The Best of both Worlds: Social and Technical Challenges of Creating Energy Islands

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Abstract: Creating so-called "energy islands" with a high level of energetic self-sufficiency is one strategy to fight climate crisis. To become a realistic goal, such a concept needs trans-disciplinary research that defines promising transformation paths towards reaching this vision. The presented paper introduces a conceptual framework that provides approaches for technical optimization across all energy vectors, socio-technical optimization of the usage of energy demand flexibility, socio-psychological interventions, and a replication strategy that considers all these different aspects. The focus lies on the architecture of a management system that answers requirements also from social sciences, on engagement strategies and on defining a cross-vector, cross-disciplinary design for flexibility in terms of demand-response schemes.

1 INTRODUCTION

We are in the midst of a climate crisis. The impacts will endanger the lives of millions of people around the world, so a plethora of ideas to limit climate change by reducing the emissions of CO2-equivalents are currently being developed. One of the approaches is to start from geographically delineated, inhabited areas and develop strategies for net-zero GHG emissions. The origin of this idea lies in the CO2 footprint concept: if people consume a lot more energy than can be generated locally in a CO2 neutral way, there will not be enough "space" for everybody. If it can be shown further that such strategies are socio-techno-economically viable, they can be replicated elsewhere, finally creating a network of sustainable districts, cities, or villages. This approach results in the concept of (urban) "Energy Islands" (EI) and has a high overlap with the concept of renewable energy communities (REC), with REC potentially being the organizational side of an EI. The authors of this work define an urban EI in the following way: *An urban EI is a geographically delineated system that is largely self-sufficient across all present energy vectors. Given a pre-existing energy infra-structure, this implies to maximize local generation and optimize its distribution, and it means to optimize demand across all energy vectors, adapting demand profiles as necessary, both by shifting demand temporarily and reducing it absolutely. From an organizational and social point of view, the EI is inhabited by people living or working there, who are the end-users of energy. They are tied to the EI through their energy usage patterns and directly and indirectly by contracts. EI inhabitants can contribute*

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individually, in the context of collective energy actions, and in the context of energy communities (EC) to EI objectives.

The differentiating factor between self-sufficiency and autarchy is the role of the EI in the context of energy grids: if necessary, the EI draws power from or injects into the external grid, providing ancillary grid services. So, it can be an active part in a cell-based system of interdependent EI cells that together form the mesh of the future energy grid, characterized by a high share of renewable energy sources (REN) and partially flexible energy demand. The electricity vector of an EI might be technically implemented by a micro-grid with a local energy market[1].

The clear goal of this definition avoids the pitfalls of energy efficiency objectives where, quite regularly, efficiency gains are compensated by increasing demand, enabled by a seemingly increased financial or resource-based budget. Thus, this "rebound effect" cannot emerge. From a social viewpoint, pursuing EI objectives can take different organizational forms: Collective energy actions are depending on "the collective involvement of energy consumers or prosumers" (DECIDE Consortium, 2022), and ECs are a subset thereof involving continuous group interactions (Bielig et al., 2022). Also, individual behaviour changes are an option – which concept to apply where and when is part of the set of social challenges of creating and operating EIs.

To start such a transition this endeavour requires a truly trans-disciplinary approach: energy flows must be optimized cross-sectorally, based on data science and ICT communication, the technical approach must make economic sense and be legally feasible, and most of all, it must not only be accepted but truly supported by the inhabitants. Thus, every system aimed at achieving such goals has to build upon a fruitful interconnection of the different disciplines: ICT, energy physics, law, psychology and sociology as well as business economics. This insight is the foundation of the EU H2020 project RENergetic that considers all these issues, while putting the island inhabitants into the centre of activities. These basic requirements result in the following actionable tasks:

- Technical optimization of supply across all available energy carriers, here: heat, electricity, and electric mobility
- Socio-technical optimization of the usage of energy demand flexibility across all available energy carriers, to adapt demand to currently available energy supply
- Socio-psychological interventions, including incentives, for reduction of energy demand when overall yearly demand exceeds overall yearly supply
- To achieve a real-world impact, replication needs to be integrated into modelling.

These tasks are reflected in the sections of the presented paper: related work is discussed in section 2. Section 3 deals with the creation of an EI from a trans-disciplinary viewpoint, i.e., engaging EI inhabitants, optimizing supply, managing demand temporarily, and finally reducing demand. Section 4 presents a replication framework, and section 5 draws conclusions for future work.

2 RELATED WORK

The term EI has been mostly used in the context of real islands that have a severe challenge of being off-grid and aim to decrease their dependency from fossil fuels (e.g (Droege, 2012; Riva Sanseverino et al., 2014)). The idea of urban EIs has entered into the discussion only recently, mainly in the context of a case study of the University of Genua (Bracco et al., 2018), however, without defining the term "urban energy island". The technical, and partially also business, challenges have been mainly dealt with in the context of "positive energy districts" (e.g. (Monti et al., 2017)) or "multi energy districts" (review in (Martinez Cesena et al., 2020)). An operating perspective is given within discussions about energy management systems. Energy management systems in modern buildings control installed equipment and are often used for energy optimization. Combining such systems with IoT concepts makes it possible to use data from the sensors for data analytics and forecasting. Generation units can also exchange information through ICT architecture, which enables provision of ancillary services in the electricity grid (Stocker et al., 2022). As a result, optimization algorithms can be applied to balance both supply of distributed renewable energy resources and energy consumption of smart build-ings, taking into account uncertainty of the sources (Saatloo et al., 2022). Disjunct from this is the discussion about energy communities, which is often characterized by the analysis of drivers and barriers from a governmental, legal, or behavioural points of view (e.g. (Bauwens &

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Devine-Wright, 2018; Walker, 2008)). There are hardly any works that try to reconcile the challenges of geographically defined EIs and socio-economically defined EC, arriving at a holis-tic framework for creating and operating an EI.

An exception is presented by Bukovszki et al. 2020 (Bukovszki et al., 2020) who identify so-called progression-factors (i.e. desired characteristics) of EC and match them with building energy modelling decision support tools. However, also in this work, the operation of an EI is not treated nor the required change of energy related behaviour of the inhabitants, contrary to the trans-disciplinary methodology in the work presented here. This approach requires understanding how to motivate people to both engage in the EI and change their behaviour, not only once but by adopting new habits. This is done best through a collective lens: evidence shows that participatory and community-based approaches in the diffusion of renewable energy technologies promote broader acceptance and support innovation (Berka & Creamer, 2018).

Intrinsic motivation to engage and change behaviour is required. One way is to leverage the social identity model for pro-environmental actions (SIMPEA; (Fritsche et al., 2018)), which describes the relevance of social identity related factors (e.g. social identification, collective emotions, social norms) for pro-environmental decision-making and collective action. Meta-analyses (Schulte et al., 2020; Udall et al., 2021) demonstrated strong links between social identification both on individual and group level and intentions for pro-environmental behavior.

Using inherent demand side flexibility can be one reason for behaviour change. For decades, demand response (DR), i.e. the planned activation of demand side flexibility, has been discussed from strictly disciplinary points of view: either technically, as e.g. optimizing transformer load curves or minimizing the usage of reserve energy, for various different use cases be it electric vehicles (Klingert & Lee, 2022; Sadeghianpourhamami et al., 2018), data centres (Basmadjian et al., 2018), or any electrical load (Subramanian et al., 2013). Or it has been viewed from a behavioural viewpoint: While there are many studies which investigate shifting electricity usage (e.g. (Kacperski et al., 2022; Laura M. Andersen et al., 2017)), DR acceptance in heating is less researched. This is critical, as flexibility for shifting behavior in heating seems less acceptable than for electricity usage (Spence et al., 2015), although heating accounts for the majority of energy usage in Europe. Therefore, a unifying DR model, merging the views of different disciplines, automation levels and energy vectors, is missing.

3 CREATING ENERGY ISLANDS

As mentioned, creating EIs needs the technical concertation and optimization, and socio-economic support of the affected inhabitants.

3.1 Involving EI Inhabitants

The question is - how can the local population be incentivized beyond simple acceptance to participate, take responsibility, and actively contribute and invest in community energy actions? In order to define an involvement strategy for the RENergetic project, we build on literature from psychology and sociology for collective pro-environmental actions (SIMPEA, (Fritsche et al., 2018)), technology acceptance (e.g. UTAUT/UTAUT2, (Venkatesh et al., 2003)), behaviour change (e.g. COM-B, (Michie et al., 2011)), and trust (Mayer et al., 1995). Two additional sources of information are a) to investigate involvement strategies in different types of collective actions, such as human rights movements or protests and b) to analyse success stories in related areas as positive energy districts or real islands (e.g. (Droege, 2012). For example, for the Samsø EI, "soft topics, such as the political and socio-cultural context, planning processes, communication and local ownership" have been named to have been the keys to its success (Sperling, 2017).

The goal is to develop and test a toolbox approach (Figure 1) to integrate the social aspects of EIs within the technical framework, building on well-established theories from psychology and sociology (level 1). As evidence shows that there is no "one-size-fits-all" tool to bring about social change (Hewitt et al., 2019), on level 2 a context analysis needs to be carried out, analysing the "situational context", i.e. environmental or technical constraints, motivations and needs of stakeholders, and defining the required level of involvement. For the latter different methods and tools are tested and evaluated through randomized controlled trials whenever feasible.

Communication and collaboration instruments in the RENergetic pilot activities are selected based on three main guidelines:

- Consideration of the local social identity and, if possible, build on it (Fritsche et al., 2018)
- Trustworthiness, i.e. transparency and consistency, in order to show good-will and assure the ability to implement communicated plans (Mayer et al., 1995)

- Usage of general and local social norms for communication, to encourage connection with the social environment (Perlaviciute, 2022).

Figure 1: The RENergetic Toolbox.

3.2 Matching Supply and Demand

The main challenge of an EI is to "make ends meet" regarding energy at all points in time. There are a lot of examples of districts claiming to be "climate neutral" or "energy positive", in terms of producing more energy than is consumed locally during some period of time. But, they are still dependent on the national grid or on fuel deliveries as they consume energy at different times than they produce it. This is already a very big step forward – however, it is still only half-way towards the overall goal of being self-sustained and additionally delivering ancillary services to an external grid. In order to achieve this overall goal, energy supply needs to be optimized, supply and demand need to match at all times, and finally, if demand in general exceeds supply, beyond mere efficiency, energy demand needs to be reduced. In RENergetic, the technical support of EI activities is provided by the RENergetic platform serving the abovementioned functionalities for heating and electricity (including EV) domains. To integrate these functionalities, it is proposed to use the service-oriented architecture shown in Figure 2. Each service is a software element that performs a specific functionality, for example forecasting, optimizing, DR services for heating. A service might interact with other services, the data storage and the interactive platform. The API and Access Management service is responsible for orchestrating the operation of all other services. It also provides an API for communicating with external systems. Most services are implemented using Java Spring Boot framework, although each service could utilize a different software stack. For example, forecasting and optimization services utilize Kubeflow platform. Services are managed by WSO2 software, and the API follows OpenAPI specifications in order to ensure compatibility with other systems. The user management service relies on the Keycloack software and is used to control access of users to the different parts of the system. The service architecture allows the system to be flexible. It is important because not all EIs have necessary data or systems required for the operation of all services. In case some functionality is not needed, the corresponding service could be excluded from installation. The service-oriented architecture also simplifies future system extensions. For instance, if optimization in an additional domain is required, a new service for that can be developed.

The RENergetic Platform provides an API for communicating with the EI systems using the Data Acquisition service which is based on Apache NiFi software to ingest data from EI devices supporting different protocols. The data from EI sensors and meters, as well as forecasts and other types of time-dependent data are stored in time series database inside RENergetic platform. Metadata, user related data and connections between different assets are stored in relational database. Utilization of two different databases provides an efficient way of storing and accessing different kinds of the data.

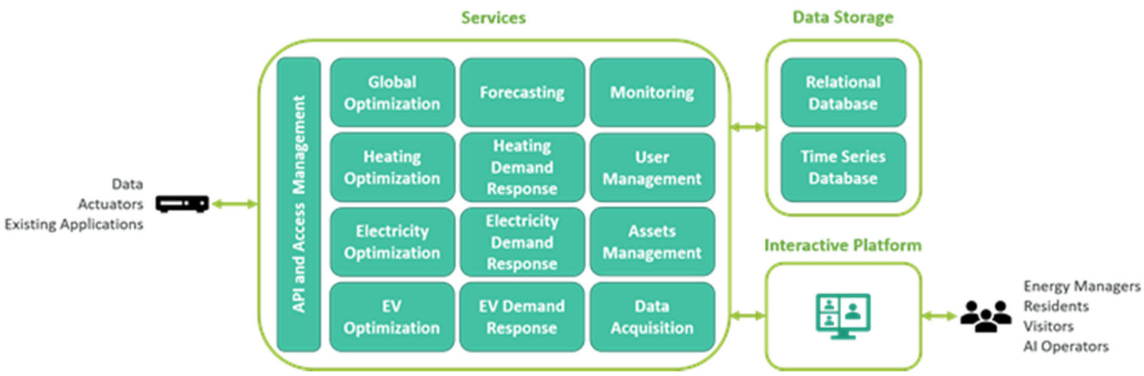

Figure 2: An Energy Island Architectural Framework.

In RENergetic, the PostgreSQL and InfluxDB are chosen as relational data storage and time series storage, respectively. All services are defined in line with the requirements of the social-science work

3.2.1 Energy Supply Optimization

With the transition of the energy system, the different sectors are becoming ever increasingly coupled. While this all being similarly true for heating, electricity and mobility, the significance of electricity as the connecting link between the different sectors deserves particular attention, as evidenced by phenomena such as e-mobility, heat-pumps based heating systems or combined heat and power plants. Therefore, an overarching global optimization across sectors is key to overall sustainability. At the same time, each sector requires specific optimization due to its particularities. Consequently, results an iterative multi-layer optimization architecture. As an example, let us assume a shortage in natural gas both for electricity and heat imposing restrictions both on electricity and on heat consumption. At the same time, electricity may be an energy source of heat via heat pumps or pure resistance driven heat production, resulting in a complex interaction pattern for global optimization on the supply side within a “web of energy”.

An optimization of supply-and-demand matching in the context of EIs is particularly challenging for the electricity domain, as matching has to be done instantaneously with very limited storage or buffering capacity and due to the dynamic nature of AC electricity. It is performed in two forms, proactively and reactively. By approaching 100 % renewable supply, one of the key questions becomes to identify and procure the sources of flexibility that can best be exploited for the “matchmaking”. This key question is arguably challenging in the context of EI with limited expansion and resources in order to achieve a maximum level of self-sustainability. Arguably the most promising resources of flexibility are due to demand-side management within the web of energy, resulting in strategies for the adaptation of both heat and electricity demand as a main focus of the RENergetic project. In contrast, a procurement of flexibility resources usable for reactive compensation of imperfect predictions seems harder to be found on the load side but rather on the supply side. Therefore, it was decided to investigate these supply side resources prototypically and selectively in a laboratory setting based on smart converters with power electronic interfaces to the grid in order to provide ancillary services to the EI and, possibly, to the preceding grid as well. By means of droop curves, the potential of grid supporting actions via power supply adaptations are investigated and feasibility is investigated in terms of technical, social and regulatory conditions in various pilot studies. While the main focus being here on primary reserves provisioning, preliminary studies on grid forming for voltage control of EIs are also performed. For the sake of complexity and effort, other EI specific ancillary services such as protection, inertia or harmonic filtering, and are left for future studies.

3.2.2 Demand Response

Optimization is almost entirely a technical challenge whereas sufficiency is almost entirely a behavioural issue (e.g., buying more efficient products or reducing the consumption of energy services). Contrary to that, DR in many cases requires a complex interconnection of data science, adaptation algorithms, communication and behavioural reactions of the end-users if it is supposed to be tapped to its full potential. This implies a trans-disciplinary approach. Traditional DR concepts as e.g. the European Commission’s DR definition (European Commission, 2013) have two major drawbacks in the context of urban EIs: 1) They relate only to electricity, which is derived from the history of DR that originates in electricity grid quality issues. For other energy vectors such as heat, this idea has not yet been fully explored. 2) DR has until recently only been discussed in the context of different, but unconnected electricity use cases such as resident DR, data center DR or EV DR, missing an overarching conceptual approach.

Therefore, in this work we extend the concept in two ways: comprising all available energy vectors, targeting both energy end-users and managers as intermediate users and interconnecting use cases. This requires a conceptual model that positions and connects these different issues. Due to the overall guiding principle of replication this should be done in a way that it can be instantiated into different use cases that are configurable for different EI projects.

An overarching model for DR needs to contain the following main design elements to allow for a full exploitation of its potential (Figure 3):

- Automated vs. manual DR: This describes the trade-off between automation that relieves people from the burden of taking active decisions but at the same time limits end-users’ autarky in decision making. Automated DR implies communication and actuation of pre-defined steering points for power in-/decrease.

End-users are not actively involved in the implementation of each adaptation process, but to increase technology acceptance, they should be invited to configure the system at the start of the adaptation period (e.g. a contract period). Automated DR is driven by technology (data science, algorithms) and gives the control to a central operator so that it comes with a high level of certainty of the flexibility harvest. Manual DR, on the other hand, requires end-users as e.g. home owners, tenants or EI energy managers to actively manipulate their power consumption upon being requested to do so. For the operator requesting flexibility, manual DR implies a lower level of certainty of the flexibility harvest.

- Trigger: Depending on the use case and energy vector, a trigger needs to be defined that starts a DR event, which implies the existence of a trigger metric and a threshold. This metric might be used to differentiate between automated and manual DR.
- Use Case: This is the context in which DR is applied, e.g. residential electricity consumption, bulk charging of EV fleets or the heating of a building complex. The use case characteristics include the main flow of actions, the corresponding stakeholders, business model as well as the legal framework of the DR solution.
- End-user rights and duties: Mirroring automated vs. manual DR, end-users rights and duties can be manifold, be it periodical configurations or over-riding rights for automated DR vs. information or capacity rights for the case of manual DR.
- Business and legal issues: The higher the level of duties and responsibility for either side, the higher the share of the system-wide benefit they will want to have. Depending on the data available and on the different options of end-users to participate in a DR program, incentives might be created. These might be financial or non-financial, as e.g. CO2 reduction information or a planned community event.

To our knowledge this is the first model of its kind, that integrates behavioural, technical, business and legal aspects into a concept of DR.

3.2.3 Reducing Energy Demand

One major problem when engaging people in energy related pro-environmental behavior is the rebound effect (Sorrell et al., 2009), which reflects a negative behavioral spillover where one pro-environmental behavior decreases the likelihood of other pro-environmental behaviors (Truelove et al., 2014).

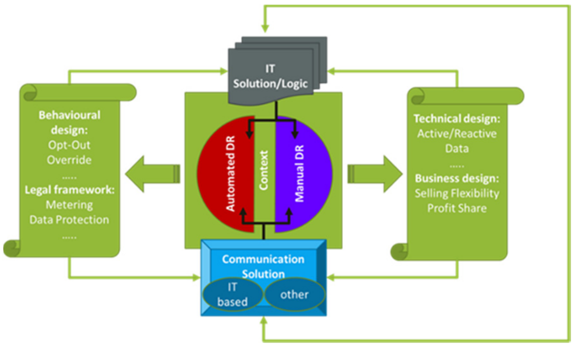

Figure 3: A Trans-disciplinary Framework for DR.

The RENergetic approach, integrating both technical and social aspects, particularly targets to counteract this effect, going beyond technical optimization and efficiency measures to reach a positive spillover, i.e. the activation of further pro-environmental behaviors based on a first one. A meta-analysis (Truelove et al., 2014) showed that the two main aspects which account for positive spillover are consistency and identity. Thereby, building on the SIMPEA model and fostering a high level of behavioral involvements, our approach aims to build a foundation for the development of a social identity related to the EI, which can then reinforce social norms and positive behavioral spillover instead of rebound effect. Collective pro-environmental activities can foster a social identity which activates social norms in further group situations.

4 REPLICATION

Replicable results are a key goal of innovation efforts and one focus of the RENergetic approach. In a sense, the RENergetic pilot actions are designed as the first replications of the developed solutions, following the core principle of the replication package of providing general solutions to be applied in specific contexts. In a first step towards developing a replication methodology a definition of "replicability" in the RENergetic context is needed. To this end, reproducibility and replicability need to be distinguished. *Reproducibility* means that results can be *reproduced by a different team using the original team's tools or software artifacts*. Whereas *replicability* means that results can be replicated by a *different team using their own tools or software artifacts*.In the RENergetic project a variety of solutions will be developed and provided via the RENergetic platform. These are designed to be reproducible, that is the software developed by RENergetic is to be taken as is and utilized by other teams to reproduce the intended results. However, these software modules need a certain context in order to be able to function as desired. This context, which is the sum of all technical, infrastructural, social, economic, and legal framework conditions is highly specific and not easily (or even impossible to be) reproduced in another site. Following from that the framework conditions, the context in which the RENergetic modules are operable, will need to be replicated by any follower site that intends to utilize the RENergetic solutions.

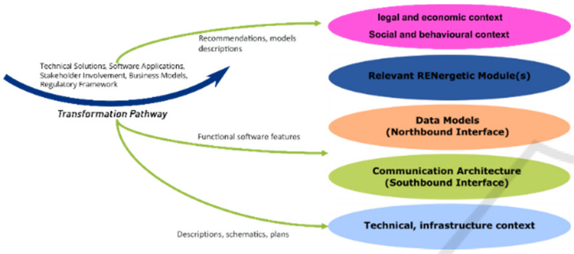

Figure 4: An Illustration of an EI Transformation Pathway.

For the replication methodology the concept of the "Transformation Pathway" (Figure 4) has been developed, which is the sum of all interventions that carried out to achieve the sustainability goals of a given EI. It is important to note that this does not only include technical interventions, but also all social, behavioural, and economic actions that are needed to accompany the base technical solutions.

As all these provided solutions need the correct technical, social, legal and economic context in order to be meaningfully deployed, the RENergetic replication package does provide a methodological toolset to replicate this needed context - infrastructure, social, legal and economic – in order to successfully reproduce the results from the RENergetic pilot sites. To build on already established concepts, the framework provided with the SGAM methodology was chosen as basis for the replication methodology which makes use of all five layers of the SGAM model. This approach allows for a standardized comparison of different approaches, paradigms, and viewpoints. The SGAM methodology is not only applied to the electric but also to the heat domain, resulting in multi-energy vector SGAM reference models of the RENergetic solutions.

5 CONCLUSION

As a summary, it could be shown that the RENergetic approach to defining a socio-technical framework for an EI operation merges the expertise from the respective disciplines in an over-arching way: specifically with regards to DR, behaviour change, incentives, communication guidelines, and constructing RENergetic DR services in the platform are tightly integrated. Next steps will be mainly the refinement of the first drafts to global optimization, as well as socio-technical DR designs for the main RENergetic use cases, i.e. EV DR, heat DR and electricity DR, based on both data availability and results from first ongoing user experiments. This will be done in-line with the requirements from the RENergetic replication package, both for ICT and social science components.

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