Designing an Explainable Techno-economic Assessment Software for Household Energy System: a Case Study for the newTRENDs Project

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by

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ABSTRACT

Text...

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Notations and Abbreviations

CO_2 Carbon dioxide. 1

EE Energy efficiency. 3

EU European Union. 2, 3, 23

GHG Greenhouse gas. 1–3

HP Heat pump. 5, 6

NAPE The National Action Plan on Energy Efficiency. 3

PV Photovoltaic. 4–8, 15, 17

RE Renewable energy. 3

SEMS Smart energy management system. 4, 5

Chapter 1

Introduction

Human-induced climate change is causing dangerous and widespread disruption in nature and affecting the lives of billions of people around the world [15]. To tackle climate change and its negative impacts, two main strategies are addressed: climate change mitigation and adaptation.

- Climate change mitigation means cutting and sequestering emissions of greenhouse gases (GHG) to prevent further increases in their atmospheric concentrations [22]. Related projects are in the areas of farming, land use, peatland management, renewable energies and energy efficiency; as well as integrated projects that implement climate change mitigation strategies and action plans at regional or national level [6]. Notably, to reduce the carbon dioxide (CO_2) emission in the energy system, we try to *(1) reduce the consumption on the demand-side by efficiency improvement and behavior change, and (2) switch the supply-side to renewables.*

- Climate change adaptation means finding ways that can help reduce the impacts of climate change on society, the various sectors of its economy, and the places in which we live [22]. Related projects are in the areas of urban adaptation and land-use planning, resilience of infrastructure, sustainable management of water in drought-prone areas, flood and coastal management, resilience of the agricultural, forestry and tourism sectors, etc. [6].

The work in this thesis falls into the first category, the climate change mitigation. Following the work in the newTRENDs project[1], we look at how the impact of "new societal trends" on the future development of the energy demand. Then, we apply the HCI techniques in designing a tool to guide decisions on household's investments in energy efficiency and renewables from a techno-economic perspective.

1.1 The newTRENDs project

The historic Paris Agreement sets long-term goals to guide all nations to substantially reduce global GHG emissions to limit the global temperature increase to 2 degrees Celsius in this century [24]. To achieve this ambitious goal, the world is facing an unprecedented imperative to a rapidly transition in the energy sector. On European Union (EU) level, "Energy 2020. A strategy for competitive, sustainable and secure energy", published in November 2010, and "Energy Roadmap 2050", published at the end of 2011, are the

[1] https://newtrends2020.eu/

most important strategy papers currently, pointing the direction for energy developments in the EU [18]. The aim is to confirm Europe's commitment to lead in global climate action and to present a vision that can lead to achieving net-zero GHG emissions by 2050 through a socially-fair transition in a cost-efficient manner [5].

Renewable energy (RE) and energy efficiency (EE) are two central strategies pursued by the EU and its Member States concerning the energy system. Investments into low-carbon power generation accounted for 15% recently are expected to rise to more than 30% by 2030, corresponding to a quadrupling in absolute volumes [3]. Solar, wind, and the investments for enabling the integration of these technologies to the grid dominate the investments into low-carbon power generation [3]. Measures to increase energy efficiency, including investments in energy savings and the consolidation of consultancy and information services, are promoted by The National Action Plan on Energy Efficiency (NAPE) [8].

Transitioning towards a sustainable energy system necessitates significant effort on both the demand and supply sides. However, previous research has shown that in many areas energy efficiency gains were counteracted by societal trends that increased corresponding activities, leading to much smaller decreases (or even increases) of energy demand than technologically feasible [4]. The aim of newTRENDs is to increase the qualitative and quantitative understanding of impacts of new societal trends on energy consumption and to improve the modelling of energy demand, energy efficiency and policy instruments [10].

1.1.1 New societal trends on energy demand

Researchers believe new societal trends have the potential to shift energy demands between sectors and might reinforce or diminish one another when they occur at the same time [4]. It is therefore important to access current and (foreseeable) future societal trends concerning the impact that they might have on future energy demand [4].

Four arising societal trend clusters that are likely to shape future energy demand in European countries (and worldwide) were established by Brugger et al. [4]: *(1) the digitalization of the economy and of private life; (2) new social and economic models, including the sharing economy and prosumaging (combination of producing, consuming and managing of energy); (3) industrial transformation, including decarbonization of industrial processes and the circular economy (including a stronger focus on material efficiency); (4) quality of life, including health effects, urbanization and regionalization.*

Considering the impact of these new societal trends on energy demand from a closer sectoral perspective, Yu et al. [26] identified four energy sectors:

- industry,
- transport,
- tertiary,
- residential.

This proposed thesis will focus on the residential sector while taking scenarios of "consumers" becoming "prosumers" (with PV) and "prosumagers" (adding energy storage and SEMS) [23] into account.

1.1.2 The modeling of residential buildings

The FLEX models of the newTRENDs project are referred to as "RC models", that calculate (simulate or optimize) the building energy demand at the hourly resolution, considering the trends of prosumaging households and energy communities, which significantly supports the analysis of relevant policies promoting the diffusion of heat pumps (HP), PV, batteries, and SEMS [26].

The figure 1.1 shows how FLEX interacts with other bottom-up models involved in the newTRENDs project.

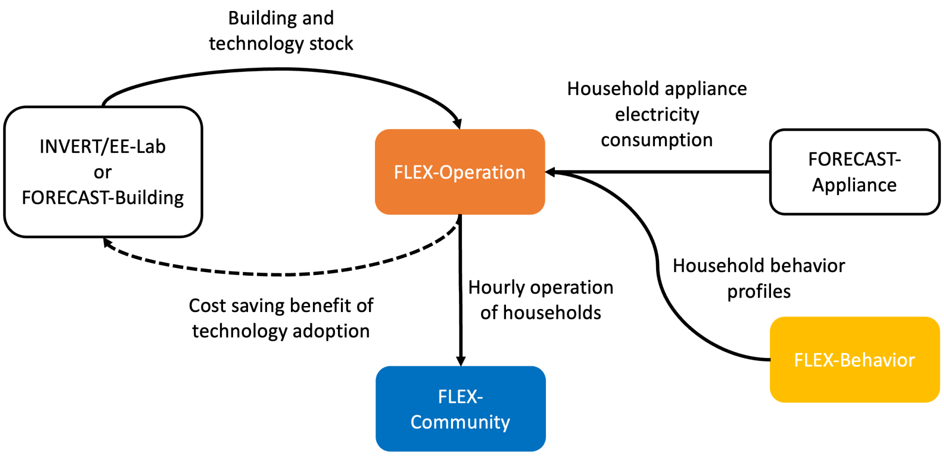

Figure 1.1: FLEX modeling suite

INVERT/EE-Lab and FORECAST-Appliance

INVERT/EE-Lab and FORECAST-Appliance are the two models that can cover the energy consumption of residential buildings. The two models complement each other and cover the total energy consumption of households.

However, both INVERT/EE-Lab and FORECAST-Appliance calculate the energy consumption at the annual resolution and cannot model the prosumaging behavior and energy community, which requires an hourly resolution to consider the impact of household behavior, PV generation, and energy storage (thermal and battery) on energy consumption. In this regard, the FLEX-Operation and FLEX-Community models were developed to improve the building modeling suite and support relevant policy analysis [26].

FLEX-Operation

FLEX-Operation models the energy system operation of an individual household in hourly resolution. It can be used to calculate the energy consumption of each representative building, including operation of technologies (e.g., battery, PV, HP, etc.) and load profiles in hourly resolution. Furthermore, FLEX-Operation can also provide implications for investment decisions, i.e., the energy-saving benefit of technology adoption [26].

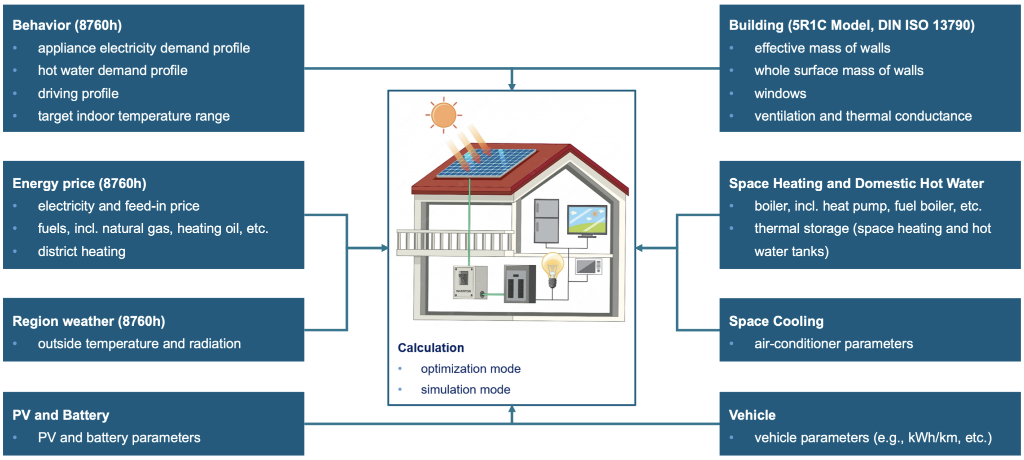

Figure 1.2: Model structure for individual households

As shown in figure 1.2, FLEX-Operation considers following five energy services [26]:

1. electric appliances, e.g., television, refrigerator, lighting, etc.;
2. space heating;
3. domestic hot water;
4. space cooling;
5. vehicle.

FLEX-Community

FLEX-Community models the operation of an energy community, i.e., household interaction, aggregator optimisation. It can be applied to support the aggregators designing and evaluating business models, as well as making investment decisions, for example, the self-owned battery, PV panels, etc. [26].

FLEX-Behavior

FLEX-Behavior models the behavior (activity profile) of households' and corresponding load profiles. It generates the hourly activity and energy demand profile of a pre-defined individual household [26]. The results include [26]:

1. appliance electricity demand,
2. domestic hot water demand,
3. driving profile, and
4. building occupation.

1.2 Motivation and aim

Buildings will play a central role in the clean energy transition [13]. High-performance buildings construction and energy renovations reduce the sector's energy use, digitalisation and smart demand-side management further reduce energy use in buildings [13]. As a part of the newTRENDs project, the proposed thesis will focus solely on the implementation of the FLEX-Operation model. The aim is to provide techno-economic assessments of configuration optimisations of households' energy systems, in order to support decision-making on technology adoption at the residential level. Despite the fact that the model primarily responds to societal trends for 2030, which means it provides more flexible integrating technology recommendations when a household already owns a PV system, this could be, as well, an opportunity to nudge European households who currently rely on other energy resources to switch to renewable energy when feasible. This project can be used to guiding decisions on the use of clean energy and energy technologies at the household level, and encouraging households to engage in energy conservation practices and investments.

1.3 Research gaps and questions

Regarding the transition to renewable energy sources, there has been a lot of study and advocacy in academy. The infrastructure has been shifted with the support of policy makers, the transformation is reaching its maturity, it is now time to motivate households to actively engage in adjusting their home energy systems.

Is there any literature review to add?

This proposed thesis attempts to answer: how HCI can help households' investment in energy efficiency and renewables from a techno-economic perspective? As well as to develop a user-friendly software for this purpose.

The following research objectives will aid in achieving the goal:

- Investigating the data required by the FLEX-Operation model.
- Identifying the typical European household types and understanding their perceptions of the household energy system.
- Designing the web application with user-centred approaches.
- Using data visualisation techniques to ensure explainability of the recommendations.
- Developing the frontend and backend web application.
- Evaluating the explainability of the recommendations from users' perspectives and measuring the impact of the households‘ perceptions towards proposed solutions.
- Allowing long-term event tracking for design iteration.

Accordingly, three subquestions are raised:

1. What are the data required by the FLEX-Operation model from households?
2. What are the typical European household profiles?
3. How to offer trustworthy and user-friendly recommendations to European households from a techno-economic perspective?

1.4 Supervision and planning

The master thesis project is worth 30 Credits at Siegen University. This proposed project will discuss both research and application aspects related to the crucial topic of techno-economic assessment. To meet the design requirements, it is expected that scientific review, data analysis, user testing, and evaluating will be involved. Thus, the project is believed to be justified for those credits.

1.4.1 Supervision

This master thesis project will be supervised by Prof. Dr. Gunnar Stevens (gunnar.stevens@uni-siegen.de) at Siegen University and Dr. Songming Yu (songmin.yu@isi.fraunhofer.de) from The Fraunhofer Institute for Systems and Innovation Research.

1.4.2 Time planning

The following is the time allocation for the research objetives, which are scheduled to be completed in 26 weeks.

1	Investigating (...)
2	Identifying (...)
3	Designing (...)
4	Using data visualisation techniques (...)
5	Developing (...)
6	Evaluating (...)
7	Allowing long-term event tracking (...)

Table 1.1: Objectives

		1	**2**	**3**	**4**	**5**	**6**	**7**
	w1							
Feb	w2							
	w3							
	w4							
	w5							
	w6							
Mar	w7							
	w8							
	w9							
	w10							
Apr	w11							
	w12							
	w13							
	w14							
May	w15							
	w16							
	w17							
	w18							
	w19							
Jun	w20							
	w21							
	w22							
	w23							
Jul	w24							
	w25							
	w26							

Table 1.2: Time planning

Chapter 2

Methodology

Introductory lines...

2.1 Design case studies

Pre-study, design, approriation.

2.2 Grounded design

A method to create concepts out of profound empirical analysis. Reduce the gap between theory and practice.

Chapter 3

Pre-study

Introductory lines...

3.1 Review

Households use energy for various purposes: space and water heating, space cooling, cooking, lighting and electrical appliances and other end-uses (mainly covering uses of energy by households outside the dwellings themselves) [7]. In 2020, households, or the residential sector, represented 27.4% of final energy consumption or 18.7% of gross inland energy consumption in the EU [7].

3.2 Input data by FLEX-Operation model

In order to accurately anticipate household's energy costs, the FLEX-Operation model takes a set of variables into account, and they can be divided into following 15 categories: *behaviour profile, battery, behaviour, boiler, building, energy price, heating element, hot water tank, PV, region, space cooling technology, space heating tank, vehicle, energy price, region weather.*

Furthermore, the specific data required within each category is shown in table 3.1.

Category	Data
Behaviour profile	id_hour, people_at_home_profile_1, hot_water_demand_profile_1, appliance_electricity_demand_profile_1, vehicle_at_home_profile_1, vehicle_distance_profile_1.
Battery	ID_Battery, capacity, capacity_unit, charge_efficiency, charge_power_max, charge_power_max_unit, discharge_efficiency, discharge_power_max, discharge_power_max_unit.
Continued on next page	

Table 3.1 – continued from previous page

Category	Data
Behaviour	ID_Behavior, id_people_at_home_profile, target_temperature_at_home_max, target_temperature_at_home_min, target_temperature_not_at_home_max, target_temperature_not_at_home_min, shading_solar_reduction_rate, shading_threshold_temperature, temperature_unit, id_hot_water_demand_profile, hot_water_demand_annual, hot_water_demand_unit, id_appliance_electricity_demand_profile, appliance_electricity_demand_annual, appliance_electricity_demand_unit, id_vehicle_at_home_profile, id_vehicle_distance_profile.
Boiler	ID_Boiler, type, power_max, power_max_unit, carnot_efficiency_factor.
Building	ID_Building, type, construction_period_start, construction_period_end, person_num, Af, Hop, Htr_w, Hve, CM_factor, Am_factor, internal_gains, effective_window_area_west_east, effective_window_area_south, effective_window_area_north, grid_power_max, supply_temperature.
Energy price	ID_EnergyPrice, id_electricity, id_electricity_feed_in, id_gases, price_unit.
Heating element	ID_HeatingElement, power, power_unit, efficiency.
	Continued on next page

Table 3.1 – continued from previous page

Category	**Data**
Hot water tank	ID_HotWaterTank, size, size_unit, surface_area, surface_area_unit, loss, loss_unit, temperature_start, temperature_max, temperature_min, temperature_surrounding, temperature_unit.
PV	ID_PV, size, size_unit.
Region	ID_Region, code, year, norm_outside_temperature.
Space cooling technology	ID_SpaceCoolingTechnology, efficiency, power, power_unit.
Space heating tank	ID_SpaceHeatingTank, size, size_unit, surface_area, surface_area_unit, loss, loss_unit, temperature_start, temperature_max, temperature_min, temperature_surrounding, temperature_unit.
Vehicle	ID_Vehicle, type, capacity, capacity_unit, consumption_rate, consumption_rate_unit, charge_efficiency, charge_power_max, charge_power_max_unit, discharge_efficiency, discharge_power_max, discharge_power_max_unit, charge_bidirectional.
Energy price	Region, year, id_hour, electricity_1, electricity_2, electricity_feed_in_1, gases_1.
	Continued on next page

Table 3.1 – continued from previous page

Category	**Data**
Region weather	region, year, id_hour, pv_generation, pv_generation_unit, temperature, temperature_unit, radiation_south, radiation_east, radiation_west, radiation_north, radiation_unit.

Table 3.1: Input data required by FLEX-Operation

Chapter 4

Design

Introductory lines...

4.1 Understanding current home energy system

4.1.1 Household profiles

The concept of household profile has been developed to provide a comprehensive understanding of the energy consumption patterns of residential buildings. This approach takes into account a range of factors, including the external environment, building materials, energy consumption behaviors, and home energy systems. The aim of creating such a profile is to gain insights into the energy demand and supply dynamics of households. This comprehensive analysis also offers insights into the specific factors that contribute to household energy consumption and highlights potential opportunities for tailored improvements to home energy systems.

4.1.2 Decision trees for asking questions

A total of 18 questions were raised to collect all the relevant information necessary for the household profile analysis. In order to optimize the user experience, a decision tree approach was employed, allowing users to navigate through the questionnaire without the need to answer all the questions.

4.2 Recommending improvements for home energy system

4.2.1 Recommendations

An effective home energy system should prioritize minimizing energy waste, reducing dependence on non-renewable fossil fuels, and lowering overall energy costs. Our recommendations are aligned with these fundamental principles and aim to promote sustainable energy practices while also reducing household energy expenditures.

The objectives of the recommendation system are multi-fold. Firstly, the system aims to support homeowners in making informed decisions regarding investments in home energy systems. Additionally, the system intends to encourage behavior change among homeowners by promoting the utilization of renewable energy sources. Finally, the recommendation system seeks to continuously refine and improve the accuracy of its predictive model, ensuring that the recommendations provided are up-to-date and effective. By providing users with tailored recommendations, the system aims to facilitate the adoption of energy technologies, ultimately leading to reduced energy demand and associated costs.

As noted by Karen Palmer et al. [20], financial considerations are of primary importance to homeowners when making decisions about energy investments. In line with this understanding, the recommendation system places a strong emphasis on providing transparent cost estimates for energy bills could be saved as well as recommended home energy system configurations. Additionally, the system seeks to encourage behavior change by providing information and education on climate change and renewable energy sources, aimed at increasing user awareness and understanding of the benefits of sustainable energy practices. To facilitate ongoing improvement and refinement of the recommendation system, a feedback survey button will be incorporated, allowing users to provide both short-term and long-term feedback on the system's performance and recommendations.

4.2.2 Explainability

In order to provide more comprehensive and understandable recommendations, we have chosen to explain our recommendations from multiple perspectives beyond just cost estimates. Specifically, we have identified user-perceived quality factors, including trust, effectiveness, education, and debugging, as key aspects to incorporate into our explanations. The overall purposes of providing such explanations are multifaceted. First, transparency is essential to provide accountability in the decision-making process, particularly in situations where users may have doubts or reservations about the recommendations. Second, building trust and confidence in the recommendation system is critical to ensure user adoption and acceptance. Third, explanations can aid in user understanding, particularly when the recommended item is not immediately intuitive or apparent. Fourth, providing users with greater control over the recommendation process can help ensure that recommendations are aligned with their goals and preferences. Finally, facilitating user learning and exploration can lead to the discovery of new items or preferences that users may not have previously considered. By incorporating these quality factors into our explanations, we aim to provide recommendations that are transparent, trustworthy, understandable, and user-centric.

Our recommendation system employs a three-level explainability framework to enhance user understanding of household energy consumption and the recommended home energy system configurations. At the first level, the system provides an end-result explanation in terms of the expected energy bill for the household. At the second level, the system offers a behavioral explanation of energy consumption patterns and the factors driving them. Finally, at the third level, the system aims to increase users' awareness and understanding of renewable energy and environmental protection.

Furthermore, the explanation process is divided into three layers: descriptive, diagnostic, and counterfactual. At the descriptive layer, users are provided with a comprehensive summary of their current energy consumption patterns. At the diagnostic layer, users are introduced to the various functionalities and benefits of the recommended energy technologies, including cost-saving potential and environmental impact. Finally, at the counterfactual layer, users are presented with simulated energy consumption data, allowing them to see the potential energy savings that could result from adopting the recommended configurations. By employing this multifaceted approach to explainability, we aim to provide users with a clear and nuanced understanding of their energy consumption habits and the potential benefits of transitioning to more sustainable energy systems.

4.3 Interactions

4.3.1 Interfaces

To facilitate user understanding of the recommended home energy system configurations and associated costs, our recommendation system will employ a visual and natural language explanation interface. Specifically, an interactive visualization tool will be implemented to enable users to explore and compare different energy system configurations in terms of energy consumption patterns and costs. Additionally, natural language explanations will be provided to further enhance user understanding and engagement with the recommended configurations.

4.3.2 Data visualisation

Appendices

Bibliography

[1] Ameli, Nadia and Nicola Brandt. "Determinants of households' investment in energy efficiency and renewables: evidence from the OECD survey on household environmental behaviour and attitudes," *Environmental Research Letters*, *10*(4):044015 (apr 2015).

[2] Anderson, Allison. "Climate Change Education for Mitigation and Adaptation," *Journal of Education for Sustainable Development*, *6*(2):191–206 (2012).

[3] Bertram, Christoph, et al. "Energy system developments and investments in the decisive decade for the Paris Agreement goals," *Environmental Research Letters*, *16*(7):074020 (jun 2021).

[4] Brugger, Heike, et al. "Energy Efficiency Vision 2050: How will new societal trends influence future energy demand in the European countries?," *Energy Policy*, *152*:112216 (2021).

[5] European Commission, "A Clean Planet for All. A European Long-Term Strategic Vision for a Prosperous, Modern, Competitive and Climate Neutral Economy," 2018.

[6] European Commission, "Climate change mitigation and adaptation," 2021.

[7] Eurostat, "Energy consumption in households." https://ec.europa.eu/eurostat/statistics-explained/index.php?title=Energy_consumption_in_households, 2023.

[8] Federal Office for Economic Affairs and Export Control, "Energy." https://www.bafa.de/EN/Energy/energy.html, 2023.

[9] Fernando, Martins, et al. "The Role of Electrification in the Decarbonization of the Energy Sector in Portugal," *Energies*, *15*(5) (2022).

[10] Fraunhofer ISI, "NewTRENDs: New trends in energy demand modeling," 2023.

[11] GERRING, JOHN. "What Is a Case Study and What Is It Good for?," *American Political Science Review*, *98*(2):341–354 (2004).

[12] Gunning, David and David Aha. "DARPA's Explainable Artificial Intelligence (XAI) Program," *AI Magazine*, *40*(2):44–58 (Jun. 2019).

[13] IEA, "The Critical Role of Buildings." https://www.iea.org/reports/the-critical-role-of-buildings, 2019.

[14] IEA, "Key World Energy Statistics." https://www.iea.org/reports/key-world-energy-statistics-2021, 2021.

[15] IPCC, "Climate change: a threat to human wellbeing and health of the planet. Taking action now can secure our future." https://www.ipcc.ch/2022/02/28/pr-wgii-ar6/, 2022.

[16] Kelly, Jack and William Knottenbelt. "The UK-DALE dataset, domestic appliance-level electricity demand and whole-house demand from five UK homes," *Scientific Data*, *2*(150007) (2015).

[17] Lacal Arantegui, Roberto and Arnulf Jäger-Waldau. "Photovoltaics and wind status in the European Union after the Paris Agreement," *Renewable and Sustainable Energy Reviews*, *81*:2460–2471 (2018).

[18] Langsdorf, Susanne. "EU Energy Policy: from the ECSC to the Energy Roadmap 2050," *Green European Foundation: Brussels, Belgium* (2011).

[19] Nicola, Armaroli and Balzani Vincenzo. "The Future of Energy Supply: Challenges and Opportunities," *Angewandte Chemie International Edition*, *46*(1-2):52–66 (2007).

[20] Palmer, Karen, et al. "Assessing the energy-efficiency information gap: results from a survey of home energy auditors," *Energy Efficiency*, *6* (2013).

[21] Pecan Street Inc, "Better tech, better decisions, a better world we're making it happen.." https://www.pecanstreet.org/, 2023.

[22] Ruth, Matthias. *Handbook of Climate Change Mitigation and Adaptation* (2 Edition). Springer Nature, 2017. Foreword.

[23] Sioshansi, Fereidoon. *Consumers, Prosumers, Prosumagers: How Service Innovations will Disrupt the Utility Business Model*. Elsevier Inc., 2019.

[24] UNFCCC. "Paris Agreement." *Paris Climate Change Conference*. 2015.

[25] World Wildlife Fund, "What's the difference between climate change mitigation and adaptation?." https://www.worldwildlife.org/stories/what-s-the-difference-between-climate-change-mitigation-and-adaptation, 2023.

[26] Yu, Songmin, et al., "Modeling of prosumagers and energy communities in energy demand models. (newTRENDs - Deliverable No. D5.2)." https://newtrends2020.eu/publications/, 2022.