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Energy transitions on European islands: Exploring technical scenarios, markets and policy proposals in Denmark, Portugal and the United Kingdom

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ABSTRACT

The energy transition is taking place across the globe and renewable energy facilities are flourishing in many places. Yet, to achieve this transition to a carbon-free economy, fit-for-purpose social and institutional set-ups are just as needed as the technical transition itself. While new energy market regulations and policy designs are proposed, the alignment of these for the transition on remote places like islands is limited. Based on technical scenarios for the transition of three European islands, this article investigates market and policy proposals that will support their technical energy transitions in a socially inclusive way. It is based on a literature study of five policy areas in combination with local stakeholders' engagement and their responses to the suggested proposals. The paper presents a comparative study and design approach for Samsø (Denmark), Orkney (United Kingdom) and Madeira (Portugal), but with transcendent solutions and replicability to other islands, placing them in the global debate on energy policy transitions. Results point to a misalignment between national policies and the policies that would actually support islands' green transition. The recommendations therefore propose to tailor energy relevant policies for islands.

1. Introduction

The latest Intergovernmental Panel on Climate Change report [1] highlights yet again the use of fossil fuels in energy as one of the main sectors contributing to climate change. Fortunately, next to the technical summary, the summary for policymakers bridges the gap between science and policy makers with recommendations to take action in the right direction. It appears that both technical efforts in the transition of the energy system and the alignment between technology and policy are needed [1].

1.1. Technical and non-technical energy transitions

Energy systems are transitioning towards 100 % renewable energy (RE) supply globally, with increased focus on regional differences [2]. However, the alignment of technical transitions with local institutions and policies in a socially inclusive way is also growing in importance. Indeed, many studies focus on Europe or the USA while other areas lag behind, though with an overall absence of information for society, policy-makers and planners in general [2]. 100 % RE systems are to be designed through an all-encompassing smart energy system approach, including both the production and consumption side in all sectors [3]. However, this increasingly complex approach also requires institutional alignment. As also supported by [4], as an important part of energy studies, the integration of technical analyses should go hand in hand with social dimensions.

The regulatory consequences and the challenges of the transition process towards high penetration of RE presented by Hvelplund and Djørup in [5] highlight the importance of governance for 100 % RE system. Often, specific technologies are reviewed in regards to their alignment with the institutional setting, such as the analysis of energy policy for wind power by Johansen [6]. However, the alignment across sectors and countries is limited and could be further investigated. Indeed, the technical transition includes not only new technologies, but

Abbreviations: RE, Renewable Energy; EV, Electric Vehicle; SMILE, Smart Islands Energy System; DSO, Distribution System Operators.

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also new systems. Departing from a traditional silo thinking with clearly defined sectors and unidirectional flows of energy from few suppliers to many consumers, smart energy systems change this scene. Here, a multitude of suppliers and technologies interact across traditional sector boundaries to provide energy services in the best and most flexible way. The realization of such an energy system requires not only technical changes but also changes in ownership, markets, regulations and much more. Sorknæs et al. take a step into the right direction by designing markets not limited to a single technology but in accordance with smart energy systems: so-called smart energy markets [7]. Yet, details on implementation barriers as well as local and regional differences to achieve this alignment are again missing. A global and local challenge is to help identify the correct approaches and timelines to foster energy transitions, such as was done during the Covid-19 pandemic, where a shift towards more RE was observed [8], a shift similar to the one needed to better align islands with the mainland and technologies with institutions.

As observed in literature, energy transitions are often closely observed and evaluated on the local and thereby social level, including the testing and modelling of highly-renewable and smart energy systems on islands [9]. This enables the study of impacts under traceable conditions due to the isolated state and the island mode perspectives on changes in the energy system. The gap between (inter)national aims and local possibilities to implement such changes is identified and resulting imaginaries presented by Skjølsvold et al. [10]. Kallis et al. have identified further possibilities for improvement and integration of justice principles through and for islands in [11]. Additionally, policy mismatches between RE and rural development have been identified by Clausen and Rudolph [12]. The role of regions is also highlighted with the support of local authorities and appropriate multilevel governance by Melica et al. [13] or with the design of specific local markets to address local context and constrains by Brolin and Pihl [14]. Heaslip & Fahy investigated transdisciplinary approaches to island energy planning, finding, e.g., value in the co-creation of scenarios with island dwellers to increase local ownership of the transition process [15]. With a focus on small-scale community-based marine energy systems – clearly also relevant in islands contexts – Proimakis [16] identified regulatory issues in terms of, e.g., required environmental impacts assessments, as well as barriers in the form of lack of funding. However, the majority of energy policies are drafted at national level without consideration of local or island conditions, but larger scales in mind. This results in a mismatch between the applicability of the policy for the mainland and its fitness for islands. To summarize, energy transitions on islands face many nuances of misalignment, from local developments and technologies to national and international alignment - with differences between islands.

1.2. The local level of investigation: the islands of Samsø, Orkney and Madeira

To address the local and social challenges and regional differences for the transition of the energy system across three regions, the Smart Islands Energy System (SMILE) project is of interest. It is a Horizon2020 project funded by the EU [17] demonstrating and analyzing the implementation of smart energy technologies. The project ran from 2017 to 2021 with a focus on the islands of Samsø, Orkney and Madeira and addressed the strategic policy approach to support technical changes [18]. The location of the three islands across different climate and national regions makes them good cases for local yet transcendent energy transition studies; with Samsø embedded centrally in the Danish Kattegat, Orkney on the northern outskirts of not only the UK but also in Scottish and North Sea terms, and Madeira in the far south from mainland Portugal in the Atlantic Ocean.

Samsø has been undergoing a long-term transition, which has been addressed in research over the years [19–21], with a focus on community engagement contributing to its success in the past but with unknown challenges in the future and for national and international replication. Orkney is known for its tidal energy and hydrogen advances [22,23] and has presented strategies, such as for EV uptake [24], to influence national policies. Yet overall, national policies are still not aligned with the local advances on the islands. Electric vehicles (EVs) and storages have also been studied for Madeira [25,26] but due to its isolated situation, impacts on national level and alignment with other regions are limited.

For further comparison, all three islands have been studied in technical details and their short to medium-term energy transition approaches presented in [27]. Samsø and Orkney have also been studied in parallel for different energy storage technologies and their impact on the whole energy system [28]. However, these studies did not include implementation and impact analyses beyond technicalities. Finally, Madeira has been introduced as the first of the three islands to highlight the need for institutional alignment with technical approaches, presenting energy market alignment suggestions [29]. With the requirement of alignment apparent to fully electrically isolated energy systems like Madeira, a further alignment of other islands as well as policies is still lacking. This is where this article picks up. A combination and comparison of several islands' energy transitions allows to identify and close gaps in the alignment with policies. The requirements of various island communities with different technical characteristics provides further insights into aspects of energy transitions beyond these islands.

1.3. Article contribution and structure

Where energy policies are usually drafted at national level, there may be a mismatch in terms of appropriateness for islands, while they can actually contribute to the shaping of policies at national and international level through acting as test sites. Reviewing the energy transitions on three islands across different regions and national policy settings can provide novelty to designing energy policies inclusive of local and isolated places, to contribute not only to local but also to national development. The following thereby aims at an impact beyond academia by pointing out the relevance and validity for real life policies of three islands and in other contexts [30]. In order to do so, the islands of Samsø, Orkney and Madeira are compared and evaluated in terms of their technical transition combined with in-depth policy barriers identification and search for solutions applicable to all islands.

To do so, this paper focuses on five key areas; a) general planning and legal framework, b) access to energy technology, c) energy markets, d) citizen engagement, and e) ownership models. In the framework by Devine-Wright et al. for addressing social acceptance, they target governance and regulation, market & innovation, and acceptance from different international down to local scales, thus also indicating the need to potentially address these levels differently [31]. These aspects are hence all important for the transition towards RE systems and are deliberated upon more extensively later in the article to answer the question whether European energy policies are aligned to the needs of islands' energy transitions.

The article proceeds as follows: Section 2 introduces the approach and methods, Section 3 presents the review of technologies, existing policies and gaps for islands, and finally Section 4 concludes.

2. Methods

In this work, the review of technical scenarios of the transition on the three islands of Samsø, Orkney and Madeira allows to propose policy designs for the energy transitions of islands more generally. The approach is based on [5] and illustrated in Fig. 1, presenting this article's structure and applied methodology. Firstly, we introduce the technical scenarios, helping to, secondly, identify the policy areas for the literature study and the two rounds of interviews, both in correspondence with the island representatives. While the scenarios as well as the literature and interviews form individual steps, they are interlinked and

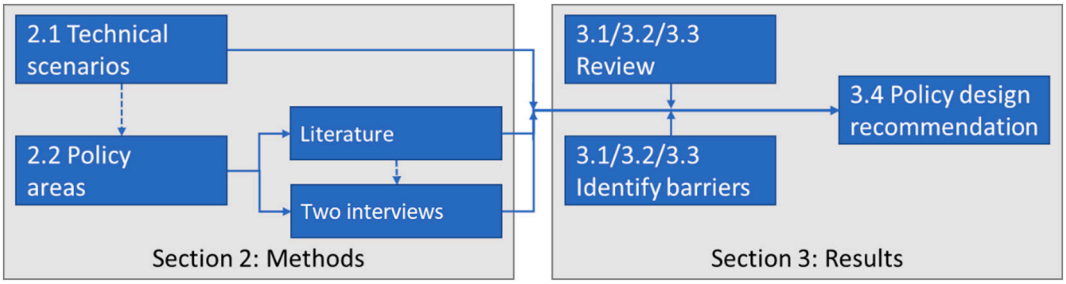

Fig. 1. Approach of technical scenarios and related policy areas investigated and reviewed to identify barriers and recommend policies.

influence each other, as indicated by the dotted arrows.

Thirdly, we revisit the methods in the review sections, where they are evaluated individually under corresponding Sections 3.1–3.3, leading up to the final results. Both these technical scenarios, as well as the literature and interviews in relation to the policy areas are reviewed in the respective sections. Table 1 presents the results of the first interview and a basis for the second interview, with corresponding results shown in Table 2. This review leads to the identification of barriers for the islands to transition to RE from a policy perspective and results in Section 3.4 with policy design recommendations, both from the island interaction and from the combined approach presented here.

2.1. Defining the technical scenarios

The technical transition scenarios present the current and potential future energy system set-ups of the islands of Samsø, Orkney and Madeira. Besides including all sectors (electricity, heating, transport, industry), we included also the supply, conversion and demand sides. These scenarios are evaluated based on stakeholder engagement and the EnergyPLAN [32] analysis, documented in [33,34]. The models include local characteristics, not just regarding wind and solar radiation potentials, but also technologies and fuels most suitable and best employed in each island. In SMILE, the reference energy systems present the 'current' situation with its potentials and weaknesses in all the above-mentioned areas. In detail, the islands vary not just in population size, but also in electricity, heating and transport demand per capita. These sectors each depend on the climatic region, geography, cultural differences and local possibilities, resulting in large variations between the islands. Hence, we present similarities and differences both technical and with regards to implementation barriers for the transition of RE on islands.

Overall, each island's reference energy system indicates the need for better integration of locally produced energy to supply electricity, heating, cooling and fulfil transport needs sustainably, leading to short-term energy scenarios for each island for 2030. Most importantly, those future scenarios not only include 2030 scenario simulations, but also build upon the technical solutions demonstrated in the three islands, including demand response, smart grid functionalities and storage, and energy system integration. Furthermore, a potentially larger deployment of the demonstration projects is addressed. In general, a shift from energy systems relying on fossil fuels to energy systems relying highly or exclusively on RE is proposed by [27] which aligns with smart energy systems and scenario development of similar studies.

However, for a better integration of local resources, technologies and demands, also the related framework conditions including policies and institutional set-ups must be met. This is where Section 3.1 continues from the technical scenarios. With increased electricity demand in the heating and transport sector, additional RE capacity, but also optimal regulation is required. For this, we address and evaluate related policy areas for the discussion and realization of the proposed 2030 scenarios.

2.2. Identifying the policy areas

The relevant policy areas are based on the technical analysis of the transition to RE on the three islands and used as a framework for the literature study, as well as the additional interviews with representatives from each island. As already put into perspective in the introduction, the policy areas indicate gaps in planning and framework conditions for islands on the continental or global scale. Misalignment was not only pointed out between technology and policy, but also in the related areas of markets and consumers, as also highlighted as main themes in the SMILE project.

SMILE has investigated the relevant technical measures in the context of the three islands to transition to RE systems – both with a focus on a series of specific technologies that were addressed in the SMILE project and more generally in the scenario work through the wider application of RE technology. However, while the scenario work has identified feasible means of transitioning the islands, there is a large step between the theoretical identification of such scenarios and the actual implementation. Thus, the identification of policy areas takes a starting point in existing research on barriers and policy suggestions, and is used in the evaluation of experienced barriers and potential solutions in the specific islands. Thereby the following interaction with the islands is factoring in local conditions regarding five main policy areas:

- general planning and legal framework (in short subsequently referred to as 'General planning'),
- access to energy technology ('Technologies'),
- energy markets ('Markets'),
- citizen engagement ('Citizens'), and
- ownership models ('Ownership').

The identification of these categories of policy areas was done through the literature review (Section 3) and a subsequent ordering of the inputs into appropriate categories.

The areas identified form together with the technical scenarios the first, basic step of the methodology in the identification and design of energy policies for the energy transitions on islands – see Sections 3.2 and 3.3.

2.3. Approach of literature and interviews

Both the literature and the dedicated interviews rely on engagement with representatives from each island. Their role was to provide feedback on the policy issues identified in the literature and as part of the SMILE project specifically through the interviews. The representatives from the islands are members of the SMILE consortium and are familiar with the technical transition of their island's energy system. For Samsø, an engineer from the Samsø Energy Academy participated, for Orkney, two members of the Community Energy Scotland office in Orkney responded, and for Madeira, one academic and one municipal stakeholder provided answers to be able to cover all questions. All interviews were conducted individually with each island's representative(s) by e-

Table 1
Representatives' agreements with literature recommendations and applicability to Samsø, Orkney and Madeira (The following symbols are applied: (✓) full agreement/applicability, (✓-) partial, (N/A) none, based on [18].

	Literature recommendations	Samsø	Orkney	Madeira
General planning	The modelling simulation process should not be designed based on the optimal quantitative goals but according to a transparent process that demonstrates the different consequences of potential pathways [44].	✓ -	✓	✓-
	Challenges on wind power development will be faced by setting a) stable conditions for project developers, b) clear distribution of competences among authorities on spatial planning, and c) incentives or requirements for full or partial local ownership [45].	✓	✓-	N/A
	The installation of new RE technologies should require the participation of NGOs, local stakeholders and representatives of the technologies even if they do not exert much influence upon the energy system [46,47].	✓-	✓	✓
	Local action should be within frames prescribed through the national energy system and coordinated in such a way as not to hinder local action elsewhere; albeit this could act as a barrier or even deterrent for local and national innovation [48].	✓ -	✓	✓
	District heating policy should establish: 1. transparency in costs and benefits; 2. robust national-level tools by encouraging single structures for assessments; 3. electricity balancing markets that can confer value to district heating and combined heat and power systems; 4. holistic energy planning across sectors [49].	✓	✓ -	N/A
	The optimal way to foster policies in innovative RE technologies is by comparing the alternative options since different technologies require different types of policy instruments [50].	✓	✓ -	✓
	Islands require a special regulatory framework that recognizes their specific situation and can be adapted to their needs, as well as provides support to achieve decarbonization goals [51].	✓	N/A	✓
Technologies	A dual-track incentive system is required to establish socio-economically and business-oriented incentives for investing in wind power and integration infrastructure between electricity, heating, and transportation sectors [52–54].	✓ -	N/A	✓-
	The "end-use demand response" should be able to provide flexibility to the electricity system alongside supply-side options – under appropriate and accommodating conditions. Further numerous changes for market structure elements, aggregation, and technical modalities [55].	✓ -	N/A	N/A
	The investments should be open to lower-income households or local communities while the barriers to entry should also be lowered by ensuring access to low-cost capital [41].	✓-	✓	✓
Markets	RE support schemes should provide incentives for investors. A good practice would be a transition to smart energy systems, adjusting the prices by integrating the heat and power markets. Consequently, electricity from RE would not be sold at a lower price than the most expensive heat alternative [7,56,57].	✓	N/A	N/A
	Taxes should not be used to discourage entirely the use of electricity. Rather taxes should discourage the use during periods of low production-to-demand ratio and encourage during high production-to-demand ratios [5,58].	✓	N/A	✓ -
	The monopolistic power of state-owned utilities (e.g., large-scale generators) should be reduced by ensuring access to the grid from various types of actors in order to increase decentralized and small-scale energy production [59].	N/A	✓	✓ -
	A policy that directly prices or restricts carbon emissions is considered to be the most cost-efficient option for the energy system, whereas a policy that will facilitate RE investment is expected to be more cost-efficient at encouraging market adoption of specific technologies [60].	N/A	✓	N/A
	New frameworks should embrace the heterogeneity of island systems offering new opportunities in the electricity market and leading to a cost-effective energy transition [61].	N/A	N/A	✓
Citizens	The heat tariff scheme should change, improving the financial incentive for heat savings, while also making the system development less vulnerable to fluctuations and shortages in capital markets [62].	✓ -	✓	N/A
	Decentralized installations of solar PV panels together with battery storage under a smart energy system could benefit consumers more than a centralized controlled installation [63].	✓	✓	✓-
	The tariff policy should change in a way that the long-term costs (which reflect the investment) of future RE systems, instead of short-term ones (which reflect the marginal and operational price), reflect on the tariff base [64].	N/A	N/A	N/A
Ownership	The policy related to citizen ownership should give investment priority to local investors to ensure that they always have the right to obtain ownership shares. This fuels the successful deployment of wind power installations [38,46].	✓	✓	N/A
	Consumer ownership model has positive potential both in terms of maintaining low energy prices and securing low coordination transaction costs in smart energy systems [65].	✓	N/A	✓ -

mail and video call.

In order to identify barriers and solutions, we conducted a literature study and synthesised results before presenting them in interview number one to island representatives. The literature study targets to reveal potential strategic policy measures that support the transition to high-RE energy systems. Analytically, it studies the current status of peer-reviewed literature in terms of the identified policy areas in relation to the islands' transitions in general, and only loosely related to the SMILE cases, finally producing a 'toolbox' with policy instruments for each one of them. Interview number two follows the first round of interviews and integrates the insights gathered. While the literature study addresses general issues and perspectives in the broader context of the technical scenarios, the interviews are more closely related to SMILE technologies and barriers in relation to the islands. Policy barriers are identified for each individual island, but with the possibility to identify transcendent barriers and solutions for other islands as well.

These interviews are intended to establish, first, an overview of barriers and potential policy suggestions as experienced or perceived by the island representatives in relation to the SMILE projects taking place on the respective islands. This first part of the interview is an open questionnaire seeking general inputs within the five identified areas. Secondly, in combination with the literature study and inputs gathered, the same representatives are asked to assess the relevance of the identified barriers and suggestions from other islands. With answer options of full, partial or no agreement/applicability on the respective island, the answers thereby provide mutual inspiration between the islands and from literature. This second part presents an assessment and island-transcending alignment of identified barriers and suggestions.

Based on the question 'Which barriers exist within [policy area] and what suggestions may be made?' for each of the identified policy area, the island representatives were asked to assess the technical scenarios relevant to their island. Barriers and suggestions did not need to be matched one-to-one; and thus, barriers might be identified without concrete policy suggestions. The overall aim was to share inputs and insights from both successful and unsuccessful implementations – i.e. needs to overcome a barrier and approaches, ideas and failures to address them in a certain way.

The final results (see Sections 3.2 and 3.3) were shared with the island representatives to identify similarities and differences to other islands and draw conclusions, as done in the next section. Finally, and based on the feedback from both the literature study and the SMILE-specific interview, a series of recommendations for policy instruments are derived and presented in Section 3.4.

Table 2
List of barriers identified by- and relevance for islands.

	List of barriers	Samsø	Orkney	Madeira
General planning	Lack of integration of energy planning and electricity network planning	X	X	X
	Lack of engagement resources	X	X	X
	Lack of localized process to engage community groups		X	X
	Lack of split metering permission	X	X	
	Difficulty for local suppliers to participate in the supply market	X	X	
	Electricity sector exclusiveness	X	X	X
Technologies	Lack of consumer knowledge resulting in lower performance of the energy systems	X	X	X
	Smart technologies are expensive with prolonged and low return on investment	X	X	X
Markets	Lack of incentive schemes for small local energy supply	X	X	
Citizens	Lack of legislation for participatory energy plans	X	X	X
	Lack of citizens awareness tackles their engagement	X	X	X
Ownership	Lack of reliability and commitment within the household participants	X	X	X
	High costs of the smart energy systems for all the involved parties	X	X	X
	Large-scale energy systems integrated by smart control provide limited benefits for the locals		X	

3. Results

The following presents the results of reviewing the technical scenarios for the islands to transition from their reference energy systems to 2030 scenarios with the impact of the SMILE demonstrator projects, as well as the related barriers identified through literature and interviews. Based on those, the final results are recommendations of policy design for the energy transitions on islands, before concluding the analysis.

3.1. Technical scenario review

The islands vary in population, electricity, heating and transport demand per capita and depend on the climatic region, geography, cultural differences and local possibilities. Samsø, for example, has a large biomass use, while Orkney produces a majority of its heat from electric devices and Madeira's heat production is mainly gas-based. The reviews of these 2030 scenarios including the SMILE demonstrations for the identification of policy barriers are presented for each individual island. Afterwards, transcendent responses are presented in the following literature study and interviews. Further information on the models can be found in the underlying technical analysis [27].

3.1.1. Review of Samsø

In the reference energy systems, Samsø provides 60 % of its energy with local RE, while 78 % of the locally produced electricity is currently exported during hours of surplus wind power production. For the 2030 scenarios, this surplus is addressed as part of the SMILE demonstration by integrating the fluctuations through sector integration and storage, resulting in an 85 % share of RE supply. The identification of barriers and conditions on Samsø is closely related to the technical advances at the demonstration site. It consists of the development of a smart harbour at the Ballen Marina with new PV panels, electricity storage and various flexible consumption technologies and customers. Besides those, Samsø's energy system with high wind power production, but also export, is further influencing the resulting barrier identification and policy design.

Samsø already has a special demonstrator position within the Danish energy system development and research, presenting opportunities to the island [35], such as allowing certain exceptions to national rules and common models, e.g. for district heating [20]. Among opportunities is also the existing handling of local energy balances, since Samsø has an agreement to use two slightly different ones, depending on the needs and aims. In one, the wind power production from Samsø's offshore wind farm is considered fully integrated and part of the Samsø energy system. In the other, the production is considered outside the island and an external part, influencing also the local responsibilities in that regard.

Due to its island status, Samsø has introduced various bottom-up initiatives, though always remaining within the realm of municipal and national regulations. Similar engagement can be found on Orkney in the British and on Madeira in the Portuguese contexts. However, a contrast lies with Samsø being well integrated into the Danish energy system via its two transmission lines. Therefore, the national legal framework on energy applies to Samsø applies - such as the Electricity Supply Act (*Elforsyningsloven*). The consequences of this situation are further detailed in [36]. Existing barriers at national level also affect Samsø, mostly regarding capacity limits to transmission lines and the need for local optimisation and integration of the energy system.

Within SMILE, Samsø demonstrates a specific solution for the integration of locally produced electricity for consumption within the same parcel, the Ballen Marina. It is comparable to other smaller or household-size island solutions, yet a roll out to larger size is suggested, e.g., to integrate the locally produced wind power in a smart way as well, which could also be relevant to other islands. However, ownership structures of RE facilities are mentioned as a potential barrier on Samsø, as they are constantly changing towards more complex and external structures, instead of clear, local ownership with local benefits. Further discussion of Samsø's demonstration project and implications on barriers and recommendations is presented in line with literature and the interview review in Section 3.2 and following.

3.1.2. Review of Orkney

In the Orkney reference energy system, 17 % of the energy is provided with local RE. Despite the remaining energy provided by fossil fuels, 32 % of the local electricity production is currently modelled to be exported, while in reality a large share of that is even curtailed. The demo sites on Orkney within the SMILE project focus on smart heating, heat storage and transport solutions for the better integration of local wind power production. This results in a RE share of 38 % in the future 2030 scenario of Orkney.

In order to identify barriers and recommendations, these demo sites are therefore discussed in the Orkney context, before relating them to the other islands. Specific to Orkney, besides the local wind production, is the complexity of the electricity grid, which encompasses the transmission line to the mainland as well as a circular distribution grid across the 20 islands of the archipelago to connect many small and large production sites. The cable connection to mainland entails that the national legal framework on energy also applies on Orkney [36]. Therefore, the British as well as the Scottish legal regimes apply, following the split of competences between the two. Conversely, since the Brexit, EU law does not apply anymore. This situation is neither found on Samsø, which does not have underwater connection cable issues, nor on Madeira, which does not have such a line at all and cannot rely on one due to its distance to the mainland.

The increase in grid and energy system complexity is mentioned by the island representatives as a limiting factor in regard to engaging and supporting the local stakeholders appropriately to their, as well as the overall islands', benefit. The main concern is the conflict of interest between local users and the distribution system operators, as well as to fit technical solutions, including the SMILE ones, into the overall system and plans. Therefore, while national regulation prevails, local flexibility and education is needed for better alignment of national with local

strategies and policies.

Similarities can also be found with Samsø, as ownership structures of local production and conversion technologies are shifting and uncertainty with regard to the future develops with the energy transitions to high RE shares. For example, the 'smartness' of technologies is mentioned, as collaboration between consumers and providers requires actual interaction with people's home and privacy for a future smart energy system. For that, community capacity-building schemes and strategies are proposed to align the overlap of private properties with communal goals and strategies. Especially new technologies, like electric storages for smart heat production requires understanding of future heating opportunities and limits. With economic barriers often existing in remote areas, the ownership of power production as well as flexible consumption assets, including the heat installs and EVs related to SMILE, needs further discussion.

While the inputs from Orkney are further reviewed in the Section 3.2 onwards in line with literature and identified barriers, general similarities of the individual experiences across all islands can be identified. For example, the alignment of local development on islands, with national – here Scottish and British – and sometimes supranational strategies is needed, as the demonstration projects also have the potential for influencing policy design on a larger scale.

3.1.3. Review of Madeira

On Madeira, 11 % of the energy system is supplied by RE in the reference system. Due to having no transmission cables to the mainland, the current system has to limit its RE exploitation or face curtailment. With the SMILE project addressing electric transportation and storage solutions, the RE share for 2030 is modelled to reach 31 % for Madeira. The review of policies for Madeira has its starting point with that technical transition. Being an EU's outmost region without a cable to the mainland results in a legal exemption from the electricity market. This allows EEM, the 100 % Madeira Regional Government-owned company to integrate production, transport, distribution and supply of electricity [36]. The island's Government and Parliament are also developing their own policies and regulations, under the control of the continental authorities, such as the Portuguese national energy regulatory authority's (ERSE).

Changes in the energy system in relation to the SMILE demonstration, and thereby their relevance for policy design, are similar to those on Samsø and Orkney, as local electricity production and balance is the main concern. However, due to the island's isolation and limited options in that regard, are not only technological change on Madeira met with regulatory obstacles, but time perspectives and economic feasibility have also a strong impact on the possibilities and changes needed for the energy transition. Issues are mentioned in regard to investments, as technologies are too expensive in the short-term, but too difficult to plan in the long-term. Hence, the need for appropriate economic incentives is discussed to support the sensitive energy system on Madeira, as well as in other remote locations.

As Madeira already demonstrates a significant need for flexibility and freedom through its isolation, further alignment of technological advances with policies to support this is highlighted. The SMILE demonstration on Madeira addresses this need for enhanced flexibility by investigating improved PV power integration and balancing, as well as opportunities created by the electrification of the transport sector. Much of the Madeira pilot projects are addressing specific needs and solutions for Madeira, though a better regulation for PV and EV charging installations and exploring balancing options is needed for the transition to high RE shares in general.

More specific details and suggestions of Madeira from literature and identified barriers are reviewed in the next sections, though general alignment of technical changes with institutional opportunities can already be highlighted. While Madeira presents a specific energy system set-up, the use of demonstration potentials and exploration of loopholes could be replicated elsewhere.

3.2. Literature review and barriers

The literature review is based on the above-presented technical transitions on the islands. The resulting identified policy areas were introduced to representatives across Samsø, Orkney and Madeira to collect responses from them.

Generally, some agreements and similarities are identified on the islands, but also many disagreements and deviating perspectives both among the islands and with the general literature introduced in Section 1. To address this gap between literature and applicability on islands, Table 1 presents where common literature recommendations misalign with the perceptions of the island representatives. Policy should be redesigned to address the misalignments between existing policies and the special situations identified on islands.

General agreements between the islands' representatives and general literature – and therefore excluded from Table 1 – consist in recommendations for the state to provide municipalities with planning instruments for them to function as energy planning authorities [37], to regulate public participation for transparency [38], and to include community energy priorities and engagement in plans [39]. These recommendations are important to every local planning level and especially valuable for isolated energy systems and communities. Furthermore, agreement was found with the need to design energy poverty policies according to spatial characteristics [40,41] and citizen employment and ownership should be factored in [42] and even encouraged for relevant investments in RE [43].

Main disagreements were identified for policies mostly applicable to isolated systems, like Madeira, compared to not-isolated/well-integrated islands, like Samsø and Orkney – and vice versa. Furthermore, special needs particular to islands were sometimes identified and agreed upon, while other times these could not be found. Although disagreements may be due to limited knowledge by the representative or due to actual differences, Table 1 shows that agreement across the three islands is not often found. This underlines the overall deviations from general literature and approaches applicable to islands, and thereby, difficulties in designing European policies across various locations, despite their similarities in other aspects.

In Table 1, many deviations from general literature recommendations can be made out, either across all islands, or with at least one. At the same time, six out of 20 statements can be either fully confirmed of partially found applicable to all islands, especially within the general planning recommendations. Where there is a disagreement between the islands, a potential of collaboration can be identified; by understanding if and how a situation is handled elsewhere, good practices can be reproduced on other islands. The importance of local level engagement further underlines the significance of a socially fair approach to energy transitions across all policy areas.

However, Table 1 shows a potentially temporary situation across the islands, depending on technologies found in place or the level of plans for the local future developments. Nonetheless, a tendency can be singled out showing difficulties in finding an alignment between general and island-specific recommendations, which is elaborated upon also in Table 2 and the following sections.

3.3. Identified barriers from interviews

Besides the general literature study and review to identify barriers, and as part of the second round of interviews, the island representatives were given the option to supply input to the five policy areas with regards to barriers and solutions for the energy transitions on their island. Afterwards, the other two islands' representatives were asked about the applicability to their island. The resulting barriers are presented in Table 2 and the individual areas are further discussed below, before the solutions are presented in Section 3.4. As Table 2 indicates, the order of barriers is not structured but follows the responses collected, and the sub-sections follow this accordingly.

The barriers that were identified by one of the islands and reviewed by the other islands in Table 2 show an agreement across all islands in nine out of 14 identified barriers. In three further cases, differences can be identified for Madeira, showing alternate possibilities overcoming the barrier. Samsø and Orkney could thereby find potential solutions to their issues with split metering, participation in supply market and incentives schemes. Likewise, Madeira and Orkney can find a good practice regarding community groups engagement on Samsø. Finally, the last barrier might be particular to Orkney with issues of large-scale integration in its rural geography.

The following five (Sections 3.3.1–3.3.5) address in further detail the qualitative inputs from the interviews within the five policy areas.

3.3.1. General planning

Based on the answers provided by Samsø, Orkney and Madeira's representatives, a lack of integration between local energy plans and electricity network planning has been outlined, since both are operated at different scales and over different periods. More specifically, the electricity network investment plans are scheduled at a fixed period (every two years with perspective for investment for 5–10 years for the case of the UK [[66] (Art. 32)]); thus, new interventions (e.g., new local energy plans) during this period are not taken into consideration, apart from some rare cases.

Another barrier that was mentioned is the lack of engagement with stakeholder, including citizens, local authorities and institutions, in the effort to modernize the electricity system into a dynamic smart distribution network, in which a wide range of players will provide grid services. In addition, there are inexistent or inefficient incentives from central governments to promote and create communities (composed of e.g., customers, local businesses, and institutions) that would contribute to the design and development of smart flexibility services to be subsequently offered to local distribution system operators (DSO). In this regard, the island of Samsø is perceived to be slightly different as local citizens are particular engaged by following a series of formal local events (e.g., public meetings, hearings, political committee decisions, etc.).

In Samsø and Orkney, split metering of electricity consumption – separated measurements for different types of consumption with potentially varying tariffs according to the types and/or time of the day or week – for different uses is not permitted; thus, consumers are obliged to receive electricity only from one supplier, which usually excludes local electricity suppliers to the benefit of large national ones or more importantly excludes the direct supply from a local producer. The 2019 electricity market directive [66], however, introduced the option for consumers to conclude an aggregation contract with any actor without the consent of the supplier, enabling to buy and sell energy services to aggregators (art. 13).

It should be noted that while split metering is an approach that may further local exploitation of RE sources, it also comes with issues. As analysed in [63], while local optimisation can be a good solution for some parts of the energy system or indeed for user acceptance or engagement, it can also come at the expense of wider system optimisation. In general, in RE-based electricity systems, optimizing local systems will cause sub-optimisation in the wider energy system. On the other hand, of course, if the surrounding system is not RE based, then there is a clear option for local optimisation.

The existing legal framework on the three islands may in certain cases limit the penetration of new local RE suppliers, who could contribute to the DSO's capabilities. An example is the citizen energy communities which have recently been transposed from EU to Danish law [67]. Yet, the above-mentioned barrier to split metering could be an issue for these structures. Similarly, there are regulations governing the supply of electricity that require energy suppliers to address high costs. As a result, local and small energy suppliers are unable to participate on even terms in the supply market.

Finally, as a generic barrier, the electricity sector's exclusiveness was acknowledged by all representatives. Specifically, the highly technical and complex framework that often surrounds this sector adversely affects citizens engagement, limiting public participation.

3.3.2. Technologies

It is a common belief among the representatives that the performance of the energy systems and the energy-saving achievements depend significantly on consumer behaviour. Thus, the lack of consumer education and awareness limits the effectiveness of innovative energy solutions (e.g., heat pumps, energy storage systems). It has been observed in many cases that prerequisite measures may have been set but they are not always implemented, and as a result, owners could not achieve energy savings or decrease their energy costs.

All the island representatives support that smart technologies remain relatively expensive with a return on investment on technology markets being quite long, and thus also some entrepreneurs have difficulties meeting return expectations. Especially in remote and peripheral areas, where few suppliers operate and long supply chains are observed, the maintenance or repair services' economic sustainability is under question. At the same time, local owners of wind turbines continue selling their shares to large external companies, while the majority of consumers is already supplied from non-island suppliers.

3.3.3. Markets

At Samsø and Orkney, there is an incentive scheme only suitable for large-scale producers which is designed to guarantee RE participation to the balancing electricity market via specific auctions. There is no equivalent or similar scheme for small-scale energy producers, limiting the potential of further RE development. There is no doubt that the electricity supply sector is heavily regulated and market conditions are demanding for new entrants. Even the option of providing flexibility services to electricity grid operators and other stakeholders is only really accessible to large-scale energy generation. Further elaborated in [67], the minimum bid size is 1 MW for balancing services markets, higher for some other services, and markets are non-existent for local services that can be offered by small producers/flexibility owners (such as voltage regulation). An alternative could be large scale aggregation of many small loads, but it is at an immature level and no incentives are available. While article 32 of the 2019 electricity directive requires local flexibility markets to be set up by DSOs, these are often still non-existent [66]. Thus, the energy supply market is not currently designed to facilitate small and local energy suppliers of energy and flexibility services, even though this option is now part of Danish law.

On Madeira, the EU legal framework for electricity and RE sources is being transposed. Although the electricity system remains operated by EEM, small producers, customers and communities benefit from increasing legal recognition and potential action. For example, since early 2021, it is possible to create RE communities, but specific regulations still need to implement it.

3.3.4. Citizens

It has been noticed that there is no statutory procedure for participatory energy planning on any of the three islands. Thus, key players (e.g., DSOs) are not required to exchange opinions with residents and follow a top-down approach, which discourages potential citizen engagement actions. On the other hand, bottom-up initiatives from citizens which do not have a specific legal basis are often impracticable, because they have to comply with municipal and national planning. Samsø applies a combination of the two approaches (bottom-up and top-down) in an effort to keep engagement and realism aligned, besides the lack of legislation.

Another barrier is the lack of awareness in terms of smart technologies, distributed energy generation and energy efficiency due to misinformation or lack of interest. Therefore, the engagement process becomes even harder for local citizens and communities. On top of that, there are neither organized community schemes nor optimal guidelines

on how energy communities could engage and develop. Exceptions include the above-mentioned options for citizen energy communities in Denmark and RE communities in Portugal with the current lack of practice and detailed rules for implementation.

3.3.5. Ownership

A lack of financial and regulatory support for private and community ownership of smart energy systems is identified in all three islands. More specifically, there is a lack of reliability in terms of commitment in the case of smart energy systems ownership, when the equipment needs to be located on private properties. For instance, the residential installations of a project need to be protected from unexpected disengagement of the homeowner in order to avoid a potential business failure. This is the case when for example a battery, that requires years of operation to benefit the project and meet business model funding, is fitted to a property. From another point of view, the technologies that are being installed should principally meet the home's requirements and effectively operate with regard to the household characteristics.

A barrier of similar importance regarding smart energy systems is the current capital and operating costs compared to the return on investments, despite providing a variety of benefits to the relevant stakeholders. Another barrier for smart energy systems which is identified only at Orkney is that large-scale energy systems (e.g., wind turbines) have complicated levels of acceptance. There must be enough head room on the grid for the DSO, a satisfying business model for the operator, and adequate buy-in by the local residents. For instance, there is no doubt that ensuring the wind turbine function under "smart" mechanisms (with external control) will assist the network operator by verifying that the local grid is not overloaded while generating time and revenue are maximized; however, there is no observed benefit for the local residents unless they own shares.

It must be noted that on all the islands, but mostly on those connected to a mainland, a shift from local ownership to external, corporate ownership takes place. There are legal grounds for offering partial local ownership of a RE project, up to a certain point. In general (at least for the three islands), the municipality cannot require that a developer establishes a common monetary fund, but it can recommend establishing one in order to gain public acceptance. In order for local people to take part, get a sense of ownership of the project and to receive benefits, energy communities can also be mentioned.

3.4. Policy design recommendations

The overall presentation and review of barriers for the demonstration islands individually as well as commonly results in the following energy policy recommendations. On the one hand, these are based on the recommendations that were suggested during the interviews with the island representatives and reviewed for better alignment of local requirements with national and international policies. On the other hand, the interviews reflect the current situation and changes of the technical scenarios and energy transitions on each island, while aiming at general recommendations for all islands and energy transitions of similar scope. While the policy areas all identify options for changes in different areas, a combined approach transcends not only the islands, but also the relevant aspects of the energy system transition.

Recommendations in line with the general planning and legal framework entail general alignments, not only of islands or between islands and mainlands, but furthermore within the different policy areas. Here, a bridge can gap the technical scenarios and solutions, existing research and developments, as well as suggestions and policies for transitions on islands. Firstly, it is recommended to align the administrative and organisational parts of operation and planning of the energy and electricity system, also with the technical aspects of production and consumption. Secondly, the alignment of planning and legal aspects with other policy areas must be addressed; with technologies and markets, as well as with citizens and ownership. And thirdly, more transparency in energy policy-making, especially in small communities like islands.

In line with the barriers mentioned above, where general perspectives are discussed, a specific solution to one of the general planning issues is the split metering, as particularly pointed out in the interview. It is suggested to enable split metering, since it could possibly increase the penetration of local RE supplies. Yet, as also mentioned in Section 3.3.1, split metering has its own issues and is currently not permitted in many places. It can be added that small-scale energy suppliers are usually unable to participate on even terms in the market. To fix this issue, network codes at EU level and detailed regulations at national level need to be amended, e.g. to lower the minimum bid size on flexibility markets, as well as to create local flexibility markets as required by article 32 of the 2019 electricity directive.

A suggested solution for the technology barriers was to raise awareness regarding the energy system operation and to adopt typologies-practices, such as load-shifting to take advantage of solar PV production and/or to purchase 'smart' appliances that can be set to start during peak-production, in order to ensure the optimal use of the applicable technologies. Another suggested solution for the technologies is that central governments support more locally led financing models, applicable to smart technologies, to drive down the capital costs through collective or bulk purchase of equipment and installation services. For example, EVs are one of the main technologies implied under smart technologies to integrate transport with other sectors or to provide flexibility. In the case of EVs, different types of incentives should be promoted to support their adoption: special household energy tariffs for EVs and promotion of "green cities" encouraging sustainable mobility, e.g., banning combustion vehicles from cities' main roads, offering free parking lots for EVs, promoting car sharing, electrifying the public transportation sector, promoting bike-sharing.

As mentioned in Section 3.3, incentives need to become available for large scale aggregation of many small loads to the advantage of the market. Another solution for the identified market barriers could be the promotion of alternative business models (e.g., the creation of energy communities accompanied by special benefits) and new energy arrangements (e.g., Demand Response) in order to foster a more active participation of energy consumers in the energy market. The promotion of relevant business models can indeed foster a more active local participation in the island energy systems. However, specific incentives have to be provided and new enabling legislation has to be laid down in order to facilitate the activity of small and local energy suppliers. Additionally, the above-mentioned flexibility markets under general planning recommendations are also applicable here, as well as the importance of citizens in energy markets, as elaborated in the following.

Solutions to the citizen barriers include various forms of engagement. Even if the development of democratically-based local energy plans and markets are at a very early stage, sufficient investment could roll them out in parallel with the setting of relevant legislation. Information sessions and Q&A with specialists, as it has successfully been done on Samsø, could be a solution to overcome these obstacles. Citizens and communities could benefit from the development of strategies and information tools to raise awareness on energy relevant topics. Sufficient investment and even technical support from national or regional level can accommodate the effective roll out of local energy plans. Additionally, local energy planning should be incorporated in the national legislation as obligatory for local authorities, which should be consulted for private energy investments in their region. As pointed out in 3.2, improving the financial incentives for citizens could also make the energy system's development more robust.

For the ownership barriers, adapted regulations need to be drafted for recovering the financial damage in the event of a homeowner leaving the project. Another solution that transpired through the interviews could be to foster shared or community ownership of smart energy technologies and co-finance the expenditure costs to spread the risk among various stakeholders. Meanwhile, technology manufacturers are

already imbedding control mechanisms within smart energy systems. For example, an operator of a cloud-based aggregator platform would be able to incorporate these technologies reducing overheads to the operator. Another paradigm is the UK government's grant mechanism on EV chargers which for now supports only the purchase of those enabled for control over an internet connection. Consequently, this leads to the creation of a charging network that could be monitored and/or controlled in the interest of homeowners too, reducing their mobility costs while reinforcing the value of shared assets. This could not only be a solution for well-connected islands, but also for non-interconnected islands, like Madeira, facing difficulties to foster optimal operation of energy systems (from the consumers' perspective), as their management requires coordination by the grid operator.

More specifically regarding ownership, there is a common method used by wind turbine planners and operators to provide financial shares to a local community organization in order to reduce the risk of local resistance. To promote support for wind turbines there would be some incentives for the homeowners or the local community to benefit from such mechanisms. For example, a platform to pair the operation of the wind turbine with domestic or community level energy systems and consumption. The first step including incentives was partly achieved by introducing that energy suppliers are required to provide dynamic electricity tariffs that benefit homeowners and communities which are willing to displace their time of electricity consumption to match the RE generation. As long as the complexity of such mechanisms is not met by a financial scheme to benefit all parties, external funding will be critical. Furthermore, a fair application across stakeholders must be paid attention to with the increase of flexibility capital through new possibilities within ownership and tariffs in the electricity sector [68].

These suggestions and identified misalignments lead to the overall policy recommendation to design pathways of better inclusion of and alignment with small and local energy actors. This would directly benefit island communities. It would be even better if regulation and policies would be adapted to the specific situation of islands, in light of their local possibilities and limits in the transition to higher RE shares. This alignment can improve the technical knowledge from and for islands, as well as their recognition at all institutional levels.

4. Conclusion and policy implications

In order to support the transitions to high RE shares on the three islands of Samsø, Orkney and Madeira, as well as islands and regions with similar characteristics elsewhere, general policy literature, framework conditions and replication opportunities were reviewed. This represents an important part of the energy system transition with its corresponding implementation issues that technical changes deal with. Both technological demonstration projects and scenarios are analysed in the three island energy systems, as well as the requirements for policy alignment as part of a better inclusion of social dimensions evaluated. Despite focusing on a selection of islands, issues and recommendations which could be further elaborated upon in future research, this study supports the implementation of the necessary steps in the transitions to high RE shares from both technical and institutional perspectives.

Island representatives were interviewed based on relevant literature for policy alignment requirements and suggestions, and inputs from Samsø, Orkney and Madeira compared and analysed. While the three islands show many differences, similar observations were made across the islands with regards to current barriers and potential solutions. However, Samsø applies Danish national regulations, Orkney follows both Scottish and UK law and Madeira has its own regime, differing to an extent from the national framework, making it difficult to find transcendent institutional barriers and design European policies accordingly. The literature and interviews, from which the policy recommendations emerge, encompass five thematic areas, which are addressed separately, though overlaps do exist. Generally, there is a lack of alignment between policy literature and applicability on the islands, implying that those need to be adjusted to include islands in the global energy transition.

Arguing for a better alignment between European or national policies and islands' situation in the transition to higher RE shares, the recommendations address general as well as specific policy design suggestions for the better integration of islands. These include better integrating technologies, simplifying their implementation in both private and public areas, allowing the establishment of local initiatives such as bottom-up planning, simplifying the integration of more RE, promoting local and alternative approaches to local issues with more freedom, shifting legal rights and ownership for enhanced local inclusion, and creating local flexibility markets for small actors. The result is an overall recommendation of taking local circumstances into account to include islands in national and international planning, with improved structures, information and support for islands in light of their local possibilities, as well as limits. The resulting discussion of similarities and differences between islands is important, rather than discussing the islands individually throughout the analysis. At the same time, technical scenarios are specific to each island, setting the frame for a combined approach to align across islands and to underline that the islands seem different between each other, but in comparison to the mainland, they have more similarities than differences.

Concluding, the transition to higher RE shares on the islands of Samsø, Orkney and Madeira as well as in other similar geographies is supported by the review of technical analyses and their institutional alignment with policies. By addressing this through stakeholder engagement on three different islands across Europe, barriers and solutions were identified and potential development pathways and solutions presented, implying a need for better alignment between local and island circumstances and wider policy design.

Declaration of competing interest

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

Data availability

data and relevant references to previous studies are available in the manuscript

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