JUNE 2020

FLEXSUS MODEL TOOLBOX

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VERSION 1.0

INTERNAL REFERENCE

Deliverable No.:	D 3.1 (2020)
Deliverable Name:	FlexSUS model tool-box
Lead Participant:	DTU Management
Work Package No.:	3
Task No. & Name:	T 3.1

DOCUMENT STATUS

	Date	Person(s)	Organisation
Author(s)	2020-06-09	Russell McKenna, Fabian Scheller	DTU Management
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ABOUT ERA-NET SMART ENERGY SYSTEMS

ERA-Net Smart Energy Systems (ERA-Net SES) is a transnational joint programming platform of 30 national and regional funding partners for initiating co-creation and promoting energy system innovation. The network of owners and managers of national and regional public funding programs along the innovation chain provides a sustainable and service oriented joint programming platform to finance projects in thematic areas like Smart Power Grids, Regional and Local Energy Systems, Heating and Cooling Networks, Digital Energy and Smart Services, etc.

Co-creating with partners that help to understand the needs of relevant stakeholders, we team up with intermediaries to provide an innovation eco-system supporting consortia for research, innovation, technical development, piloting and demonstration activities. These co-operations pave the way towards implementation in real-life environments and market introduction.

Beyond that, ERA-Net SES provides a Knowledge Community, involving key demo projects and experts from all over Europe, to facilitate learning between projects and programs from the local level up to the European level.

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1. INTRODUCTION AND OVERVIEW

The main objective of FlexSUS is to support city planners and decision-makers in their cities' transition towards climate-friendly economies by giving them an array of options in planning and designing low carbon solutions. FlexSUS achieves its objectives by developing a decision support platform that answers the following questions:

1. Which are the common protocols and semantics that facilitate the integration of different models and tools in the decision support platform?

2. Which methods and techniques can be implemented towards robust and effective optimal energy-system planning, which considers all relevant sectors, actors and energy vectors, as far as possible employing open data?

3. How can the developed methods be integrated with a participative planning process, that not only they reach cost-optimal solutions, but also to consider the 'softer' preferences and desires of the wider stakeholders in the context of the cities' targets and objectives?

4. Where is the balance between a detailed tailored solution and a generic one that is easily scalable? What are the drawbacks of each solution and how this can be translated into technical terms?

5. How can the central decision support platform be developed to enable both expert and non-expert user modes, whereby the former enables a more flexible configuration and operation, and the latter employs default settings and focuses on communicating different solutions to the general target audience?

Against this background, this deliverable presents a review of energy system models developed and applied to municipal-scale energy systems. The objective is thereby to identify and address gaps and weaknesses of the models as planning tools from the urban actor perspective. This report presents a synthesis of previous publications in this area by the authors (* indicates a FlexSUS-related output):

- Weinand, J. M. (2020): Reviewing Municipal Energy System Planning in a Bibliometric Analysis: Evolution of the Research Field between 1991 and 2019. In: Energies 13. https://doi.org/10.3390/en13061367

- *Weinand, J., Scheller, F., McKenna (2020): Reviewing energy system modelling of decentralized energy autonomy, Energy, 203, 117817, https://doi.org/10.1016/j.energy.2020.117817.

- *Scheller, F., Burkhardt R., Schwarzeit, R., McKenna, R. (2020): Competition between simultaneous demand-side flexibility options: the case of community electricity storage systems, Applied Energy, 269, 114969, ttps://doi.org/10.1016/j.apenergy.2020.114969.

- Scheller, F.; Bruckner, T.: Energy system optimization at the municipal level: An analysis of modeling approaches and challenges, Renewable and Sustainable Energy Reviews (2019) 105: 444-461. DOI: 10.1016/j.rser.2019.02.005.

This Deliverable is structured as follows: after this introduction, section 2 summarizes the findings of Weinand et al. (2020) and Weinand (2020) on energy system modelling applications to decentralized autonomous energy systems; section 3 characterizes selected models for municipal energy system analysis, based on Scheller & Bruckner (2019), Weinand et al. (2020) and additional analysis; and section 4 provides a summary of the main findings and an outlook for future developments.

2. ENERGY SYSTEM MODELLING APPLICATIONS TO DECENTRALIZED ENERGY SYSTEMS

The energy transition aims at decarbonising the energy system by introducing more renewable energy technologies, which results in partly-stochastic supply. This can cause temporal and spatial mismatches between supply and demand that lead to an increased requirement for storage and energy infrastructure respectively. The energy transition also requires demand reduction and energy efficiency all along the energy value chain. In this context, energy system planning is becoming increasingly relevant for decentralised systems (Weinand 2020). Consequently, the number of publications on municipal energy system planning has increased exponentially between 1991 and 2019, amounting to 1,235 at the time of writing. China is the most important contributor with 225 articles, followed by the USA (205), whose total number of publications also has the highest h-index (33), and Germany (120). Furthermore, the *Sustainable Energy Planning Research Group* of the Aalborg University in Denmark led by Henrik Lund seems to play a central role in municipal energy system planning according to the global and local citations of articles. The core journals on municipal energy system planning are *Energy, Applied Energy, Energy Policy, Energies* and *Renewable Energy,* which published 37% of the 1,235 articles. By far the most articles were published by *Energy*, while *Applied Energy* has the highest h-index (33). In addition, the journal *Energies* has experienced the strongest increase in the number of publications in recent years and published the most publications on the subject for the first time in 2019. The most relevant subject among the *Web of Science* categories is energy fuels, while the analysis of the *Author keywords* shows that municipal energy system planning focuses mainly on *renewable energies, optimization* and *hybrid energy systems*. Furthermore, district heating seems to be a core topic in municipal energy system planning: two of the most relevant authors (Henrik Lund and Brian Vad Mathiesen) address this subject and three of the top five most cited articles focus on district heating. It is also the most frequently stated technology in the journals *Energy, Applied Energy, Energy Policy* and *Energies* as well as among the *Author keywords* and thus seems to be a crucial technology for the energy transition at the municipal level (Weinand 2020).

Weinand et al. (2020) reviewed energy system model applications to analysing decentralised autonomous energy systems – whereby autonomy here relates to electricity and is defined as either complete (off-grid) or annually balanced. The paper investigated a total of 359 studies, of which a subset of 123 in detail. Most case studies apply to middle-income countries and only focus on the supply of electricity in the residential sector. Furthermore, many of the studies are comparable regarding objectives and applied methods. By analysing the studies, many improvements for future studies could be identified:

- Mostly conventional/established energy technologies are analysed, with less attention paid to emerging but potentially game-changing technologies such as deep geothermal energy and fuel cell vehicles;
- The sectoral focus is on residential, with much less consideration of industrial and transportation sectors;
- Network infrastructure is rarely considered, including electricity, gas and heat/cooling;
- Only a minority of studies account for the existing infrastructure as well as the transition from this state to some improved future state along a pathway;
- Most studies focus on complete energy autonomy (i.e. off-grid), with some (12%) dealing with balanced energy autonomy.

3. OVERVIEW OF EMPLOYED MODELS FOR MUNICIPAL ENERGY SYSTEM MODELLING

This section presents an overview of selected energy system models for municipal energy systems. It does not purport to be comprehensive, but as mentioned in the introduction it draws on the main insights from Scheller & Bruckner (2019) and Weinand et al (2020). We note here that other generic modelling frameworks such as TIMES may also be applied at the municipal level, but intentionally do not include them in this analysis, as they represent an application/instance of a framework rather than a model tailored to the municipal level. In this context, reviews of energy system models regarding different spatial, temporal, and contextual resolutions are presented by Connolly et al. (2010), Huang et al. (2015), Tozzi and Ho Jo (2017), Keles et al. (2017), Ringkjøb et al. (2018), Groissböck et al. (2019). Scheller & Bruckner (2019) characterize Energy System Optimization Models (ESOMs) for municipal energy systems by analysing their capabilities with respect to municipal energy systems – Integrated Multi-Modal Energy Systems (IMMES). These energy systems are affected by spatial, cross-sectoral, technological, structural, social, economic, conceptual, environmental and institutional issues and interactions. They employ the working definition as follows: an IMMES enables the integrated operational optimization of technical and environmental energy chain processes of multiple energy fuels, carriers and services in a multi-energy system network by simultaneous consideration and coordination of the social, economic and institutional network of relationships of market actors in a spatial context. Based on the IMMES definition, various system entities and system dynamics are in form of characteristics derivable, as shown in Table 1. Even though such a categorization is only a conventional one, the elaborated characteristics represent requirements to comprehensively design municipal energy system models. In order to perform well in municipal energy system modelling, a particular tool should perform well in all of these characteristics, but compromises are inevitable.

Table 1: Requirements employed by Scheller & Bruckner (2019) to characterise models of Integrated Multi-Model Energy Systems (IMMES)

Characteristic	Description	Examples
Spatial anchoring	Physical space of the municipality defining the system boundaries.	• land-use planning patterns: placement and potential of energy installations like e.g. wind power plants are dependent on the available areas in the municipality • material resource assessments and limitations: due to the fact that resources (e.g. biomass) are limited in absolute terms and in rates of resource uptake, this can result in a limited availability or usability for the energy system
Network topology	Technical and commercial interconnection of system elements.	• municipal layout modelling: this includes the ability to set up a (decentralized) energy supply and demand system by coupling the necessary processes, e.g. with the help of a directed graph approach and a physical stock and flow resource network • hierarchical scheme: this includes different system levels to integrate spatial effects, e.g. system, zone, sub-zone and building type
Commercial actor	Market participant from which distinct activities are derived.	• stakeholder with different interest criteria: availability of different commercial actors with differing technology component, process-mediated relationship, e.g. households or communities, energy producers, energy suppliers, service providers, aggregators, balance responsible parties, policy makers • equity and distributional effects: changes in energy supply structure can have significant impacts of ownership, governance, and the welfare and fairness of system stakeholders, one example is energy poverty
Actor activity	Distinct services along the energy chain provided by social actors.	• multi-party cooperation: actors of the municipality hold bilateral contracts between each other that handle business transactions, e.g. approaches to represent price formations and commercial relationships • technology acceptance and adoption: some technologies like e.g. wind face local oppositions and new technologies like e.g. heat pumps are only slowly adopted by consumers. This question aims at the model's capability of reflecting these consumer choices, adoption and resistance to technologies. • lifestyle aspects: this includes the influence of different and maybe changing lifestyles to consumption patterns of the different energy services resulting in relative and absolute changes in energy demand, e.g. rebound effect
Coordination strategy	Decision rules for optimizing actor activities concerning their conditions.	• management framework: management framework to coordinate actions and contains operational coordination mechanisms, e.g. innovative framework design allows for the merger of technical and facilitates

		allocations when costs and benefits do not boil down to the same actor • modular and adaptable modelling systems: options to choose only parts of the model / only one actor perspective for certain applications and adjust it to the user's needs • multi-criteria and multi-level decision approaches: evaluation of multiple criteria in decision making from different stakeholder perspectives
Engineering component	Technical system components from which relevant processes are derived.	• demand side and supply side technology heterogeneity: this includes differentiations between available technologies that consume and generate energy like e.g. different engine types or different heating systems • innovative storage possibilities: this includes the availability of different storage systems, e.g. heat storage in district heating, hot dry rock technologies or hydrogen caverns
Energy service	Outbound energy portfolio that components can provide.	• multi-energy carriers: multiple outbound energy and material portfolios that demand, conversion, storage and transmission technologies can utilize • cross-sectoral approaches: integrated considerations of the sectors electricity, heat, mobility and industry and the technologies that can connect them like e.g. power-to-x-approaches
Primary fuel	Inbound energy portfolio that components can utilize.	• multi-materials: availability of multiple and innovative inbound material possibilities generation and conversion technologies can utilize like e.g. coal, gas, biomass • non-conventional energy supply sources: this includes potential sources for electricity, heat and mobility like e.g. waste/excess heat or any other sources that could broadly be considered as supply
Technical process	Functional characteristics of a specific component along the energy chain.	• detailed technology process models: this includes modelling of physical and thermodynamic properties of generation and conversion technologies, like e.g. steam temperatures of steam turbines • innovative storage modelling: this includes a detailed modelling and differentiation between storage systems of different sizes, carriers, and possible modes of operation • heat and power network characteristics: modelling heat and power networks in greater detail • consumption process models: this includes modelling of physical and thermodynamic properties of demand technologies, like e.g. the industrial process of steel manufacturing where specific temperatures are required
Operation status	Service mode of a specific component along the energy chain	• dynamics of start-up modelling and ramping capabilities: this includes modelling of functional technical limitations of generation and conversion technologies through binary variables for the online

	(with the help of binary variables).	and offline behaviour, like e.g. maximum ramping up speed of a turbine • reheating processes: mathematical framework for integrating the temperature drop and rise of e.g. thermal units and thus the off-time dependent start-up costs
Smart metering	Connection points required to measure bundled load capacities.	• power connection bundles: innovative future business models might also give more weight to a capacity charge instead of energy rate; this includes modelling of respective bundles of technologies for measuring the capacity of different technologies at a certain timestep or over a certain period • capacity charge: possibility to measure the maximum power consumption of individual technologies considering various power connection points of final consumers with different technologies
Market principle	Construct of regulatory and product requirements without market reference.	• regulatory and policy frameworks: this includes modelling the influence of different regulation and policy measures in terms of different business models, like e.g. direct consumption and direct marketing • ancillary services and spinning reserve: for maintaining grid stability and security, operation requirements and restrictions might be necessary for specific plants or the whole energy system • virtual power plants: aggregation of the capacities of heterogeneous distributed energy resources to enhance generation possibilities
Environmental issues	External setting which influences actor behaviour and component processes	• weather effects: this includes the consideration of weather or climate effects in terms of renewable energy sources • nexus issues: land/energy/water/food: there are interdependencies and trade-offs between the use of land and water for energy and food, like e.g. using farm land for energy crops or limiting water availability due to water plant installations. • non-energy sector impacts: this could e.g. include consideration of life cycle impact assessments and waste management initiatives

Based on the characteristics from Table 1, Scheller & Bruckner (2019) characterised a total of nine IMMES as follows:

- deeco - Dynamic Energy, Emission, and Cost Optimization model (Bruckner T. 1996, Bruckner et al. 1997, Bruckner T. 2001, Bruckner et al. 2006)
- xeona - Extensible Entity-Oriented Optimization-Based Network-Mediated Analysis model (Morrison et al. 2004, Morrison et al. 2005)
- DER-CAM- Distributed Energy Resources Customer Adoption Model (Stadler et al. 2014)

- EnergyHub Model (Geidl M. & Andersson G. 2007, Geidl M. 2007, Krause et al. 2011, Mohammadi et al. 2017)
- urbs - Urban Research Toolbox: Energy Systems Model (Dorfner J. 2016, Dorfner J. 2020)
- KomMod - Kommunales Energiesystem-Modell (Urban Energy System Model) (Eggers J-B. 2017, Eggers J-b. & Stryi-Hipp G. 2013, Stryi-Hipp G. & Eggers J-B. 2015)
- MMESD - Multi-Modal On-Site Energy System Design Model. (Thiem et al. 2017, Thiem S. 2017, Thiem et al. 2015)
- RE3ASON - Renewable Energies and Energy Efficiency Analysis System Optimization (McKenna et al. 2018, Mainzer et al. 2014, Mainzer et al. 2017)
- IRPopt – Integrated Integrated Resource Planning and Optimization (Scheller et al. 2018, Kühne et al. 2019, Scheller et al. 2020)

For a detailed description of each of the models, the reader is referred to the original publication. Here we focus attention of the characterisation of these models according to the criteria in Table 1, as presented in Figure 1 below.

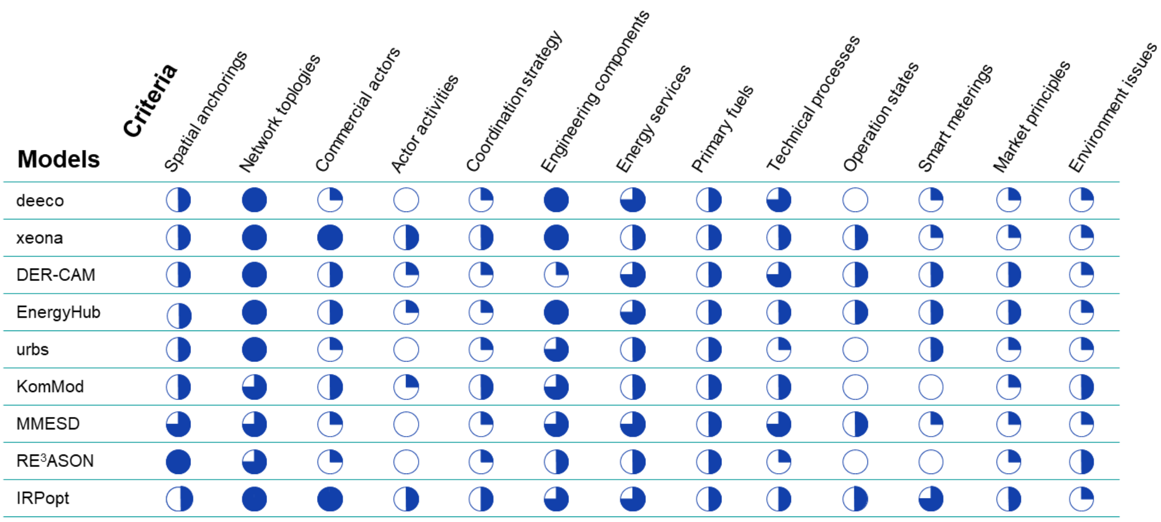

Figure 1 Evaluation of selected ESOMs with respect to the IMMES criteria from Table 1, from Scheller and Bruckner (2019)

From Figure 1 the following general observations can be made:

- Most models perform capacity and/or dispatch optimisation based on a minimum-cost approach.
- Most of the models have a good to very good consideration of **spatial characteristics**, whereby REA3SON has the highest level of detail due to the automatic/GIS-based retrieval of spatial characteristics of a selected municipality, based on open data from Bing maps and Open Street Map.

- All models have a very good or excellent consideration of **energy network topologies**, with the majority of models employing directed graphs to connected nodes within the system.

- In general, the nine considered models are not strong in the **consideration of commercial actors' activities and coordination strategies**. The exceptions here are xeona and IRPopt, which both include approaches to represent price formations and commercial relationships, based on agent entities of sufficient sophistication to allow a good consideration of these aspects.

- The models represent **engineering components (e.g. heat pumps) and technical processes (e.g. energy conversion)** in different degrees of accuracy – here deeco and MMESD are the superior models. However, it should be mentioned that dispatch only models are more likely to show a higher temporal resolution.

- Most of the reviewed models are relatively weak when it comes to **smart meterings** and further **market principles**, especially their capability to integrate smart meter data at the household level or above – here IRPopt is the exception – which means their temporal resolution is generally quite rough. The same applies to balancing service provision.

- Most of the models are quite weak when it comes to considering the **contextual aspects**, i.e. all economic, technical and social dimensions of the context in which the municipal energy system is located. In this respect, Kommod and RE3ASON perform best.

Two additional models that are frequently employed for municipal energy system analyses are HOMER and EnergyPlan. EnergyPlan is essentially a dispatch optimisation tool for a given energy system configuration, whereas HOMER is a simulation model which employs heuristics to determine the best ("optimum") scenario from several depending on the selected criterion (e.g. minimization of costs or fuel usage) (HOMER Energy 2019). This explorative approach to identifying a pareto front does not necessarily yield the optimal solution. The vast majority of the studies reviewed in Weinand et al. (2020) here in which HOMER is used have a similar structure: First, the economic parameters, the load profile, as well as the renewable potentials and the energy system under consideration, are described for a particular application. The best energy system is then usually selected on the basis of costs (97% of cases). Analyses based on this model typically focus on case studies rather than methodological innovations. In three studies, newly developed methods were compared with the HOMER model. The results showed that a Biogeography Based Optimization (BBO) algorithm (Kumar et al. 2013), a Genetic Algorithm (Javed et al. 2019) or the so-called LINGO model (Kanase-Patil et al. 2010) perform better than the HOMER model in terms of computing time and minimization of costs. The BBO algorithm, for example, found a better solution than HOMER and reduced the computing time from 15 h to 0.7 h (Kumar et al. 2013).

Of the eleven above-considered models the following additional characteristics can be noted (for references see bullet points above):

- Data requirements: the data requirements of the models depends very much on the specific research questions and application. In general, most of these models employ large amounts of public and proprietary data at the municipal level, and they typically rely on merging multiple datasets alongside expert assumptions to fill in the gaps. It is challenging to generalize about the models' data requirements without also specifying the application and/or research questions.
- Open source data and models:
  - Fully open source: urbs and deeco
  - Open access model: urbs, DER-CAM, EnergyHub, HOMER and EnergyPlan
  - Open data: most of the reviewed models use data that is specific to the application/research questions. Only RE3ASON employs open geospatial data that is in principle globally available.
- Capacity and/or dispatch optimisation:
  - The following models do both: DER-CAM, EnergyHub, urbs, Kommod, MMESD, RE3ASON
  - The following models perform a dispatch optimization: IRPopt, deco, xeona, HOMER and EnergyPlan
- Transformation pathway: this list contains examples, as a definitive categorization is difficult here:
  - Considered: RE3ASON
  - Not considered: Kommod, HOMER, EnergyPlan

4. CONCLUSIONS AND OUTLOOK

The number of publications on municipal energy system planning has increased exponentially between 1991 and 2019, amounting to 1,235 at the time of the analysis in Weinand (2020). The study shows that the most relevant subject among the Web of Science categories is energy fuels, while the analysis of the Author keywords shows that municipal energy system planning focuses mainly on renewable energies, optimization and hybrid energy systems. Furthermore, district heating seems to be a core topic in municipal energy system planning: two of the most relevant authors (Henrik Lund and Brian Vad Mathiesen) address this subject and the three of the top five most cited articles focus on district heating. It is also the most frequently stated technology in the journals Energy, Applied Energy, Energy Policy and Energies as well as among the Author keywords and thus seems to be a crucial technology for the energy transition at the municipal level.

In addition, research attention on decentralized autonomous energy systems has increased exponentially in the past three decades, as demonstrated by the absolute number of publications and the share of these studies in the corpus of energy system modelling literature. Most case studies were conducted in the middle-income countries India, Iran and

China as well as the high-income country Germany. In the middle-income country studies, mostly remote rural areas without an electricity network connection are considered, whereas in high-income countries the case studies are much more diverse and also include cities and islands. In addition, most studies only focus on the residential sector and the supply of electricity. A wide range of technologies has already been covered in the literature, including less common technologies such as power-to-gas and fuel cell vehicles. However, the network infrastructure is rarely considered. The levelized costs of electricity for local autonomous energy systems in 83 case studies amount to 0.41 $/kWh on average. Thereby, studies are identified in which the resulting costs should be questioned, as they deviate strongly from the average.

In terms of the employed methodology, most of the reviewed literature on decentralized autonomous energy systems reports an optimization or simulation approach, with a central planner perspective. They typically employ a time resolution of one hour, but for some studies also increase this to 15-minute resolution. Whilst it is commendable that some of the studies also consider non-economic criteria such as social and environmental aspects, neither the system-level impacts nor the diverse stakeholders are included in most works. Furthermore, there is a general lack of transparency across most reviewed literature, meaning that neither open data nor open models are widely applied to local energy systems.

Selected ESOMs already cover a wide range of required system characteristics. Different implementation approaches define an excellent foundation for further model development. At the same time, none of the assessed models addresses all the requirements as summarized in Table 1. In view of the results of the analysis conducted in this research, the following key issues need to be considered for an advanced mapping of an IMMES:

- Integrated view to provide opportunities for participating communities and actors: only one model, Scheller et al. (2018), above allows an actor-oriented optimization. This overcomes the problem of a single, central planner perspective (Scheller & Bruckner 2019, Weinand et al. 2020).
- Multi-layered approach to capitalizing on the market and statutory benefits of renewable energy projects, which should include at least technical/physical, economic/market, agent/social and information layers (Scheller & Bruckner 2019, Scheller et al. 2020)
- Spatial planning and mapping in GIS, as far as possible with public/open data to ensure transferability of methods (Scheller & Bruckner 2019)
- Non-economic criteria and impacts, such as social (e.g. technology adoption) and environmental (e.g. material input, water use) aspects should be improved (Weinand et al. 2020)
- Transparency with open models and open data, including validation, needs further attention (Weinand et al. 2020)
- Models need to analyse parallel revenue streams and the cannibalization effect of competing storage opportunities, especially in different frameworks, with different ownership/business models and considering social dimensions of technology diffusion (Scheller et al. 2020)

Ultimately, though, the choice of model depends largely on the research questions and objectives as well as data availability

FUNDING

This document was created as part of the ERA-Net Smart Energy Systems project FlexSUS, funded from the European Union's Horizon 2020 research and innovation programme under grant agreement no. 646039 (SG+) / no. 775970 (RegSys).

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