for small markets. The elaboration and inclusion of islands in national or European directives and special responsibilities could address this, such as the case in Scotland through a Minister for Energy, Connectivity and the Islands [17].

Following the discussion on presenting renewable energy islands as lighthouses also in politics, a reflection of artificial 'energy islands' and the reconsideration of their definition and purpose is suggested. To explore this topic beyond what the PhD thesis covers, Table 4-1 was created to introduce the typology concerning 'smart' and 'renewable' island, as well as areas for discussion and further research presented afterwards. First, the definitions and foci of the terms energy island, smart island and renewable island are suggested, as has been suggested in the previous chapters. Second, a comparison of their development and application is made, and third, their purpose is highlighted.

Table 4-1: 'Energy island' typology for further resulting research

	Energy island	*Smart island*	*Renewable island*
Focus	Energy production, incl. especially wind power	Smart technology demonstration, e.g. smart grids	Renewable energy technology, incl. various renewable energy sources
Development	New	Well-researched island or system	Well-integrated use of renewable energy
Application	Remote	Specific	Inclusive
Purpose	Electricity production, potential for electrolysis	Research, whole electricity system	Research and increase of renewable energy share locally and nationally, integrated

As introduced in the Danish climate agreement [30], [31], energy islands refer to the artificially yet-to-be-developed islands in the North and Baltic Seas. Electricity production is the main aim, primarily through the use of wind resources. In relation to this, the conversion to hydrogen via electrolysers is discussed. Energy islands thereby exclusively present technical aspects and electricity production. Renewable energy islands, as presented throughout this PhD thesis through the case studies and models, present a contrast by being inclusive of all resources, sectors and contexts. Smart islands are not further discussed as their definition can overlap with the definition of renewable islands, but they can often be related to smart-grid and electricity-focused research. Nonetheless, similarities exist across all types, and it is recommended that these be made use of in further research on energy islands. Even though energy islands might not represent decentralisation in the perspective presented throughout the thesis, similar conditions exist, including resource and research potentials. Well-developed renewable energy islands like Samsø or Orkney present energy islands to some extent [17], [37]. This underlines both the importance of island modelling for the development of artificial energy islands as well as the need for both island typologies to be recognised in further research.

With all types of energy islands making use of local resources, this is further reflected in light of the largest resource: marine energy. As introduced in Chapter 1, limited research and development have been observed in the field of marine renewable energy [27] besides the development of offshore wind farms and future energy islands [31]. Even though islands comprise only 1.5% of the Earth's surface [16], their potential for modelling and learning also suggests that future research should focus more on marine energy sources and demands, instead of only on onshore and continental solutions. Studies indicate marine energy to contribute up to 23% to the world's electricity demand [77], [78], further demonstrating the relevance of islands. However, it is not just coastal communities and islands that could benefit from both the resources and the understanding from modelling with islands emerging from this PhD thesis. The European marine renewable energy centre on Orkney is already addressing this and presents areas for future energy systems, despite the limits in the field, such as the impacts of the ocean environment and remoteness. Thus, while islands already may benefit from this understanding, potentials also exist for supplying non-coastal energy systems as well as for replication in rivers or lakes [17].

This reflection presents marine energy potentials, and thereby further perspectives and research opportunities, by addressing the role of marine in the energy system of islands, but also in other water-bound regions. As presented throughout the thesis, marine demands may seem irrelevant from a continental perspective, but they are fundamental for locals. Locally available marine resources, which are only included throughout the PhD publications to a small extent in the model of Orkney [4], include waves, tidal currents, salinity and temperature gradients, and algae. However, they can also extend to the wind and solar resources above the seas. With existing expertise in the offshore oil and gas industry, knowledge can be transferred from islands to offshore wind parks as well as other forms of future energy exploration, supporting the coastal regions with local green jobs. With examples of grid-connected wave and tidal power devices in Orkney and Shetland and the main challenges soon to be overcome [17], new potentials can be explored through further research [77]. Finally, the better inclusion of marine energy requires updates to the EnergyPLAN modelling tool, which can be supported by the learnings from the PhD thesis with insights from island experience, although further research is still required.

With marine energy and oceans connecting islands around the world, their contributing role in global sustainable energy planning is highlighted. Not only are they and their potential to be recognised from a global perspective, but furthermore they themselves should be recognised in areas where they are often overlooked, like in countries that do not consider themselves 'island countries'. While the share of the population living on Danish islands is close to the global average, other countries, like Germany, have a much smaller share; nevertheless, islands should be similarly included [73]. Furthermore, the collaboration potential presented through horizontal governance (cf. Section 3.2) points to the importance of cross-border cooperation, as Danish and German islands may have more in common with each other than with their respective mainlands. Programs on the international, regional or national level, such as *Small Islands Organisation* (SMILO), *Northsea Interreg* or the German *Island and Hallig Conference*, are already making use of this and could be further researched and elaborated in energy planning [16], [48], [78]. This could result in not only a replication potential of renewable energy solutions on other islands but also an up-scaling of those to the mainland in the respective countries. This shows the global scale of the local possibilities and the value of islands, since it is the scale that ultimately matters [13].

While Figure 4-1 presents the increase in the content and qualitative learnings from the analysis throughout Sections 3.1 to 3.3, Figure 4-5 includes the aspects brought to attention through the reflection on modelling islands and the perspective of islands as lighthouses. While complexity, self-sufficiency, local focus and sector integration already support higher CO_2 reductions and renewable energy shares, the further perspectives and research presented throughout this section and based on the research during the PhD period highlight additional aspects. They range from the recognition of islands from the mainland, via contributing to mainland activities, to involvements in and impacts on various areas and levels. The importance of these aspects from and around island research presents the resilience of islands and their potential as lighthouses.

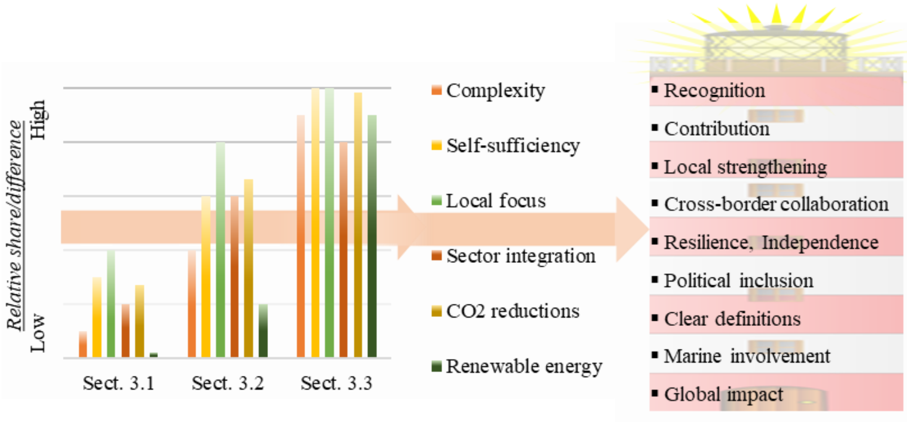


Figure 4-5: The role of modelling islands presented through a relative increase of complexity elaborated through further island research

With the various areas of further perspectives and research potentials now highlighted, we may be closer to solving the global puzzle of energy planning by a more inclusive use of the learnings from and beyond the edge in this PhD thesis. Through these reflections, and thereby contributing to the Paris Agreement and the fight against climate change by supporting the uptake of renewable energy across islands and nations worldwide, the contributing role of modelling renewable energy islands to sustainable energy planning is presented.

CHAPTER 5. CONCLUSION: ENERGY ON THE EDGE

Islands light the way to fight climate change by adding an edge.

This chapter offers a conclusion to the problem statement and research questions from Chapter 1 by reviewing the framework from Chapter 2 and the analysis from Chapter 3. While Chapter 4 reflects on the analysis in detail by summarising the perspectives of modelling with islands and the resulting consequences for sustainable energy planning and further research, an overall conclusion of all chapters is presented here.

Chapter 1 presents the understanding and potentials of islands in the fight to limit climate change by pointing out the need to decentralise, yet to include all geographical areas. Being on the edge provides an advantage for islands and energy planners, not only through modelling in island mode but also by adding perspectives from the outmost regions of countries and energy systems. The potential to thereby support the transition towards renewable energy is, however, currently hindered by the underrepresentation of islands in energy planning and the lack of a clear understanding of how their experiences and perspectives can contribute to sustainable energy planning. The following main research question addresses this, with the sub-research questions building upon one another to support the main one. Chapter 1 thereby concludes that while climate change does not stop at the edges of our countries, it does start there, and so must the fight against it by defining the role of islands and island modelling in sustainable energy planning:

‘What role can modelling renewable energy islands have in sustainable energy planning?’

1. How can modelling of islands be used to evaluate renewable energy technologies?
2. Why and how should modelling on islands be improved by considering and comparing local conditions?
3. How can contextual and institutional alignment elaborate modelling from islands?

Chapter 2 addresses the problem statement by presenting the framework to the analyses applied in the thesis as well as in the corresponding PhD Publications [1]–[5]. The concepts of energy systems and islands define the context and the delimitations and describe the areas of contribution from the thesis. Likewise, the theoretical understanding and relation of energy transitions, governance, and modelling question and shape the contributions of islands to sustainable energy planning. Elaborating on the energy system analysis and case studies defines the methodological approach to the PhD research, concluding the framework of the thesis.

With a close connection to the SMILE project and the case study islands of Samsø, Orkney and Madeira, yet with an eye beyond the project limitations, the thesis makes use of both quantitative and qualitative insights and creates new understandings. Presenting three different islands and island energy systems does not comprise a review of all 2700 European or 80,000 global islands, but the additional look beyond validates and verifies the approach taken nonetheless.

Chapter 3 answers the three sub-research questions by discussing the perspectives of modelling *of* islands, *on* islands and *from* islands through a look at the cutting-edge research published during the PhD research. It thereby addresses the role of islands in energy planning by showing what works, what does not and what can be learned from that. In Section 3.1, PhD Publications [1], [2] and [3] demonstrate how the modelling *of* islands can be used to evaluate renewable energy technologies by analysing specific aspects in island energy systems, yet with a non-inclusive perspective as the modelling is mostly done with an outside perspective of islands. Section 3.2 addresses the weaknesses of the modelling *of* islands, and PhD Publications [3] and [4] add perspectives *on* islands. These include local conditions and compare similarities and differences to improve the modelling done with islands. Finally, in Section 3.3, PhD Publication [5] elaborates on renewable energy island modelling by adding further details and perspectives *from* islands through contextual and institutional coordination. Chapter 3 thereby concludes that islands provide good settings for testing, but considering the conditions on islands and ensuring an alignment with the context facilitates better coordination and collaboration to enable innovation and development in energy planning.

- Modelling *of* islands enables the evaluation of renewable energy technologies in an island setting, but with an outside view *of* islands.
- Modelling *on* islands addresses the limitations of the outside view and improves the modelling by including and comparing local conditions *on* islands.
- Modelling *from* islands elaborates the potentials of island modelling by adding contextual and institutional aspects through perspectives *from* islands and islanders.

Chapter 4 picks up from the perspectives introduced before and adds further reflections of the edges of both countries and research and beyond. By summarising the analysis, the chapter concludes that modelling renewable energy islands should be done *with* islands, from which both energy planners and islanders benefit, as illustrated especially in Section 4.1 (cf. p. 77f.). Chapter 4 thereby contributes to a new understanding of islands as places for niche innovation through transition theory by considering all perspectives, and adds transparency to energy planning coordination through multi-level governance, including horizontal and bottom-up actions. This changes the way sustainable energy planning can be understood by discussing the quantitative and qualitative importance of islands and island models as well as the understanding of self-sufficiency and cross-border developments in Section 4.2. This results in islands being given a role that is worth recognising, contributing to the coordination and strengthening of energy systems, collaboration across borders, innovation, and independence. This benefits energy planning by being inclusive of island views and limits, resulting in a reduction of emissions and limiting climate change through islands on a global scale. Hence, countries like Denmark should see themselves as countries *of* islands, attributing more to islands than their simply being seen as additions to these countries. The resulting recommendation of acknowledging the versatile role of islands answers the main research question:

- Modelling renewable energy islands contributes to energy planning with potentials for coordination, collaboration, innovation, and island mode optimisation, yet with a global impact. This is achieved when the modelling is done *with* islands.

The answer to the main research question is thereby given, opening up possibilities for further research. Therefore, Chapter 4 concludes that modelling renewable energy islands contributes to research and new understandings of energy system modelling, energy policy, energy islands, marine development, and resilience. In contrast to Chapter 1, islands are thereby recognised as more than places for testing, rather becoming lights on the horizon to look out for. Furthermore, this provides a better understanding of how the 600 million islanders and the 80,000 islands across the globe are connected and should be used for inspiration and innovation, concluding that islands are not only important in energy planning but are also charged with a variety of potentials and energies, as supported by Figure 5-1.

Figure 5-1: View of Orkney and the surrounding (tidal) energy

Concluding, the energy of islands contributes to the conceptual, theoretical and methodological understandings of sustainable energy planning. The first is achieved by islands playing a well-represented part in energy planning and energy being an important part of islands, the second by islands providing a place for innovation and collaboration, as supported by theory, and the third by improving the modelling of renewable energy. Having a closer look at islands presents them as *lights on the horizon* or lighthouses on the edge and ready for the energy transition. Including islands and their models thereby addresses the Paris Agreement and the fight against climate change through greenhouse gas reductions and the decentralisation of sustainable energy, and, hence, this should be kept an eye out for – to make the world a better place.

There is a light on the horizon; it might be coming from an island to show us the way.

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APPENDIX

The following pages include the appendices containing PhD Publications [1]–[5]:

[1] "*Residential versus communal combination of photovoltaic and battery in smart energy systems*" by H. M. Marczinkowski and P. A. Østergaard, Energy, available 29/03/2018, doi:10.1016/J.ENERGY.2018.03.153.
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[2] "*Business and socioeconomic assessment of introducing heat pumps with heat storage in small-scale district heating systems*" by P. A. Østergaard, J. Jantzen, H. M. Marczinkowski, and M. Kristensen, Renew. Energy, available 01/03/2019, doi:https://doi.org/10.1016/j.renene.2019.02.140.
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[3] "*Evaluation of electricity storage versus thermal storage as part of two different energy planning approaches for the islands Samsø and Orkney*" by H. M. Marczinkowski and P. A. Østergaard Energy, available 19/03/2019, doi:10.1016/j.energy.2019.03.103.
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[4] "*Transitioning island energy systems—Local conditions, development phases, and renewable energy integration*" by H. M. Marczinkowski, P. A. Østergaard, and S. R. Djørup, Energies, available 10/09/2019, doi:10.3390/en12183484.
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[5] "*Technical Approaches and Institutional Alignment to 100% Renewable Energy System Transition of Madeira Island—Electrification, Smart Energy and the Required Flexible Market Conditions*" by H. M. Marczinkowski and L. Barros, Energies, available 27/08/2020, doi:https://doi.org/10.3390/en13174434.
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SUMMARY

This PhD thesis defines the role of islands in the field of sustainable energy planning. It addresses the Paris Agreement through the uptake of renewable energy technologies and how the 80,000 islands globally may contribute to developing those both on islands and elsewhere. With a particular focus on the case studies Samsø, Orkney and Madeira, the thesis highlights perspectives of islands, the potentials and limitations on islands, and the understanding to gain from them. Thus, the thesis contributes to energy planning in three ways. First, the concepts of smart energy systems and islands are elaborated and combined. Second, the theories of transition and governance are illustrated through island perspective. And third, the methods of energy system analysis and case studies are contemplated through a review of publications on modelling with islands. The thesis critically reflects on the work done with islands and, despite being located on the edge, on the benefits for both energy planners and islanders through cutting-edge contributions. The coordination of the research with islands supports the transition towards 100% renewable energy share and the fight against climate change.

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