Filling the Information Gap of House Owners and Technologies: A Design Case Study of a recommender for home energy system

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ABSTRACT

The transition to clean energy and energy-efficient technologies is crucial for reducing carbon emissions and mitigating climate change. However, households lack the sufficient knowledge and guidance on these technologies, including the potential benefits that can be obtained through their adoption. This study aims to fill the information gap and support decision-making on the adoption of clean energy and energy technologies for house owners. Design Case Studies will be used as the research framework.

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Chapter 1

Introduction

1.1 Background

Human-induced climate change is causing dangerous and widespread disruption in nature, thereby affecting billions of lives globally [17]. To tackle climate change and its negative impacts, two main strategies are addressed: climate change mitigation and adaptation.

- **Climate change mitigation** refers to the actions taken to reduce or prevent greenhouse gas (GHG) emissions and ultimately stabilize the concentration of these gases in the atmosphere to limit global warming and its adverse effects [24]. This goal entails a range of related projects, spanning farming, land use, peatland management, renewable energies, and energy efficiency. Integrated projects that implement climate change mitigation strategies and action plans at regional or national levels are also pertinent [8]. Notably, to curb carbon dioxide

(CO_2) emissions in the energy system, two main approaches are pursued: *(1) reducing energy consumption on the demand side through efficiency improvement and behavioral changes and (2) transitioning to renewable energy sources on the supply side.*

- **Climate change adaptation** encompasses measures to manage the adverse impacts of climate change, such as natural disasters, changes in precipitation patterns, and rising sea levels, among others [24], which includes projects relating to urban adaptation and land-use planning, infrastructure resilience, sustainable water management in drought-prone areas, flood and coastal management, as well as the resilience of the agricultural, forestry, and tourism sectors [8].

The work in this thesis belongs to the category of climate change mitigation.

1.1.1 Mitigating climate change through energy transition

The Paris Agreement, a historic international agreement, sets long-term goals to substantially reduce global emissions and limit the global temperature increase to 2 degrees Celsius in this century [26]. To achieve this ambitious goal, the world is facing an unprecedented imperative to a rapid transition in the energy sector. The European Union (EU)'s "Energy 2020. A strategy for competitive, sustainable and secure energy" and "Energy Roadmap 2050" are key strategy papers guiding energy developments in the EU [20], aiming to lead in global climate action and achieve net-zero emissions by 2050 through a socially-fair and cost-efficient transition [7].

1.1.2 Households in energy transition

Households are a crucial component of the energy transition, as they are responsible for a significant proportion of final energy consumption in the EU, as highlighted by Eurostat's 2023 report. In fact, in 2020, the residential sector accounted for 27.4% of total final energy consumption or 18.7% of gross inland energy consumption in the EU [9]. Therefore, reducing energy consumption in households through energy-efficient building construction and renovations, as well as digitalisation and smart demand-side management, can have a significant impact on achieving the EU's energy and climate targets [15]. This underscores the importance of developing and implementing effective policies and strategies to promote energy efficiency and renewable energy use in households to facilitate the energy transition.

1.1.3 Technologies for home energy system

Technologies for home energy systems have rapidly advanced in recent years, with a growing focus on energy efficiency and renewable energy sources. Smart home technologies, such as energy management systems, allow households to optimise their energy consumption and reduce waste. Moreover, rooftop solar panels and home battery storage systems enable households to generate and store their own renewable energy, reducing dependence on the grid and lowering electricity bills. In addition, the integration of electric vehicles with home energy systems can further reduce household carbon emissions and provide a source of backup power. These technologies have the potential to significantly transform the way households consume and generate energy, contributing to a more sustainable and resilient energy system.

1.2 Opportunity

Despite the growing availability and accessibility of home energy technologies, there remains a significant information gap regarding their effective utilisation. A survey conducted by Palmer et al. [22] identified a lack of knowledge and guidance among homeowners, preventing them from maximising the benefits of these investments in terms of reducing future energy expenses. Therefore, there is an opportunity in exploring effective ways to educate and inform house owners on home energy technologies.

1.3 Research questions and aims

The following research questions were raised throughout the process and guided the study:

- **What practice can effectively bridge the information gap for house owners in the adoption of renewable energy and energy-efficient technologies?**

- **How to develop effective explanations that build trust for a recommender in supporting households making sustainable decisions?**

The aim of this study is to address the information gap and support house owners in their decision-making process regarding the adoption of clean energy and energy-efficient technologies.

This thesis seeks to contribute to the HCI community by offering insights into the design and development of personalised and professional home energy system recommendations and their effectiveness in promoting the adoption of those technologies. Overall, the findings of this thesis hopefully can inform the development of future HCI interventions to address environmental challenges.

Chapter 2

Methodology

The study uses Design Case Studies [28] as the research framework.

Chapter 3

Pre-study

3.1 Social practices

Currently, homeowners have limited avenues to access information about home energy systems. Presently, individuals seeking such information typically have two options. One approach is visiting the official websites of specific technology providers or physically visiting nearby stores that specialise in the sale of one or various energy technologies. However, this necessitates a prerequisite understanding of the particular energy technology. Moreover, the information obtained through this approach may be restricted to the specific technology being explored, thus failing to offer a holistic perspective on the overall energy system, as energy technologies often function collaboratively. An alternative approach is through professional home energy assessments, commonly known as home energy audits. These assessments are conducted by experts who visit the house and perform a comprehensive inspection. Following the assessment, these professionals provide recommendations regarding house renovations, and in some cases, advice on suitable energy technologies to optimise energy efficiency [1].

3.2 Recommender systems

Recommender systems (RS) typically refer to software programs that furnish personalised suggestions of products, services, or content to users. These systems employ different methods and algorithms to produce recommendations and are commonly implemented across different domains.

Kirsten Swearingen and Rashmi Sinha's research [2] suggests that an effective recommender system is perceived by users as a trustworthy system that can be relied upon. To enable trust in an RS, they recommend implementing the following measures: *having transparent system logic; suggesting novel items; offering comprehensive information about recommended items; and enabling users to refine their recommendations by specifying preferred or excluded genres.*

3.3 The FLEX models

The FLEX models [29], are referred to as "RC models," developed under the newTRENDs project[1] by the Fraunhofer Institute for Systems and Innovation Research, are capable of calculating the energy demand of buildings at an

[1] https://newtrends2020.eu/

hourly resolution while taking into account the emerging trends of prosumaging[2] households and energy communities. These models offer evidence-based information to decision-makers in industry, government, and civil society. By providing a comprehensive assessment of the impacts of emerging technologies and innovation strategies, these models enable stakeholders to make informed decisions concerning policies related to technology and innovation.

The Figure 3.1 shows how FLEX interacts with other bottom-up models involved in the newTRENDs project, where FLEX-Operation and FLEX-Behaviour models are closely related to the demand and supply of energy for households.

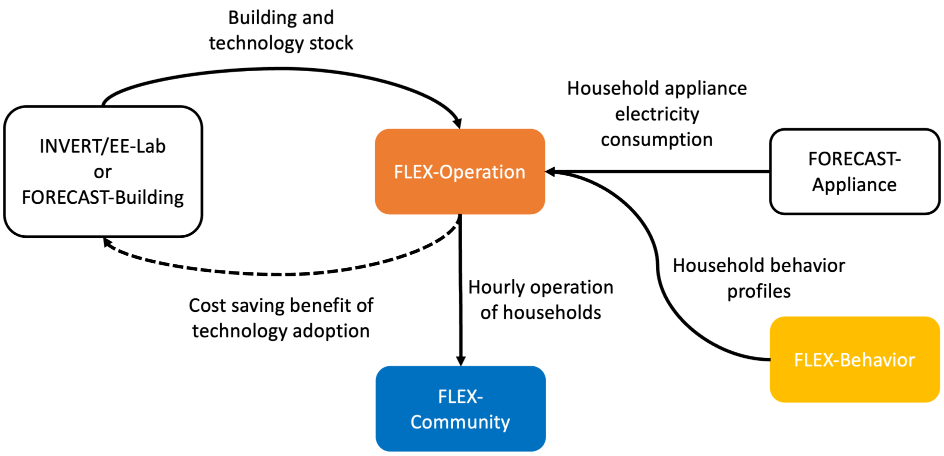

Figure 3.1: FLEX modeling suite

[2]The term "prosumager" is a combination of the words "producer" and "consumer" and refers to a person or entity that both produces and consumes energy.

3.3.1 The FLEX-Operation model

The FLEX-Operation model [29] enables the detailed simulation of energy system operation for individual households at an hourly resolution. This model provides a comprehensive assessment of the energy consumption of a representative building, incorporating technology operation (such as battery, PV, and HP systems) and load profiles at an hourly resolution. In addition to its capability of modeling energy system operation, FLEX-Operation can also aid in investment decision-making by evaluating the energy-saving benefits associated with technology adoption.

As shown in Figure 3.2, FLEX-Operation considers following services:

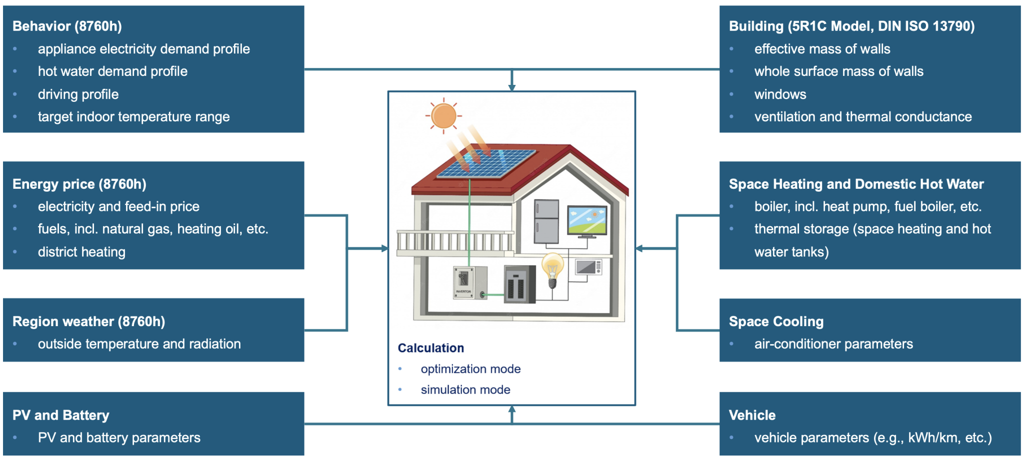

Figure 3.2: Model structure for individual households

3.3.2 The FLEX-Behaviour model

The FLEX-Behaviour model [29] facilitates the modeling of household behavior, including activity profiles and corresponding load profiles. By generating an hourly activity and energy demand profile for a pre-defined household, this model provides a comprehensive assessment of the energy consumption patterns of an individual household.

The estimates generated by the FLEX-Behaviour model refer to:

- appliance electricity demand,
- domestic hot water demand,
- driving profile, and
- building occupation.

Chapter 4

Design

In order to bridge the information gap regarding home energy systems, this study aims to provide households with knowledge of available technologies in the market. To address the potential issue of information overload, the study proposes a home energy system recommender to present households with a tailored selection of technologies that better fit their unique home situations, such as by learning the location of the house, in order to estimate the amount of sunlight it is likely to receive over the course of a year, to evaluate whether installing a PV system would be a viable and effective way for the household. The learning theory suggests that individuals learn new knowledge by connecting it with existing knowledge and experiences, as this helps to create a framework for understanding and retention of the new information. Therefore, by focusing on personalised recommendations, the study hypothesises that households may be more receptive to learning about home energy technologies. Additionally, with the intention of nudging house owners towards making informed decisions.

4.1 Design concept

The design concept of the home energy system recommender involves the utilisation of personalised recommendations based on the unique situations of households. By gaining a deep understanding of the household's energy demands and supply dynamics, the recommender can offer tailored recommendations to optimise energy efficiency and costs. Through this approach, the recommender not only provides guidance on these technologies but also educates the house owners on the potential benefits of transitioning to more sustainable energy sources. To ensure the effectiveness of the recommendations, clear and concise explanations are provided to enable users to make informed decisions.

4.2 Input to the system

4.2.1 Household profiles

The concept of household profile has been developed to gain insights into the energy demand and supply dynamics of households. To ensure the accuracy of this profile, various factors that may impact the household's energy consumption must be taken into consideration, as shown in Figure 4.1, including *the external environment, building materials, energy consumption behaviors, and the current home energy system.* By creating such a profile, a comprehensive understanding of the household's situation can be attained, enabling the offering of more tailored and effective recommendations.

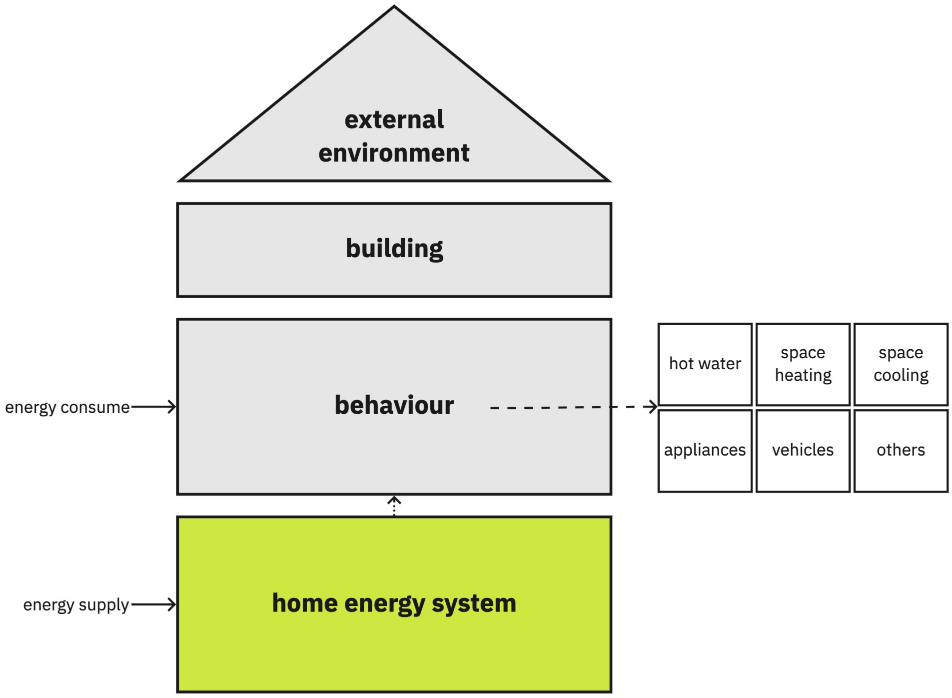

Figure 4.1: Household profile

Input data by FLEX models

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 by the FLEX-Operation model within each category can be found in Appendix A.

4.2.2 Decision trees for asking questions

A total of 14 questions, see Table 4.1, were raised to collect all the relevant information necessary for the household profile analysis. In order to optimise the user experience, a decision tree approach was employed, allowing users to navigate through the questionnaire without the need to answer all the questions.

Category	Question	Note
External environment	Where is the house located?	Understanding the location of the house can provide valuable insight into its environmental factors, such as the amount of sunlight it receives.
House condition	When was the house built?	Knowing the year a house was built can provide insight into its construction materials, such as the composition of the walls.
	Has the house ever been renovated before?	Renovations can include upgrading insulation, replacing windows with energy-efficient ones, installing high-efficiency HVAC systems, sealing air leaks, etc.

	What have been renovated in the house?	
Energy use	How many people are living in the house? How often does each adult work from home? Is there any air conditioner in the house? What type of heating energy is used in the house?	
Home energy system	Is there a photovoltaic (PV) system in the House?	A PV system is a system that uses solar panels to convert sunlight into electricity for use in a building.
	What is the size of the PV system?	The average size of a PV system is 5 kilowatt-peak.
	Is there a battery system in the house?	A home battery system is a device that stores energy produced by solar panels or other sources to be used later when needed.
	What is the capacity of the battery?	The average capacity of a home battery system is around 7 kilowatt-hours.

	Is there a smart energy management system in the house?	

Table 4.1: Survey questions

4.3 Output to the system

4.3.1 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. [22], 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 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.

4.3.2 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 4 key objectives, including *trust, effectiveness, education, and debugging*, as key aspects to incorporate into our explanations. *Trust*, we build trust with our users by using reliable data sources and providing transparent services. *Effectiveness*, we strive to enhance the effectiveness of our service by offering recommendations that could actually benefit users economically. *Education*, we seek to educate our users on the importance of environmental protection by sharing relevant knowledge and insights. *De-bugging*, we value user feedback as an important tool for identifying and resolving any issues or bugs in our system, allowing us to continuously improve and refine our service. The reasons for offering such explanations are to familiarise users with these technologies, establish accountability in the decision-making process, and encourage a shift towards environmentally conscious behaviour. By incorporating these concepts into our explanations, we aim to provide recommendations that are transparent, trustworthy, understandable, and user-centred.

Our recommendation system employs a three-level explainability framework to enhance user understanding of the recommended home energy system configurations. At the first level, the system provides an explanation in terms of the expected energy bill for the household. At the second level, the system offers a behavioural 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 is divided into three layers. At the first layer, users are provided with a comprehensive summary of their current energy consumption patterns. At the second 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 last layer, users are presented with simulated energy demand and supply data, allowing them to see the potential energy savings that could result from adopting the recommended configurations.

Through the implementation of a comprehensive approach to explainability, our objective is to offer users an overview of energy technologies, enabling them to gain insight into their energy consumption patterns and to recognize the advantages of shifting towards more sustainable energy systems.

4.3.3 Investments

Technology	Cost (€)			
	Lowest	Highest	Installation	Maintenance
PV system	1957.68/kWp	2231.76/kWp	included	0
Battery system	790.80/kW h	2520.00/kW h	included	0
SEMS	/	1516,11	379,03	0
HP	432.15/kW	2370.31/kW	included	0
Hot water tank	1	1	1	0
Space heating tank	1	1	1	0
Air conditioner	1	1	1	0
Basement renovation	132.12/m^2	157.64/m^2	included	0
Roof renovation	40.95/m^2	409.38/m^2	included	0
Wall renovation	67.57/m^2	408.93/m^2	included	0
Window renovation	364.63/m^2	958.92/m^2	included	0

Table 4.2: Investment costs of different technologies

4.4 Interactions

4.4.1 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.

4.4.2 Data visualisation

Appendices

Appendix A

Input of the FLEX-Operation model

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.

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Table A.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 A.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 A.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 A.1: Input data of the FLEX-Operation model

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