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

In partial fulfilment of the requirement for the degree of

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in

Human Computer Interaction

by

Yanwei Miao

(1627738)

Under the supervision of

Prof. Dr. Gunnar Stevens

Dr. Songmin Yu

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ABSTRACT

Climate change is a threat to the environment and society. Evidences show human behaviours are the main contributions to the global warming. There is an ergent need to slow down the process of global warming. The goal has been raised in the Paris Agreement. And at the EU level, there are 2 goals that should be achieved by 2030 and 2050.

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Chapter 1

Introduction

Human-induced climate change is causing dangerous and widespread disruption in nature, thereby affecting billions of lives globally. [15]. 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 [22]. 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 [6]. 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 [22], 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 [6].

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

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 [24]. 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 [18], aiming to lead in global climate action and achieve net-zero emissions by 2050 through a socially-fair and cost-efficient transition [5].

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 [7]. 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 [13]. 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.

1.3 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.

1.4 Research gaps

Despite the growing availability and accessibility of home energy technologies, such as renewable energy sources and energy-efficient equipment, there remains a significant information gap regarding their effective utilisation. Government policies aimed at promoting the adoption of these technologies have resulted in an infrastructure that supports the use of electricity and lowers the costs of using renewable energy. However, a survey conducted by Palmer et al. 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 [20]. As a result, there is a research gap in exploring effective ways to educate and inform house owners on the utilisation of home energy technologies.

1.5 Research questions and aims

The following research questions will guide this study:

1. How can HCI help fill the information gap in households' knowledge of energy technology and support decision-making on the adoption of clean energy and energy-efficient technologies?
2. Is the information making a difference?

The aim of this study is to address the information gap and support homeowners in their decision-making process regarding the adoption of clean energy and energy-efficient technologies. The study also seeks to evaluate the effectiveness of such a nudging approach.

The following research objectives will aid in answering the research questions:

- 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.

1.6 Supervision and planning

The proposed thesis project will combine research and application aspects, which is important because it will allow for a comprehensive understanding of the topic being studied. Conducting a thorough literature review will provide a strong foundation for the research, while the development of software applications will allow for practical implementation of the findings. In addition, interviews with industry professionals and stakeholders will provide valuable insights into the real-world challenges and opportunities in the field. Finally, the evaluation process will involve much data analysis, enabling the research to draw valid and reliable conclusions. Thus, the proposed thesis project will contribute to a well-rounded and informative study, and is believed to be justified for 30 credits.

1.6.1 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.

1.6.2 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
Feb	w1							
	w2							
	w3							
	w4							
	w5							
Mar	w6							
	w7							
	w8							
	w9							
Apr	w10							
	w11							
	w12							
	w13							
May	w14							
	w15							
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	w17							
	w18							
Jun	w19							
	w20							
	w21							
	w22							
Jul	w23							
	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

3.1 Academia

Within the academic community, there exists a concerted effort to address issues related to energy efficiency and the adoption of renewable energy sources. There are numerous research and ongoing projects aimed at establishing a robust social energy infrastructure capable of adapting to the utilization of renewable energy sources. Studies are also investigating the feasibility and practicalities of establishing zero-emission households and buildings. Technological innovations designed to support these goals have also been a focal point in the academic discourse surrounding energy efficiency and the transition to renewable energy.

In the meantime, Palmer et al. [20] drew attention to the fact that engineering studies have identified various investments in new energy-efficient equipment or building retrofits that would generate savings surpassing their costs in terms of lower future energy expenses. However, homeowners and businesses lack sufficient knowledge and guidance on how to effectively utilize these opportunities to their advantage.

3.2 Industry

3.3 Regulations

3.4 The newTRENDs project

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].

3.4.1 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.

3.4.2 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 3.1 shows how FLEX interacts with other bottom-up models involved in the newTRENDs project.

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

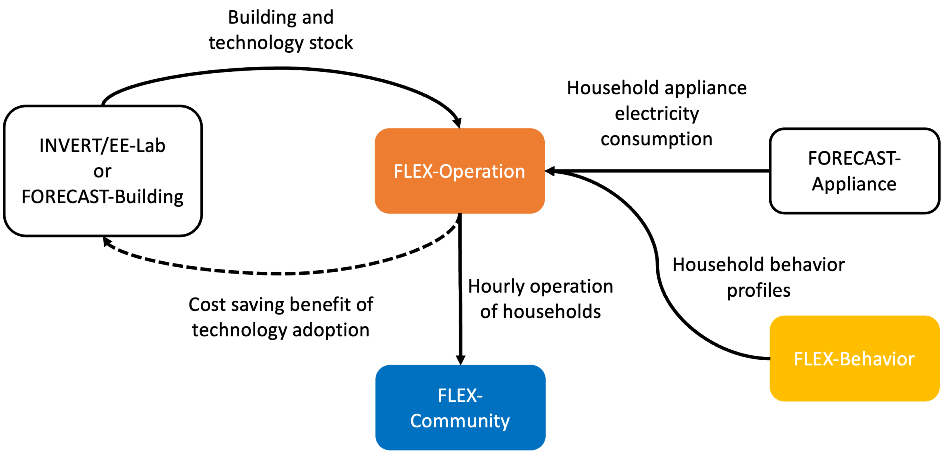

Figure 3.1: FLEX modeling suite

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].

As shown in figure 3.2, FLEX-Operation considers following five energy services [26]:

1. electric appliances, e.g., television, refrigerator, lighting, etc.;

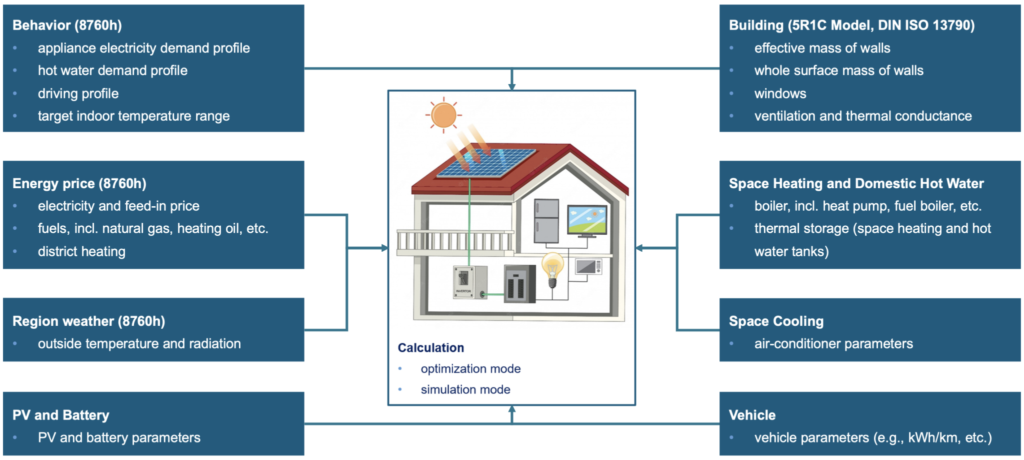

Figure 3.2: Model structure for individual households

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.

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.

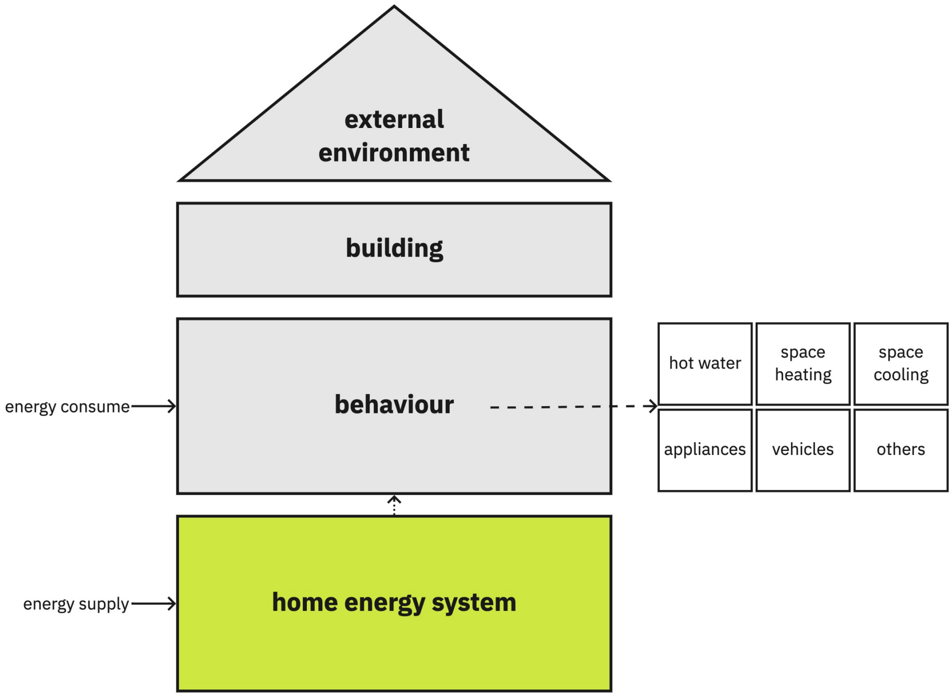

Figure 4.1: Household profile

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 4.1.

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.
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.

Continued on next page

Table 4.1 – continued from previous page

Category	Data
Energy price	ID_EnergyPrice, id_electricity, id_electricity_feed_in, id_gases, price_unit.
Heating element	ID_HeatingElement, power, power_unit, efficiency.
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.
	Continued on next page

Table 4.1 – continued from previous page

Category	Data
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.
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 4.1: Input data required by FLEX-Operation

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 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

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