Exploring Potential Roles of Home Energy Management System (HEMS) as Boundary Objects: A Case Study in Taiwan

Thesis report

by

Chuntzu Fan
Delft University of Technology

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Supervisor:
Dr. Éva Kalmár — Applied Science, TU Delft

Thesis committee:
Dr. Caroline Wehrmann — Applied Science, TU Delft
Dr.ir. Milos Cvetkovic — Electrical Engineering, Mathematics and Computer Science, TU Delft
Prof.dr. Marc de Vries — Applied Science, TU Delft

Student number: 5156351

Faculty of Applied Science · Delft University of Technology

Preface

In a world grappling with the challenges of energy consumption and sustainability, the integration of innovative technologies becomes paramount. Home Energy Management Systems (HEMS) have emerged as a significant stride within the realm of energy efficiency, offering the promise of optimised consumption and reduced carbon footprints. Taiwan, a proactive player in advancing its smart grid infrastructure, has embraced HEMS as a cornerstone in its pursuit of sustainable energy utilisation.

This study ventures into the dynamic landscape of HEMS adoption in Taiwan, delving beyond the surface to unravel its intricate role in enhancing energy efficiency. The core question looms: How effectively can HEMS bridge the gap between theoretical potential and tangible outcomes in energy efficiency improvement?

As we navigate through the study's explorations, we encounter the concept of boundary objects—an intriguing lens through which to view HEMS. Boundary objects possess a unique ability to transcend the boundaries of knowledge domains, fostering collaboration and shared understanding within complex socio-technical systems. This notion sparks a thought-provoking inquiry: Can HEMS operate as such boundary objects, effectively weaving together diverse threads of technology, user behaviour, and knowledge to enhance energy efficiency?

Guided by this compelling question, the study constructs an evaluative framework, a roadmap of insights drawn from complex system understanding and the theory of boundary objects. This framework unravels the layers that underpin HEMS' potential, showcasing the interplay between components, relationships, and patterns that together pave the path toward amplified energy efficiency.

Through a comprehensive methodology that intertwines systematic literature review with in-depth interviews, the study navigates the complex waters of HEMS adoption. As the findings illuminate the multifaceted interactions within this realm, we gain a comprehensive understanding of the challenges, the opportunities, and the potential inherent in HEMS' role within Taiwan's evolving smart grid milieu.

This exploration is more than a study; it is a journey through the intricate landscape of technology, human behaviour, and knowledge dynamics. As we journey through these pages, we aim to contribute insights into the potential of HEMS, not only within Taiwan but also as a modest effort in the broader context of global strides towards sustainable energy utilisation.

Contents

List of Figures

List of Tables

1 Introduction

The adoption of Home Energy Management Systems (HEMS) has been steadily increasing as a viable low-carbon solution to enhance energy efficiency. Recognising its potential, the Taiwan's government has integrated HEMS technologies into its smart grid development plan, acknowledging them as a crucial instrument for optimising energy consumption, in particular, in residential areas.

The development of HEMS in Taiwan is about to reach the market development. HEMS is one of the building block of developing the smart energy system in Taiwan. Along with the smart grid development, several field experiments were done, showing the technological feasibility of HEMS product to be deployed. Therefore, energy service companies are increasingly paying attention to the evaluation of business model of HEMS. However, while HEMS products are to be delivered by private sectors, the ultimate goal of energy efficiency is not assured, especially when HEMS is introduced "without saying" (Schwartz et al., 2015). It is because HEMS would be provided by potential deliverers based on their pursuing their own interests. The differently-perceived potential benefits may not lead to a consistent interpretation of the improvement in energy efficiency. Therefore, it is critical to explicit the role of HEMS to foster a more certain basis for the market development.

The adoption of HEMS is an instrument to improve energy efficiency, which is, specifically, more balanced energy use pattern and reduced energy cost. HEMS could contribute to energy efficiency in various ways. For instance, the improved energy balance could benefit from reduced consumption, increased energy savings, reduced peak load, reduced curtailment of renewable energy, etc. The managed energy use pattern could, consequently, lead to reduced cost with helps from particular tariff mechanism and the operations. Therefore, under the goal of approaching improved energy efficiency, the designs of HEMS may differ; and, it could be acknowledged that there exist different and more explicit interpretations of the improved energy efficiency achieved by HEMS depending on the context.

While the purpose of adopting HEMS as an energy efficiency instrument is obvious, the effectiveness of HEMS is subject to discussions, making the positioning of HEMS role problematic. Some research has highlighted concerns regarding the observed energy use patterns after the adoption of HEMS in real cases, suggesting the adoption of HEMS may not meet expectations, that, for instance, it does not necessarily lead to reduced energy consumption (McKerracher & Torriti, 2013; Nilsson, Wester, Lazarevic, & Brandt, 2018a). Regardless of the context, previous studies suggested the potential failure of HEMS adoption to achieve its goal of energy efficiency improvement.

The discrepancy between expected and actual energy savings achieved through HEMS adoption can be seen as an energy efficiency gap, indicating a lack of sufficient investment in the energy-efficient instrument to address inefficient energy use (Andor, Bernstein, & Sommer, 2020; Gerarden, Newell, & Stavins, 2017; Jaffe & Stavins, 1994; Solà, de Ayala, Galarraga, & Escapa, 2020). In other words, in the case of adopting HEMS, sufficient efforts should be invested to overcome potential barriers. Generally, these barriers could further be categorised into market or informational failures, behavioural explanations, and model-related errors (Gerarden et al., 2017; Solà et al., 2020). Consequently, the elaboration of barriers from different aspects implies the perspectives of addressing energy efficiency gap.

To take into account the issue of energy efficiency gap of adopting HEMS, this study put the focus on HEMS itself, considering its playing a central role of leading to the prospected efficiency. HEMS is a technology designed to address primary sources of inefficient energy consumption at the household ends. Specifically, household-level inefficient energy use is dependent on consumers' investment in energy-efficient technologies and their energy usage (Andor et al., 2020). Therefore, this study considered HEMS capabilities of overcoming informational and behavioural barriers determining in suggesting the potential efficiency. On the other hand, the positioning of HEMS in market development requires careful evaluation on HEMS interactions with the potential users.

To foster the justifiable evaluation, the critical question is "what would be the role HEMS could play in a sufficient manner to contribute to the prospected improvement in energy efficiency". To be specific, the interpretation of sufficiency in the research is that HEMS to be designed adequately to approach the goal, which is based on explicit and justifiable understanding of the HEMS interactions with end users. Accordingly, the following sub-issues are considered in order to address the research questions: (a) how to evaluate role of HEMS considering its sufficiency to meeting the goal; and (b) what are the justifiable characteristics describing such adequately designed HEMS. Through clarifying the sub-issues, this study tried to evaluate the potential role of HEMS in a manner supporting the market development in Taiwan.

In addressing the issues, this study recognised the complex nature of adopting HEMS. The complexity is due to several reasons. Although it is critical to advice HEMS designs through clarifying the capabilities of HEMS to lead to informational and behavioural changes of users, it is difficult to comprehend the interactions formed between HEMS and various users without actually adopting HEMS. As suggested by Ma, Norregaard, Asmussen, et al. (2015), the adoption of smart grid solutions is leading to a transitioning process within which social and technological factors are interrelated, so does the case of adopting HEMS. To address a complex problem, it is merely possible to comprehend the transitioning system. Rather, the clarification of the HEMS capacities is to elaborate characteristics that leverage sustained power guiding the complex system changes towards prospective efficiency.

In addition, this study found the concept of boundary objects helpful in elaborating the role of HEMS. It is an object-centred analytic perspective which emphasises the recognition of particular element capable of crossing knowledge boundaries in a collaborative context. In the case of adopting HEMS, the adopted HEMS technologies, while aimed to achieve improved energy efficiency, represent the role as boundary objects to cross knowledge boundaries that are embodied as informational and behavioural barriers. Based on the perspective, this study intended to incorporate the concept of boundary objects to addressing the issue. Therefore, this study sees the HEMS functioning as boundary objects to support the elaboration of justifiable characteristics while looking for the sufficient role of HEMS.

To address the issue, this study aimed to evaluate the potential role of HEMS as boundary objects. By developing a framework capable of addressing related sub-questions, the study seeks to explore how HEMS could perform its functions to overcome barriers to energy efficiency.

In this study, two approaches are taken to address the research questions. First, a systematic literature review is conducted to collect information and insights that will inform the development of the evaluation framework. This review encompasses studies that explore HEMS adoption, energy efficiency, and the concept of boundary objects. By synthesising and analysing the findings from these studies, the framework is designed to provide a comprehensive assessment of the adoption process.

Additionally, a semi-structured interview approach is employed to gather further information specifically related to the case of HEMS adoption in Taiwan. This interview allows for in-depth discussions and insights from the stakeholder involved in the adoption process. By incorporating the perspectives and experiences of the key stakeholder, the study aims to enhance the understanding of the complexities and challenges associated with HEMS adoption.

By combining the outcomes of the systematic literature review and the insights from the semi-structured interviews, this study presented an evaluation of the adoption of HEMS in Taiwan. The proposed framework serves as a tool for assessing the potential role of HEMS as boundary objects, thereby contributing to the development of strategies to close the energy efficiency gap.

2

Problem descriptions

2.1 The context of introducing HEMS in Taiwan

The adoption of HEMS technologies is one of the building blocks of the smart energy systems in Taiwan. The development of smart grid infrastructure has been high on the priorities since the establishment of the national-level Implementation Plan in 2018. The deployment of the Advanced Metering Infrastructure (AMI) is especially emphasised, which enables the communication of electricity information between the grid and diversified end users, to support further collection, analysis, management and applications of energy information. To facilitate the applications, the smart infrastructure is proposed to accommodate two energy management routes. As shown in Figure 2.1, while one route (Route A) is connected to the head-ends that manages to aggregate massive data properly and optimise the distribution, the other (Route B) is provided allowing future connections to HEMS applications through users' home internet. In other words, the adoption of HEMS serves to facilitate the real-time and responsive residential ends' energy management within the smart grid future.

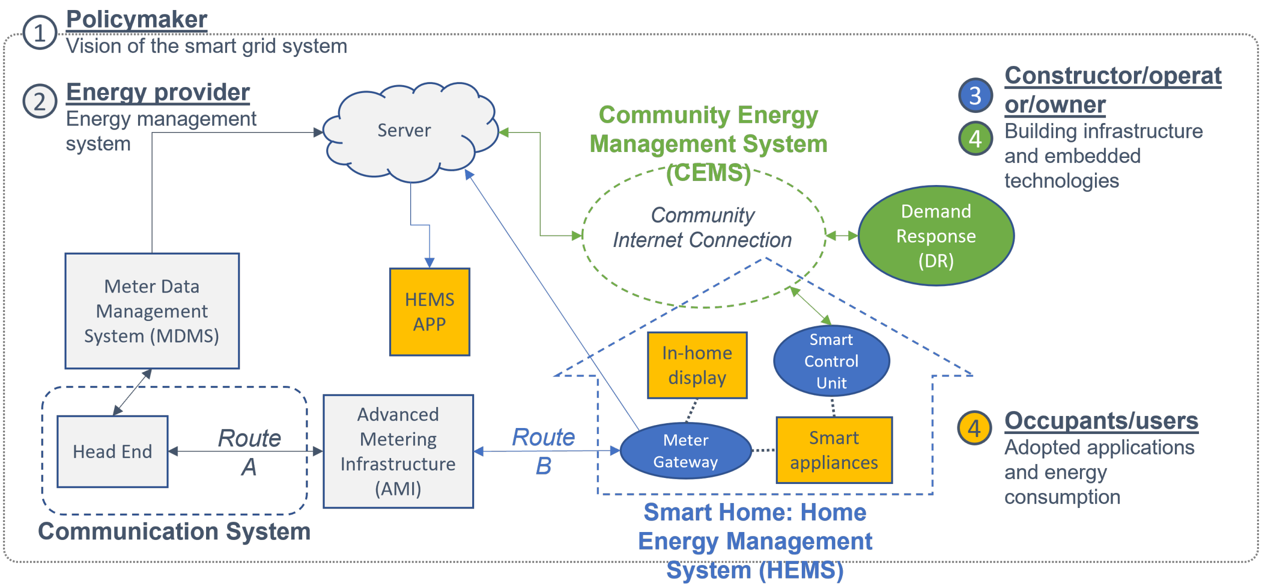

Figure 2.1: The structure of integrated smart grid system with HEMS applications in Taiwan

The plan targets to have AMI to be installed over three million households by 2024, a number equivalent to around one fifth of the total amount of the electricity users in Taiwan. Although there is a clear plan of fulfilling the infrastructure requirements, the adoption of HEMS technologies is one of the main challenges. The technical components of HEMS in

Route B could hardly be deployed as a premise, but would be planned and installed with considerations of on-site situation, welcoming further improvement in energy use efficiency. Therefore, Route B, as opposed to the distribution route that could mainly be led by programmed or automatic mechanisms, is subject to much more uncertainties since the the adoption of HEMS applications is determined by occupants and their behaviours. Although the possible expansion of bridging HEMS is preferable, there is no guarantee of the optimum adoption rate and energy use behaviours will be realised.

2.2 The development of HEMS in Taiwan

Under the policy framework of the smart grid development, there is a sequence of public-led projects relevant to the implementation of HEMS and its development. Specifically, five relevant projects are finished. In 2017, an pilot project is done to test feasibility of AMI with 1,000 user ends (Taiwan Power Company, 2017). Following up the project, another project is done within a larger-scale side of 200,000 low-voltage users and the cost efficiency is evaluated (Taiwan Power Company, 2020). suggesting the communication infrastructure for HEMS application is empirically sound.

While the communication between low-voltage user and the grid through the AMI is tested well, the utility introduced the first study which put specific attention on the application of HEMS to the AMI using the dormitory area as an empirical case, a study for future planning on evaluating the 'aggregator' and the business model feasibility (Cho, Chang, & Ku, 2019). In this study, HEMS was tested with Automatic Demand Response (ADR) and smart plugs, and it is connected CEMS. Based on the empirical knowledge on case of testing HEMS, the utility conducted another HEMS-relevant study while putting more focus on testing CEMS (including HEMS) with AMI (Cho & Cheng, 2022). In general, these public-led projects demonstrates the feasibility of HEMS regarding the technology development.

Consequently, the current agenda of adopting HEMS is the introduction HEMS product to the market, while which requires proposing the business model. A project to study business model *Research of the Application and Business Model for Home Energy Management System (HEMS) analysing HEMS adoption strategy* is launched (NextDrive, 2022). In this project, a large-scale survey was conducted to evaluate the profile consumers who are potentially more prone to the the adoption of HEMS.

2.3 The challenge of adopting HEMS in Taiwan

The adoption stage of HEMS in Taiwan is just reaching the market development. The process of adopting HEMS technologies and services follows three stages, the field experimentations, the market development and then the wider-scale implementation.

The technological feasibility of HEMS has been examined through a sequence of projects. In 2016, the HEMS applications are provided as a part of components constituting the prototype of smart public housing. Since 2018, other than constructing HEMS with newly-built public smart communities, the Taiwan Power Company led the pilot project of experimenting HEMS with existing housing units through deploying HEMS technologies in a selected site of dormitories (Taiwan Power Company, 2020). Therefore, the HEMS capacity in household energy management and its compatibility to the existing infrastructures are both tested.

However, these public-led projects for HEMS adoption tend to be technologically-focused. In order to develop a supportive environment for the smart grid development, the government introduced the Smart Gird General Project has been proposed responsible for technology development and application, including implementing HEMS which are to be delivered through Smart Home Energy Management Projects. The Smart Home Projects were proposed with focuses on HEMS application with other smart grid technologies such as transmission and distribution control, AMI and ICT, and energy management and demand response technology. It could be implied that the HEMS adoption has been treated as a part to best deploy technology solutions to enable the reformation of energy markets.

In those experiment projects, HEMS applications are provided and tested in a rather controlled environment, which is limited to support the justification of achieving the social optimum stage of adopting HEMS. Specifically, the broad scale adoption of HEMS is rather uncertain due to the complexity subject to diverse behaviours, preferences and energy use patterns at household ends. The market development stage is meant to create a supporting environment for the introduction of HEMS to the society.

However, difficulties were already shown in previous projects, that residents may refused to take part in the project or did not make use of the appliances (Zhuo & Chang, 2019). The social heterogeneity is possibly ignored during the current adoption approach, which may make reduce the potential benefit of adopting HEMS.

For the market development, various needs should be responded to in order to facilitate the implementation and optimisation of the HEMS. In between 2020 and 2021, a public-funded project to study the business model of HEMS had been conducted, which introduced the first investigation on regular households market through surveying potential users' attitudes towards HEMS. While this study tried to examine the profile of potential customers, more efforts could be put into clarify the potential role of HEMS in achieving the prospected efficiency taking into account HEMS relationships with users.

3

Research Questions

While the HEMS development is about to reach the market development stage in Taiwan, this study reflected on the concerns raised by scholars regarding the issue of energy efficiency gap in HEMS adoption. Further understanding is required over clarifying the role of HEMS in contributing to energy efficiency taking into account the diverse nature of the society to provide a more certain basis for market development.

In order to foster a justifiable understanding of the HEMS roles, this study formed the research question as:

What would be the role HEMS could play in a sufficient manner to contribute to the prospected improvement in energy efficiency?

Specifically, this study tried to evaluate the potential role of HEMS in a manner supporting the market development in Taiwan, which is approached through clarifying the following sub-issues:

1. How to evaluate the role of HEMS considering its sufficiency to meeting the goal?
2. What are the justifiable characteristics describing such adequately designed HEMS?

4

Theoretical framework

4.1 Adopting HEMS is an investment in energy efficiency

As a part of mechanisms contributing to the smart grid structure, the adoption of HEMS is expected to bring about improvement in energy efficiency. Specifically, through the HEMS adoption, the energy use could be optimised through minimising energy waste and avoiding household occupant interventions. Furthermore, the optimisation can contribute to lower residential peak and the reduction of the operational cost of electricity (Beaudin & Zareipour, 2015).

However, while cases with limited sample size may sometimes show more optimal results, McKerracher and Torriti (2013) conducted a meta-analysis on larger-scale energy consumption data, which result shows a lower rate of energy save, suggesting that the seemly effective HEMS strategies adopted may turn out to be not be cost-effective. Nilsson et al. (2018a) also suggests that HEMS application may not necessarily contribute to reduced energy consumption while obstacles emerge hindering the behavioural change. Therefore, although many studies on the introduction of HEMS technologies suggest a positive effect on end-use energy consumption and energy management, some raise the concern that the effectiveness may be under expectations.

The circumstances that the adopting of HEMS fails to realise the prospected energy savings and improvement in energy consumption at household ends suggest the issue of energy efficiency gap, an issue subject to long-standing discussions especially in the field of introducing energy efficiency technologies (Andor et al., 2020; Gerarden et al., 2017; Jaffe & Stavins, 1994; Solà et al., 2020). In other words, although it is considered a promising instrument the adoption of HEMS to improve energy efficiency, some evidence suggests the existence of or remained inefficiency in residential energy consumption although introducing HEMS technologies.

To ensure the HEMS adoption a cost-effective instrument of improving energy efficiency, there is a necessity to elaborate the HEMS adoption an investment, an effort to establish technical and non-technical elements to address sources of inefficiency. To improve the inefficient energy consumption at residential levels, Andor et al. (2020) identifies the main sources of inefficiency are consumers' hesitation to invest in high efficient technology and their inefficient energy-use behaviours. The investment of HEMS adoption is especially meant to overcome such obstacles.

From decision-making perspective, there are various factors to be considered to address sources of inefficiency. To elaborate key factors, Gerarden et al. (2017) conceptualises the potential explanations privately, publicly or socially related, which could be subject to market failures, behavioural explanations, and model and measurement errors. Through examining decisions made for the adoption of energy efficiency measures, Gerarden et al. (2017) identified the existence of social gap that the diffusion rate of technology is more slowly than the optimal scenario, and the need of strengthen behavioural knowledge to address potential failures on private side. To address the main failures, it is prioritised to improve the understanding of consumers' demand for energy efficiency product (Gerarden et al., 2017).

Following up the efforts made, Solà et al. (2020) looked particularly into the underinvestment in energy efficiency at residential level, investigating the effectiveness of different policy instruments to overcome potential barriers categorised as market-related, behavioural, and other factors. Through the review, evidence suggests that among different policy instruments, the effectiveness of informational instruments like feedback tools and smart meters like HEMS seems theoretically promising, but the technology is not adopted in the way that addresses the sources of inefficiency effectively. As suggested by (Solà et al., 2020), more research is needed to understand how to enables consumers' deciding on energy efficient technologies.

4.2 The investment of HEMS emphasises addressing informational and behavioural barriers

Knowledge related to the consumer side, including consumers' demand for product attributes and their decision making on adopting energy efficient technologies, are considered essential to address the inefficiency at household. Generally, the incorporation of social knowledge also shows the potential of ensuring the efficiency of adopting smart grid technologies. Sintov and Schultz (2015) explored the opportunities of knowledge in behavioural science in facilitating the adoption of smart grid technologies. Efficiency-wise, the performance of smart technologies of feedback mechanism and dis-aggregation could be enhanced by reduced energy consumption, driven by social influence or message re-framing. Demand peak managing-related technologies such as demand response and time-of-use pricing plans are also dependent on strategic message framing, aiming to amplify the effectiveness through engaging more participants.

Asensio and Delmas (2016) looked especially into how the behaviour responses were caused by message framing, finding out that health framing could lead to a more durable effect of contributing to energy conservation while cost-saving message's effect, though significant in short time, is diminished over time. Furthermore, the group received health treatments achieved its highest energy savings (peak conservation) in shorter time (within less than a day) than the group received cost treatments did, which peak elapsed a few days. With an expectation that the effects leading to energy savings would possibly wear off over time, it becomes critical that whether or not a strategy is durable. Not only the whole effect of a strategy matters, but the persistence of the influence matters while long-term influence could sometimes be more deterministic to the path to achieve the best performance.

Besides the strategic actions on increasing customers acceptance and enhancing their engagement, the effects of social influence has also been studied. Cassidy and Nehorai (2014) took an agent-based perspective, putting into consideration the social networks, to develop a model investigating how price change, knowledge possessed and connectivity affect the adoption of smart grid. The simulations revealed that price and knowledge could significantly disturb the energy use behaviour, further pushing it to reach another equilibrium. On the other hand, though the connectivity caused some disturbance, the overall energy consumption has been remained at a similar level.

Anderson, Lee, and Menassa (2014) also developed a model based on social network to study the dynamics of intervention's effect on energy use behaviour, but with a focus specifically on comparing scenarios within which different types of social network based on building connectivity are assigned. Through simulating adopting intervention strategies to affect energy use behaviour, different paths of changes in energy use were shown, suggesting that different patterns of social connections create different premises for the materialisation of achieving the improvement in energy efficiency.

4.3 The complexity of adopting HEMS

On the other hand, studies on behavioural science and social knowledge unfold the complex nature of the adoption of smart grid technologies, while the consequence is a product of emerged outcomes generated through the interaction between multiple participants. As implied by the research on whether the energy saving is sustained without assigning additional interventions (Asensio & Delmas, 2016), that a self-organising system is formed among the interactions between occupants and the energy efficiency treatments introduced. The effect of the treatment deflects as the changing system leads to a decision made different from the one made at previous stage.

In a similar vein, Ma et al. (2015) perceives the adoption of the smart grid solution as a process, which is determined by consumers' acceptance and behaviour change, leading to a transitioning process within which social and technological factors are interrelated. To understand how potential factors affect the adoption, Ma et al. (2015) looked into the interactions between human and non-human actors, identifying that a serious of factors would be derived from the interactions, further contributing to the progression of consumers' acceptance. In other words, the adoption process is constantly, but not linearly, affected by multiple factors, which were emerged through interactions between actors.

The underlying heterogeneity pertinent to energy consumption behaviour has also been unveiled, including that end users could respond differently to the introduction of HEMS, and that their decision could as well be affected by external factors identified within different context. The heterogeneity exists is reflecting the uncertainties that can hardly be predicted, which has been a growing issue in improving the efficiency of HEMS applications. Various approaches were proposed to increase the modelling capability to address the issue, through incorporating considerations of uncertainties into the model or enhancing the algorithms to instantly response to uncertainties (Beaudin & Zareipour, 2015). Taking into account the difficulty of the estimation under uncertainties, methods of HEMS technologies are increasingly developed to facilitate the optimisation rather than scheduling.

Consequently, although it has been iterated that the consumers' deciding on adopting the technology and the sustaining of their use are determining to the achievement of HEMS effectiveness, the complexity of addressing uncertainties is remained a problem, especially that as the time steps grow, the size of the problem scope multiplies. In addressing an issue of materialising the energy transition considering a thirty-year time horizon, Cuppen, Nikolic, Kwakkel, and Quist (2021) visualises the deep uncertainty concept. The illustration exemplifies the scenario space where possible futures could be inexhaustible given the long-term time horizon allowing numerous decisions to be made. A certain destination is not deliverable among such amount of possibilities, unless a vast amount of effort is exerted to stick to the plan. From decision making perspective, the approach of adopting HEMS as a cost-efficient instrument could not be an exhausting process.

4.4 Evaluating the potential role of HEMS in a complex nature

The adoption of HEMS is an investment in energy efficiency, elaborated as cost-minimising decisions overcoming barriers, especially those that hinder consumers' adopting and using HEMS (Andor et al., 2020; Gerarden et al., 2017; Solà et al., 2020). It is argued the investment is more like an articulation work, that adopting HEMS which improves residential energy efficiency cost-effectively is when desired interactions between users and newly-introduced HEMS products are established and sustained. To address an issue subject to a complex nature, Carlile (2004) develops a framework to describe the range of possible circumstances. Based on the framework, potential circumstances are described with understanding of the complex properties of knowledge, which are *differences, dependence and novelty*, developing progressively complex works and activities across knowledge boundaries.

It is suggested that knowledge is an invested property and path-dependent, that changes in knowledge, being denied or acquired, reflect the costs of time and resources. In the case of adopting HEMS, multiple fields of expertise and diverse knowledge possessed by involved actors are required more than as their playing the role in their domain, but their investing specialised knowledge into facilitating the adopting process. In other words, the knowledge is "at stake" (Carlile, 2004) in pursuit of facilitating the adoption of HEMS. On the other hand, efforts made in knowledge management are the investment in addressing potential barriers.

Additionally, the third property, novelty, distinguishes the process of overcoming informational and behavioural barriers from merely information management and coordination. As suggested by Carlile (2004), common knowledge does not usually exist when novelty arises, suggesting the inability of communicating across knowledge boundaries. The lack of communication function is commonly comprehended as a consequence resulted from uncertainty. Similarly, the adoption of HEMS is subject to unpredictable customer decisions and energy use behaviours, which could undermine the assumed HEMS ability of improving residence energy efficiency. Carlile (2004) further argues that the elaboration of the novelty of knowledge, is an deliberate effort internalising the management of uncertain properties, with implications of stressing the competence of understanding the differences of knowledge and its self-dependency, and the ability of identifying challenges and developing solutions.

To assess the knowledge management within the complexity, Carlile (2004) further elaborates the three types of knowledge management process, transfer, translation and transformation that attend the progressively complex forms of boundary. Such three processes depict different levels of communication complexity, from information processing, learning and creating shared meanings, to negotiation. In pursuit of the development of common interests among knowledge boundaries, Carlile (2004) emphasises different types of boundary objects as the solution to materialise the *pragmatic boundary*.

Among different perspectives taken to expand the concept development, boundary objects embody the *interpretive flexibility*, allowing knowledge integration among the heterogeneity within multiple boundaries, which can lead to the coherence of a set of activities; on the other hands, it is a process silencing undesirable characterisation in a manner facilitating desired attachments between involved actors (Star & Griesemer, 1989; Trompette & Vinck, 2009). Rather than comprehending the structure to achieve the ultimate energy efficiency within a complex context, the establishment of the boundary objects adopts another approach to achieving the potential of the social optimality along with the process of adopting HEMS technologies.

4.5 Boundary objects to manage knowledge boundaries

In the field of studying energy efficiency measures, studies increasingly recognise the adoption of smart grid technologies as the establishment of boundary objects conducive to energy transition. Of implementing the energy efficiency programme, the facilitation of knowledge creation among stakeholders is emphasised to overcome informational and communication barriers (Palm & Backman, 2020).

In a similar vein, Köhlke (2019) recognises that knowledge integration plays a crucial role in facilitating the integration of intricate interests within the adoption of smart grid projects. Through decoding the process of overcoming semantic, syntactic, and pragmatic barriers attached to the progressively complex boundaries, the translations among different social worlds are developing cooperation boundaries. Knowledge integration is particularly distinct from knowledge transfer or knowledge sharing that is the development of undirectional flow of information or understanding between knowledge fields, but leverages more directional and collective efforts pushing forward the establishment of dominant perspective of understanding the smart grid development that leads to the reconfiguration of the current social-technical regime.

Forming collective works

From an analytical perspective, boundary barriers are investigated based on the recognition of different social worlds as their possessing distinct understandings of energy efficiency programmes. Different social worlds are usually represented by stakeholders characterised or allied in terms of their attachments to the transitioning regime of energy use and supply. Boundary works are provided to facilitate the desired attachments between different social groups and technical structures that contributes to collective and constructive works.

In the study conducted by Engels and Münch (2015), the project of developing micro smart grid in Germany is proposed as the creation of a *social-technical imaginary* in a manner supporting the energy transition. Within 'the imaginary', boundary objects are established, intertwined with the cooperative and experimental environment provided, within which stakeholders are enabled to deal with uncertainties. Regardless of the incompleteness of technical components, the common understanding and commitments being generated across different *social worlds* are drawing them into the collective works of developing the shared vision. Similarly, Poderi, Bonifacio, Capaccioli, D'andra, and Marchese (2014) recognises the crucial role of smart metering technology as a boundary object, while being in the midst of diversified interests, to facilitate the collective work among discrete social worlds.

Contributing to meaning creations

The smart technologies being adopted as boundary objects eventually contributes to the concretisation and specification of the meaning of the technology adopted. According to Poderi et al. (2014), through investigating the implementation of CIVIS project, an EU-funded project paying attention to the social development along with smart energy programmes, the smart metering technology materialised as a boundary object emerged in the social-technical system in a constructive manner. With CIVIS activities, the smart metering are established with connections to diverse stakeholders, namely the manufacturers of smart meter and its add-ons, ICT infrastructure, electricity utility, electricity users, and the vision of the project in the case, leveraging connections stable enough to maintain the changing system 'functioning'. On the other hand, the technology adopted is strongly attached to the context and flexibly tailored to local needs.

In another case studied by Engels and Münch (2015), through enabling stakeholders to address uncertainties, the establishment of micro smart grids sets up to becoming holding the shared visions where directions are provided accordingly. The meanings are constructed along with the adoption process, embodied as desired attachments between technology and stakeholders and flexible interpretations. The dominant configuration, eventually growing smart enough to establish decentralised energy use and supply, would consequently replace the current social-technical regime.

Object-centred analytical perspective

The object-centred analytical position of boundary object concept is particularly stressed, while looking into the changing role of digital meters along with the establishment of boundary objects, which respond to and mediate distinct interests, emerge within conflicts and the process of work, leading to its reconfiguration along with the context Lovell, Pullinger, and Webb (2017). The notion of object is specifically conceptualised by Nicolini, Mengis, and Swan (2012) in accordance with the recognition of the role it plays in collaborative context. For accomplishing the collaboration work, the boundary object is perceived mainly performing the function of enabling participants to work collaboratively across various boundaries.

Comparably, Nicolini et al. (2012) elaborate that objects could be recognised performing different types of work in supporting collaborations. In addition to boundary object, objects could be *epistemic* when being not known yet that serves as a driving source mobilising the knowledge development, or, could be what understood as *activity object* that emerge within a contradictory context and constantly direct activities. Furthermore, objects could be, or become *material* constituting infrastructure that supports the cross-disciplinary work without being contested. Although different perspectives are grounded within different aspects of the academic world, the notions are provided in a supplement manner.

The *boundary object* functions particularly at the secondary level that embodies flexibilities and bridges works across boundaries, as opposed to primary objects which constantly fuel the epistemic development and activities but subject to a fragmented, emergent and incomplete nature, or infrastructure material which performs the stable role, constituting and embedded within the working patterns.

Digital meters as boundary objects

Through looking into three different cases of implementing digital meters, Lovell et al. (2017) uses the concept of boundary object to assess the involvement of stakeholders in the collective work, conflicts that emerged along with the adopting process, and the roles of meters. In one of the cases, while digital meters were initially viewed by the government and utilities as an instrument to facilitate energy innovations, the *collective work* was not shared by many of householders who represent a different group of the *social worlds* due to the lack of consideration of social reform.

In another case, the meters are constructed as what that hold shared values. Accordingly, the focus is put on establishing meters as boundary objects to mediate conflicts emerging. The other project put a focus on the household users' early engagement. Along with the introduction of meters, the project focused on developing the perceived benefit of making use of digital meters, reflecting an effort of establishing *epistemic things* and developing prospected outcomes (Nicolini et al., 2012) that initiate the momentum from household sides that mobilises changes. Established within the context, the meters become 'open and malleable', which provides flexible interpretations referring to the energy management among different stakeholders.

4.6 Potential role of HEMS as boundary objects

Building upon discussions surrounding cooperation and learning boundaries within the adoption of smart grid technologies, this study extended the conversation to the adoption of HEMS in residential units. In addition, based on the understanding of the complexity, this study recognises that the adoption of HEMS to achieve prospected efficiency is an investment to cross knowledge boundaries possessed by different social worlds.

To achieve the desired improvements in energy efficiency through the adoption of HEMS, various challenges must be overcome, including increasing consumer acceptance, promoting behaviour change, and sustaining these changes as discussed in previous studies. However, achieving optimised energy efficiency comes with costs in terms of time and resources, as the evolving knowledge is considered "at stake" (Carlile, 2004).

Therefore, efforts should be made to facilitate the collective works, leveraging the developing power towards achieving the shared objective. The investment in adopting HEMS is an investment in knowledge management. The cost-efficiency of the HEMS is a matter of overcoming potential barriers.

5

Methodology

5.1 Research Design

The overarching objective of this study is to enhance the understanding of the role of HEMS as boundary objects in achieving energy efficiency. The deployment of HEMS is viewed as a means of establishing these boundary objects, enabling complex yet constructive communication processes. These boundary objects play a pivotal role in the evolution of ”smart consumers,” actively engaged in the intelligent transition of energy use and management (Lin, Chen, Lu, & Hsu, 2016).

To foster a justifiable evaluation, this study employed a structured research design to achieve a comprehensive evaluation of HEMS' role as boundary objects, allowing efforts invested could be understood and assessed. The key components of the research design were described below:

Firstly, the foundation of this study rests on a deep understanding of complex properties and the concept of boundary objects. Drawing inspiration from Carlile's framework (Carlile, 2004), the study dived into the complex characteristics of *knowledge transfer, translation, and transformation* across boundaries. These complex properties—namely, *differences, dependence, and novelty*—serve as foundational elements for assessing the effectiveness of HEMS as boundary objects.

Based on this understanding of complex properties and the potential of boundary objects to foster knowledge development, the study develops an evaluation framework. This framework seeks to unravel the multifaceted dimensions of the HEMS adoption process, thereby enabling a comprehensive assessment of its effectiveness.

As an integral part of the evaluation framework development, this study intended to elaborate on the constituent *elements*, their *interrelationships*, and the *emergence of patterns* within the context of HEMS adoption. By examining how these elements interact, evolve, and contribute to *meaning creations* and *collective works* while also form *social worlds* that demonstrate *knowledge boundaries*, the study aimed to construct a nuanced understanding of the intricate dynamics involved. Through understanding how HEMS can navigate these properties, the study uncovers its potential to address informational and behavioural barriers.

This study adopted a two-pronged approach to address the research questions. Firstly, a **systematic literature review** is conducted following the methodology proposed by Torres-Carrion, González González, Aciar, and Rodriguez (2018). This comprehensive review aims to gather relevant information from existing literature to inform the development of the evaluation framework. Secondly, a **semi-structured interview** was conducted to gather practical insights from the stakeholder involved in the development of HEMS in Taiwan. The interview could offer nuanced perspectives that enrich the evaluation process and complement the insights drawn from the literature review. With knowledge gained from both practical experience and literature review, this study sought to discuss the potential of HEMS adoption in promoting efficient energy use in Taiwan.

5.2 Systematic literature review

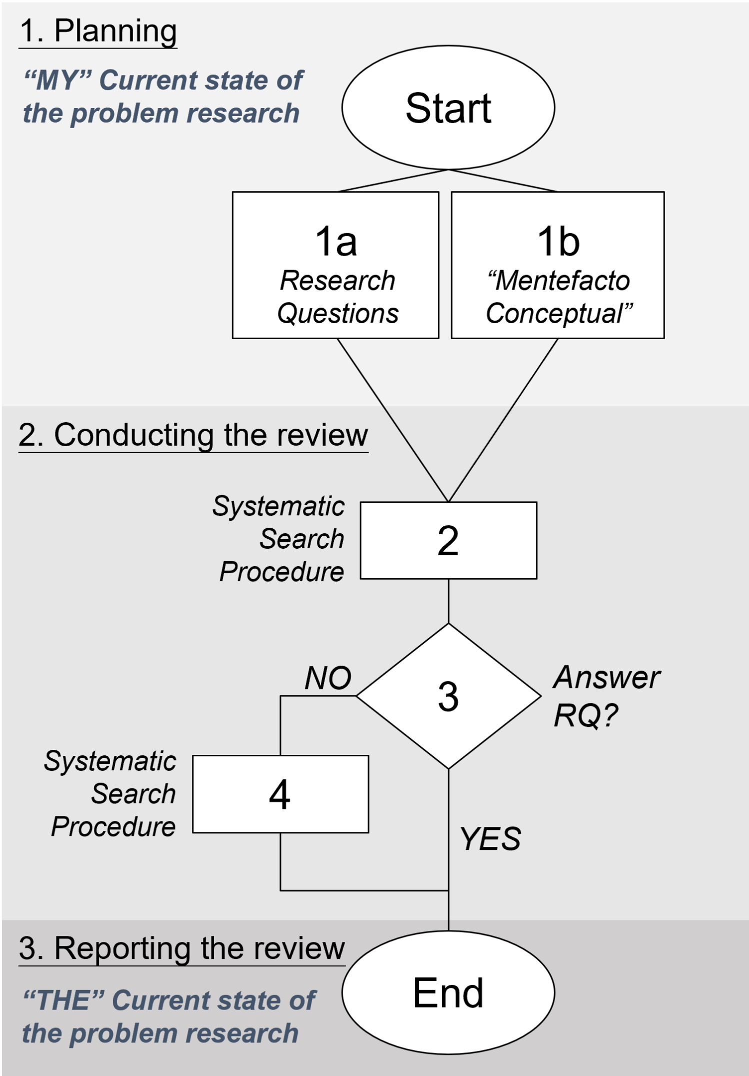

Figure 5.1: Systematic literature search procedure

The problem scope

The first stage of planning for the literature search is defining the problem scope. This study already began with an unstructured approach to review accessible information and knowledge, and discuss the current state of the issue in the case of Taiwan from "MY" point of view. Based on the current knowledge, the problem scope of this study was drawn, which elaborates the connotation within the concept of materialising the HEMS adoption in a manner justifying the energy efficiency potential through introducing HEMS as the delivery of boundary objects (Figure 5.2).

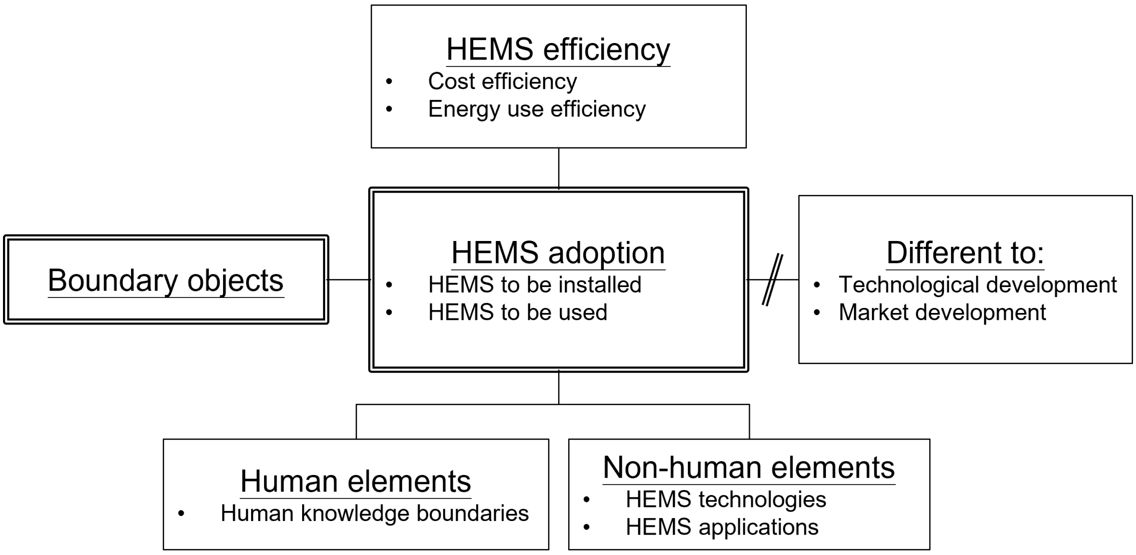

Figure 5.2: The problem scope

Systematic search procedure

This study followed a systematic search procedure, a process for systematically searching and selecting papers from databases, which are Web of Science (WoS) and Scopus in this study. The procedure includes five sub-steps as proposed by Torres-Carrion et al. (2018), and is given as below.

1. **Generating the word lists from thesaurus** based on keywords extracted from research.
2. **Developing the semantic structure** for conducting the searching.
3. **Building the search scripts** in accordance with the databases (i.e., WoS and Scopus).
4. **Conducting the searching and selecting papers.**
5. **Organising the resulted papers.** The list of papers will be extracted and each of them will be categorised and labelled in accordance with its relatedness to research questions.

In order to approach knowledge relevant to the research questions, the systematic search procedure could, and may be iterated through refining the keywords lists and search scripts.

Semantic structure for related literature searching

In accordance with the problem scope defined in the previous section, the searching scripts are developed consisting of five components to ensure the resulted papers meet all requirements, that they must include (1) term(s) representing HEMS, (2) term(s) suggesting the study is related to house or residential unit, (3) term(s) suggesting energy efficiency is mentioned in the study, (4) knowledge of boundary object is involved, and (5) human elements are involved, and roles are specified. In other words, once meeting the criteria given above, the paper would be resulted. (Table 5.1)

The searching scripts are structured in accordance with the searching rules of each of the databases (Table 5.2). Accordingly, keywords and synonyms are listed and adopted to search in the fields of title, author keywords and abstract. An initial search adopted with combination of as many as possible terms representing the required components resulted in no paper (Appendix B). It is because the term boundary object and its synonyms did not exist in the title, author keywords or abstract field of HEMS-relevant studies. It is implied that the concept of boundary object has merely been adopted in the subject discussed. In contrast, many studies related to HEMS and its efficiency were retrieved from its interchangeable terms provided, suggesting the imbalance of current knowledge possessed in two subjects. To address the circumstance, this study iterated literature searching through refining the keywords for two knowledge fields. The refined keywords and synonyms of searching scripts are elaborated in Table 5.3.

Table 5.1 Components of searching scripts and main keywords

Components		Example of interchangeable terms of concepts
HEMS and efficiency	1.Terms representing HEMS	HEMS, demand-side/energy management, smart/optimized energy management, energy consumption control/schedule, smart home control/schedule, power control/schedule
	2.Limited to residential units	home, house, residential
	3.Efficiency of HEMS	1.cost efficiency 2.energy use efficiency
Boundary object	4.Boundary objects	boundary object, boundary work, boundary organisation
	5.Human elements	resident, occupant, consumer, user, operator, governor

Table 5.2 Semantic structure and results

Database	Semantic structure	Results	Overlaps *(72/60/26) results/valid/related*		
			Properties of systems or networks	Interacting processes	Knowledge manage-ment
WoS	TS=((key1 AND key2 AND (key3_1 NEAR/10 key3_2)) AND key4 AND key5) AND DT=(Book OR Article OR Book Chapter)	178	*38/36/13*	*27/21/16*	*16/11/2*
Scopus	TITLE-ABS-KEY(key1 AND key2 AND (key3_1 W/10 key3_2)) AND key4 AND key5) AND DOCTYPE(AR OR BK OR CH)	80			

Review protocol

Through the initial search of applying scripts developed in accordance with the semantic structure, papers considered related with the problem were extracted. For the following systematic review, a review protocol is developed to set up the principle for execution. The procedures will be executed twice for each of the databases, i.e., WoS and Scopus, to enhance the validation of the searching results.

Table 5.3 Keywords and synonyms of searching scripts

Compo-nents	HEMS and efficiency			Boundary object	
	Key1 *(dynamic)*	Key2 *(static)*	Key3_1/Key3_2 *(dynamic)*	Key4 *(dynamic)*	Key5 *(dynamic)*
Terms	• energy management system • power control • smart device	home*	• optimi*/use • optimi*/power • optimi*/cost* • reduc*/cost* • reduc*/use • improv*/efficiency • optimi*/efficiency	*Properties of systems or networks* • transition* • uncertain* • perspective* *Interacting processes* • cooperation • negotiation • participat* • engag* *Knowledge management* • knowledge • acceptance	• resident* • occupant* • consumer* • user* • operator* • governor*

Selection of Journals

This study is committed to justify the energy efficiency potential. Therefore, this systematic review is not an exhausting process of defining the ultimate scenario. Instead, the study exemplifies an exploring process that appreciates the knowledge development. The purpose of this step is to ensure the quality of the resulted papers. Given the papers extracted from the initial search, a list of source journals is extracted accordingly. The SJR ranking provide by Scimago and JCR report are consulted to assess the validity of listed journals in accordance with the following steps:

1. Extracted journals will be listed and ordered according to SJR ranking.
2. Variables including SJR Best Quartile, H index and 2021 Journal Impact Factor are assigned to each of the journals, suggesting the quality of the publication.
3. Any journal lack of one or more variables are considered invalid for this study as the quality of that journal cannot be fairly compared with other journals.
4. Journals with complete information are considered valid source for this study.

The lists of selected journals are shown in Table 5.4. Accordingly, validated papers are extracted from the resulting papers, which are 60 papers as a result.

Selection of References

This step conducts a qualitatively procedure to review the validated papers from two databases listed in Appendix A, for selecting the references that provides knowledge to address the research questions. In this step, the titles and abstracts of each of the papers will be reviewed and be labelled with its related research question(s). A general criteria is given as below to ensure the relatedness to the research question:

The energy efficiency due to the HEMS adoption should be suggested by the study, including both the baseline scenario without the HEMS adoption and the scenario with HEMS adoption.

Moreover, special criteria for each of the sub-questions is given as below:

Table 5.4 List of selected journals

Name	SJR	SJR Best Quartile	H index	2021 JIF	number of papers
Ieee Transactions On Industrial Informatics	4333	Q1	151	11.648	2
Applied Energy	3062	Q1	235	11.446	2
Energy Research & Social Science	2551	Q1	76	8.514	1
Energy	2041	Q1	212	8.857	2
Sustainable Cities And Society	2015	Q1	82	10.696	2
Energy And Buildings	1682	Q1	198	7.201	3
Iet Generation Transmission & Distribution	1110	Q1	117	2.503	1
Electric Power Systems Research	1109	Q1	130	3.818	1
Ieee Access	927	Q1	158	3.476	2
Energy Reports	894	Q1	49	4.937	1
Energy Efficiency	837	Q2	45	3.134	1
Frontiers In Energy Research	705	Q2	38	3.858	1
Sustainability	664	Q1	109	3.889	3
Energies	653	Q1	111	3.252	1
Interacting With Computers	373	Q2	86	1.623	1
Electric Power Components And Systems	361	Q3	54	1.276	1
Journal Of Electrical Engineering & Technology	314	Q3	30	1.528	1

1. The context of the HEMS adoption could be recognised in the study.
2. The knowledge boundaries or any form of communication process can recognised in the study.
3. The study suggests efforts made in knowledge management which embody the boundary works.

Coding the contents

26 papers resulted from previous steps are selected as references for the literature review in this study, suggesting possibilities of providing relevant knowledge for addressing the research questions. Open coding and axial coding are used to extract knowledge from the references. Open coding is conducted to get an overview of the topic discussed, research questions, main methods and perspectives of each of the selected literature. The extracted information is categorized to provide a general understanding of selected literature. On the other hands, axial coding is used to extract relevant knowledge from references in accordance with each of the research questions and sub questions that supports addressing the research questions. The guideline for conducting open coding and axial coding is given in Table 5.5.

Accordingly, this paper will first identify the complex properties accompanying the HEMS adoption. And, the processes or activities of communications across boundaries will be discussed, suggesting the knowledge management to be made to achieve the energy efficiency potential.

Table 5.5 Coding guideline

Methods	Open coding	Axial coding
Purpose	**To determine the relevance of the research to research questions.**	**To extract knowledge in accordance with the given subjects for addressing research questions.**
What elements are involved within the HEMS adoption, and what informational and behavioural barriers possibly exist which hinders the adoption of HEMS?	To record information such as research type, methodology, main approaches to research questions, objectives and study topics, and other information worth to be noted, outlining the theoretical framework and perspectives of the research.	• Based-on system perspective, the complex properties of HEMS adoption that can be recognized. • Specifically, the (human and non-human) elements that are involved, and the interactions among them.
What are the processes or activities of knowledge management to overcome potential sources of inefficiency?		• Knowledge possessed by (human or non-human) elements or (sub) systems. • Knowledge change, and the corresponding knowledge management processes or activities.
To facilitate the knowledge management process, what elements should be considered or delivered within the decision making process of adopting HEMS?		• The (quantitatively or qualitatively assessed) energy efficiency potential. • The knowledge management process/practice/circumstance that suggests additional energy efficiency potential, or the justification. • (Internal or external) Factor(s) enabling/contributing to knowledge management in terms of HEMS adoption.

5.3 Semi-structured Interview

An interview is conducted to collect information for the case discussion. In order to exemplify the framework of evaluating the roles HEMS could play as boundary objects using the case of Taiwan, the interview is conducted after the literature review. Through the interview, this study could acquire relevant information close to the reality of the case for addressing research questions.

The interview guide

Interview purpose

The purpose of conducting interviews in this study is to gather primary data that can complement the understanding of the case being examined and provide valuable insights for the case discussions within the evaluation framework. Given the limited availability of accessible information, particularly in the form of final reports from relevant public-led projects, the interviews aim to engage with key individuals who can provide direct and relevant information pertaining to the development and adoption of HEMS in Taiwan.

Interviewee

For the interviewee selection, this study had chosen NextDrive Company, a HEMS service provider in Taiwan, considering their significant involvement in determining HEMS products and their contributions to the development of HEMS infrastructure. NextDrive Company has been a close partner to the power company in infrastructure development required for HEMS applications, and they are currently leading a public-funded research project evaluating the business model of HEMS. Therefore, interviewing NextDrive Company is deemed essential to gather pertinent information related to HEMS adoption in Taiwan.

In practice, this study reached one personnel of NextDrive company who have been involved in HEMS development while capable of reasonably representing the stands of the company. The targeted personnel is the marketing manager of NextDrive company, who is also the leader of a project of testing HEMS prototype among ten-thousand households at the moment (when conducting information collection from the interview and till the finalising of this study).

Interview questions

The interview questions are designed with coverage of three themes including the role of the company in HEMS development in Taiwan (Part I), the company's strategy of providing HEMS products and service (Part II) and the company's reflection on the role of HEMS based on their experience (Part III). Each of the themes serves difference purpose for this study. The first part is to correct the initial understanding of this study and develop an adequate comprehension of the issue. The second part is to elaborate HEMS products and services provided by the company, including the objectives and precise elements of HEMS in Taiwan. The third part is to collect information from their experience. Particularly, the last part is to learn the (potential) role of HEMS from practical knowledge and from the company's point of view as a HEMS provider. Accordingly, ten questions in total are drawn and listed in Appendix C

In addition, questions are designed in the way that could collect relevant information corresponding to discussions among research questions while not to be used to address research question directly. One of the reasons is that the purpose of the case discussion is to exemplify the evaluation framework proposed by this study, the information relevant to the case should be collected in the way that could demonstrate the issue as close to the reality as possible instead of fitting to the evaluation framework. The other reason is that some concepts and terms used by this study might not be explicit to the interviewee, the questions including specific terms might confuse or mislead the interviewee. Nevertheless, questions still include the collection of important elements relevant to the theoretical framework necessary for the following up discussions among research questions. As a result, the purposes and relevance of questions design are summed in Table 5.6.

Table 5.6 Interview questions design

Theme	Purpose	Relevance to research questions
Part I: The company's role in HEMS development: relationships (collaborations/interactions) with the government, power company, other energy service providers, and users, etc.	To improve the understanding of the network of HEMS development and adoption in Taiwan.	Possibly recognisable complex properties subject to the issue.
Part II: The company's strategy in designing and providing HEMS products and services to respond to the uncertainty involved in the process, such as diverse user needs, behaviours and preferences.	To elaborate the role of HEMS proposed, and to discuss the potential of HEMS to address (informational and behavioural) barriers.	Possibly recognisable complex properties subject to the issue and the objectives of HEMS.
Part III: Experience with current products and services offered, such as the "1% Energy Action Plan" project launched by NextDrive company.	To assess what does the status suggest, and to enhance the discussion of the role of HEMS as boundary object(s) to facilitate the adoption of HEMS.	Main barriers and the roles HEMS currently or could potentially play.

Interview approach

This study took a semi-structured approach to conduct the interview because flexibility is needed for collecting information. The flexibility is for adjusting questions and the way of asking questions depending on the response of the interview during the interview. The considerations include that questions designed based on open accessible second hand data collected by this study might not provide proper understanding of the case and that the interviewee might not be acquaintance to some terms used by this study in the questions. Therefore, the researcher would adjust questions according to the interviewee's response while generally follows the structure that could cover all themes of questions designed.

Ethical issue and data management

The ethical issues to conduct an interview in this study include the potential risks of the reveal of the participant's personally identifiable information. To address the issue, this study adopted the following measures:

- An Informed Consent Form is provided to and signed by the interview in advance of the interview, which includes descriptions of research topic, data to be collected, the usage of data, potential risks of participating and data protection information and the statements confirming the participant's understandings to ensure the participant is informed and agreed to participate in the interview.
- Data protection: the recording of the interview and the transcript will be stored securely with limited access, which is only accessible by the investigator of this interview, to minimise the threat of a data breach.

Organising the contents

The collection of interview information also follows a systematic approach considering that a semi-structured approach of conducting the interview might lead to arbitrary results. The systemic approach is to ensure that information are to be collected in an organised and consistent way regardless of the interview results. Therefore, the steps of coding the contents are proposed to identify and extract relevant information as described below:

1. **Transcription:** the recorded interview is fully transcribed in original language.
2. **Annotation:** the transcribed content is viewed thoroughly and key sentences are marked and annotated using the classification labels. Classification labels are given according to the information's relevance to the research questions, specific labels are illustrated in Table 5.7.
3. **Collection:** marked sentences are numbered, collected and grouped according to the classification labels.
4. **Extracting information:** collected sentences are reviewed again and information relevant to addressing research questions are extracted accordingly. During the process, information is organised and summarised by the author index number of the original sentence.
5. **Translation:** for the case discussion chapter, the extracted information and quotations of original sentences are translated into English.

Table 5.7 Classification labels

Relevant aspect to research questions	Examples of classification labels
Complex properties	diversity (e.g., knowledge differences) dependence (e.g., path dependence of elements or self-dependency properties of the system), novelty (e.g., knowledge not existed at present or knowledge developed within the context).
HEMS objectives	objectives (of whom), energy efficiency.
Barriers	barriers, conflicts, boundary reflected by conflicts, alliances.
HEMS roles	HEMS functions, HEMS performing functions as boundary objects.

Table 5.8 Number of paragraphs labelled and collected

Aspects	Labels	Collected paragraphs
complex properties	self-dependency of the system	8
	path dependence of elements	32
	knowledge difference	5
	novelty	9
barriers	barriers	17
	boundary & conflicts recognised	12
	alliance	29
HEMS objectives	objectives	20
	energy efficiency	7
HEMS roles	HEMS functions	10
	as boundary objects	8
case relevant	roles & relationships	11
	roles & characteristics	22
	unclassified	21
Total		211

The interview provided information to different degree covering main aspects relevant to the research questions. The coverage is shown in Table 5.8 with counts of the paragraphs collected from the transcription of the interview result. Among the aspects relevant to research questions, the interview provided more information on suggesting the complex properties and barriers. In contrast, information relevant to the HEMS roles is rather limited. Besides, there are additional labels assigned to paragraphs which provide information that could improve the comprehension of the case. Generally, the interview provided more information for elaborating elements involved and the context.

6

Developing evaluation framework

6.1 Overview of the literature review result

The overview demonstrates various research topics related to the issue of exploring the potential efficiency of HEMS adoption, and the different perspectives and approaches to address the problems. The selected literature could be categorised into three clusters according to their main purpose and topics discussed:

1. To explore the social knowledge or/and its potential of contributing to the HEMS adoption and/or its efficiency (4 papers).
2. To improve the optimisation model of HEMS through its ability of incorporating knowledge from social aspects (e.g., the ability to learn and respond to energy use patterns or users' comfort) (21 papers).
3. To strengthen the theoretical base - the literature review study (1 paper).

Model development references contribute directly to the justification of the potential role of HEMS. There are several ways to justify the HEMS role in contributing to improved energy efficiency. Different approaches deliver the justification from different perspectives. These approaches are not mutually exclusive. Instead, the justifications from different perspectives enhance the knowledge of HEMS adoption (Table 6.1).

Table 6.1 Justifying the role of HEMS in general

Justification	Approach examples	Suggesting the potential role of HEMS
HEMS efficiency	Evaluating the proposed HEMS's effect within the given social-technical environment	HEMS could contribute to the efficiency given a certain condition
	Assessing the effect of the adoption of HEMS on the given case	The adoption of HEMS could contribute to the efficiency within the given case
	Assessing the adopted HEMS's effect within the given case	The adopted HEMS could sustain the efficiency within the given case
More efficient HEMS	Comparing the proposed HEMS's effect within different patterns of social-technical environment	The given HEMS is more appreciated by particular social-technical network pattern
	Evaluating differently designed HEMSs within the given social-technical environment	Particular HEMS approach is more competent in contributing to the efficiency

HEMS objectives

There are various ways the adoption of HEMS could contribute to the energy efficiency. In general, the HEMS are implemented to improve the energy efficiency on three aspects: the optimisation of the grid energy management, the optimisation of end-use energy balance, and the energy management considering the users' well-being.

For the **grid optimisation**, the HEMS is implemented in a manner supporting the energy management of the grid. The focus is on suppliers' making use of the flexibility after optimising end-use energy consumption. In other words, the adoption of HEMS focuses on supporting the suppliers' decision making on the energy supply and distribution and the provisions of other instruments.

Accordingly, the broad-scale efficiency is developed upon the base of **energy management at end-use level**. It implies that HEMS could also manage to optimise the energy production and consumption of households. To be specific, HEMS is implemented to minimise the households' energy cost, through balancing the local generation and consumption, i.e., increasing the share of self-consumption or maximising the self-sufficiency, or through implementing demand side management strategies.

The optimisation of end-use level energy balance could further be complicated by **incorporating the management of users' well-being**. The disturbance on energy consumptions caused by HEMS implementation could exert effects on consumers in various ways, which may lead to the users' active change of energy use behaviours. The users' well-being is therefore increasingly taken as a determining factor that should be addressed along with the development and implementation of HEMS.

The multiple interpretations of the improvement of energy efficiency suggest various representations of HEMS which serve different objectives, through providing solutions to address various sources of inefficiency. The results cover several main objectives of the provision of HEMS and its service. While the modelling approach of HEMS is designed with consideration of its objective, which could also be developed for addressing multiple objectivities.

Table 6.2 Solutions provided by HEMS to meet objectives

Solutions	Examples	References
reduced energy cost	household or (and) community energy cost reduction; aggressive cost reduction while considering users' well-being and PV curtailment; minimising cost while sustaining users' well-being	Alıç and Filik (2021); Jafari, Samet, Seifi, and Rastegar (2018); Kwon, Kim, Baek, and Kim (2020); Monyei and Adewumi (2018); Munankarmi et al. (2021); Shafie-Khah and Siano (2017)
reduced energy consumption; increased energy savings; increased curtailed load	household energy use reduction; energy consumption reduced through DR programme; aggregated demand from household (community level) through DR programme (with CEMS)	Munankarmi et al. (2021); Ni and Das (2018); Nilsson, Wester, Lazarevic, and Brandt (2018b); Schwartz et al. (2015); Shin, Bae, and Kim (2018)
reduced energy loss (waste)	electrical distribution system loss	Jafari et al. (2018)

Table 6.2 Solutions provided by HEMS to meet objectives

Solutions	Examples	References
reduced peak demand	household load shifting (within CEMS)	Aloise-Young et al. (2021); Lu, Zhang, and L"u (2020); Munankarmi et al. (2021)
reduced renewable energy curtailment	offsite PV curtailment	Kwon et al. (2020)
increased system flexibility	shift-able loads; distributed energy storage and supply [*note]	Monyei and Adewumi (2018)
maintained or improved well-being	consumers' comfort, satisfaction, convenience, etc.	Alıç and Filik (2021); Kwon et al. (2020); Ni and Das (2018)

HEMS components

The HEMS system is composed of various elements to enhance its capacity to meet different objectives. The most common elements consisting the HEMS system include:

- Energy management model. The energy management model is the core of the HEMS. There are different modelling approaches adopted in order to meet different objectives of the adoption of HEMS. The modelling approach is usually based on the main aspects of the energy efficiency the HEMS is provided for, including: stochastic system, predictive control-based scheduling (predicting generation and consumption), and model with demand response mechanisms such as incentive-based or price-based model.
- Reward-penalty mechanism: The incentive-based demand response is designed with reward or penalty mechanism to increase the users' willingness to change their energy use behaviours.
- Tariff structure: Tariff mechanism is provided with price-based model to incentivise more participants to demand response programmes. The commonly used structures include Time-of-Use (TOU) pricing, Real time pricing, and dynamic energy pricing.
- Sensors: The smartplugs points are to capture appliance-level consumption.
- Smart energy server or smart control of connected appliances.
- In-home display for users to monitor or consult the consumption.
- User interface for HEMS modelling system to receive input from user ends.
- Remote control allowing user-appliance immediate interactions

6.2 Elaborating elements involved in the context of adopting HEMS

While the adoption of HEMS technologies is a process, the elaboration of the elements, their roles and the configuration of the systems within the context is subject to a changing nature. Accordingly, the understanding of involved elements and the systems could not disentangle the adopting stages. This study elaborated elements involved in accordance with two stages: the status quo and the adoption of HEMS, to distinguish the assessment of different status of the configuration along with a changing context. For elaborating both of the stages in a reasonable manner, this study followed the process of discussing the complex properties belonging to the particular stage.

The status quo is when the HEMS technologies are about to be adopted before their starting to disturb the current configuration, a stage provides the initial conditions for the introductions of HEMS. At this stage, both human and non-human elements are assumed playing critical roles in the adoption of HEMS, which constitutes the existing energy use patterns and tends to sustain the inertia. Specifically, current users of home appliances, the types of appliances and HEMS and its relevant technologies are playing determining role for the provision of HEMS components and functions. The involved elements and the relevant sources of dependence are viewed considering their possible connectivities to HEMS technologies. (Table 6.3)

Table 6.3 Elements and dependence

Elements	Dependence of knowledge	Connected elements	Reference
single element			
(Potential) HEMS users, occupants or consumers	their energy use habits and preference, and their preference on choosing new technologies	appliances; other users	Kwon et al. (2020); Monyei and Adewumi (2018); Munankarmi et al. (2021); Nilsson et al. (2018b); Pfeiffer et al. (2020); Schwartz et al. (2015); Yanxue, Zhang, Gao, and Qiao (2022)
Utilities	their duty on energy management and the main objective of improving energy efficiency (reduce management cost, reduce peak load, improve distribution)	grid at household, building, community or district scale	Jamil et al. (2019); Monyei and Adewumi (2018); Munankarmi et al. (2021); Pfeiffer et al. (2020)
HEMS (service) provider	their prospected profit of providing the HEMS service, might be dependent on their customers' needs	(potential) users; utilities; other HEMS (service) provider	Pfeiffer et al. (2020)
appliances	their initial conditions of controllability to connect to HEMS applications, which could be uncontrollable, curtailable, non-interruptable (time controllable), shiftable (time and power controllable), or regulating (power controllable)	users	Barbato et al. (2014); Jafari et al. (2018); Jamil et al. (2019); Javadi et al. (2020, 2022); Kwon et al. (2020); Li et al. (2019); Lu, L"u, Leng, and Zhang (2020); Mahmoudi, Afsharchi, and Khodayifar (2020); Munankarmi et al. (2021); Ren et al. (2022)
subsystem composed of multiple elements			
household level energy systems (e.g, HVAC, cooling, space heating, local generation, PV, or small wind turbines system, heat storage, and energy storage system)	their initial conditions of controllability to connect to HEMS applications and its energy management system	users; HEMS provider	Barbato et al. (2014); Javadi et al. (2020, 2022); Kwon et al. (2020); Li et al. (2019); Lu, L"u, et al. (2020); Pfeiffer et al. (2020); Ren et al. (2022)

Table 6.3 Elements and dependence

Elements	Dependence of knowledge	Connected elements	Reference
community or district energy systems (e.g.,EV, CEMS, supply-side EMS, smart meters, the electricity gird, and the local energy market)	their initial conditions of controllability to connect to HEMS applications and their predetermined objectives	utilities,	Barbato et al. (2014); Jamil et al. (2019); Javadi et al. (2022); Mahmoudi et al. (2020); Monyei and Adewumi (2018); Ni and Das (2018); Schwartz et al. (2015); Shafie-Khah and Siano (2017); Yanxue et al. (2022)
(Proposed) instruments relevant to HEMS technologies (e.g., demand and supply side energy management resources, time-varying tariff, RTP Tariff, satisfaction or dissatisfaction model, trading model, demand response programmes)	their predetermined objectives; their intention to include more participants (e.g., demand response)	users, utilities, HEMS provider, (con-nectable) appliances, household grid, community or district grid	Alıç and Filik (2021); Aloise-Young et al. (2021); Jamil et al. (2019); Javadi et al. (2022); Kwon et al. (2020); Monyei and Adewumi (2018); Munankarmi et al. (2021); Shafie-Khah and Siano (2017)

6.3 Meaning creations

During the processes of adopting HEMS, the relationships between existing elements and introduced elements are being formed. The adoption of HEMS is understood as an evolving process, when the HEMS technologies have been introduced and implemented. During these processes, HEMS elements are provided and involved.

The relationships developed between HEMS and potential users are based on the HEMS's modelling approach. Specifically, under the objectives of HEMS, the way through which HEMS provides attachment to potential users is based on its modelling approach of taking into account the value of "well-being".

Interpretations of well-being

From the modelling perspective, the value of well-being could be described as, for instance, comfort, convenience, satisfaction or preference. The term user's comfort is commonly seen, which is used by (Jamil et al., 2019; Lu, L"u, et al., 2020; Ni & Das, 2018; Shafie-Khah & Siano, 2017) to represent the value of well-being. Different interpretations suggest the recognition of socially-related variables that could potentially influence the effectiveness of HEMS.

However, the exact term used does not mean a lot while definitions are not given in a consistent way among different studies. For instance, Shafie-Khah and Siano (2017) uses both user's comfort and satisfaction interchangeably to refer to the same value considered in their study. In fact, these representative terms are used to give name to, or for the development of particular quantifiable indicator used by HEMS modelling in these studies.

The type of information collected is more determining in suggesting the relationships development.

For example, user's switching on/off appliances could be collected to indicate user's comfort. Jamil et al. (2019) collects information of user's switching on/off appliances to learn user's interruption behaviours. Similarly, (Kwon et al., 2020)'s proposed model could surveys users' switching on/off appliance, while the data collected is further processed to learn the states of the appliance.

Another purpose of collecting socially related information is learning user's energy use pattern, which is usually based on information of time and load of appliances used. Such information is interpreted as habit and preference of energy consumption in Ni and Das (2018)'s study, while being described as comfort by Lu, L"u, et al. (2020).

While energy use pattern could be learned in a general manner, it could also be elaborated through multiple variables defined. For instance Shin et al. (2018) simply collects energy consumption pattern to evaluate the mismatch between actual and planned usage in order to suggest the convenience status. From another perspective, to manifest user's preference, (Aloise-Young et al., 2021) defines multiple variables ranging from comfortable air temperature, shower length, shower temperature, saving money, lowering the environmental impact, when needed that dishes to be clean to when needed that clothes to be clean and dry when needed. While more explicit and localised knowledge is required for HEMS model, more efforts is required to be invested in defining the problem assigned to HEMS.

In addition, in some cases the value of well-being is interpreted as socio-economic factors, which means the value of well-being is obscured in HEMS models. For instance, (Jafari et al., 2018) designs the indicator of consumers' desired cost to represent users' satisfaction while such value is obtained by the model. In another case, (Shafie-Khah & Siano, 2017) proposes the "response fatique index" to take into account users' satisfaction through combining inputs from both the frequency and duration of Demand Response event and the importance appliances that their operation are affected by Demand Response. Therefore, fields of knowledge. While behavioural and informational science may enhance understanding of modelling user's well-being, social-economic knowledge could benefit more.

The approach of developing the well-being indicator to some extent suggests the expected interactions between the proposed HEMS and users. At the same time, the trade-off is implied, that is between investment in mathematical capacity improvement for supporting calculation and in knowledge requisition for specifying the problem to be assigned to HEMS. In addition, users' well-being could be addressed by HEMS in various based on representative variable designed, causing the essential knowledge for understanding relationships between HEMS and users may relies in different fields of knowledge.

Approach to modelling well-being

The modelling approach provides more specific suggestions on the relationships between HEMS and users, with regard to the coordination of multiple objectives through HEMS and interactions formed between HEMS and users and the energy consumption patterns to be formed with the adoption of HEMS (Table 6.4).

The first consideration is the number of, and what objectives to be coordinated while solving the optimisation problem. In HEMS models that take into account well-being, the most common objective assigned is to achieve cost minimisation (Jamil et al., 2019; Kwon et al., 2020,?; Lu, L"u, et al., 2020; Munankarmi et al., 2021; Ni & Das, 2018; Shafie-Khah & Siano, 2017; Shin et al., 2018). Some values positively related to cost minimisation could be additionally assigned in some cases, such as energy use reduction (Lu, Zhang, & L”u, 2020) and peak reduction (shifted) (Jamil et al., 2019). While the problem is framed differently in terms of scales or complexity of the network, other objective(s) may be assigned (Jafari et al., 2018; Kwon et al., 2020; Munankarmi et al., 2021). The assigned objectives suggests the values that are bounded or correlated, while such attachments allow understandable trade-offs between given objectives.

Table 6.4 Approach of modelling well-being

Reference	Objectives assigned to the optimisation problem	Approach of modelling well-being
Shin et al. (2018)	Cost minimisation (household) Discomfort index minimisation (user)	Weighted sum of values including well-being: weights are not premised but generated through the model
Munankarmi et al. (2021)	Cost minimisation (household) Discomfort index minimisation (user) Equipment degradation minimisation (household)	Weighted sum of values including well-being: weights are not premised but generated through the model
Ni and Das (2018)	Cost minimisation (utility) Discomfort index minimisation (user)	Taking into account users’ energy use patterns regarding selected appliances to represent consumers’ preference, used as an index to form estimated reward to utility
Jamil et al. (2019)	Cost minimisation (household)	Taking into account users’ behaviours to form constraints for the objective function
Kwon et al. (2020)	Cost minimisation (household) PV curtailment minimisation (community)	Taking into account users’ switching on/off appliances to form dissatisfaction index as a constraint for the objective function
Jafari et al. (2018)	Cost minimisation (household) Electrical distribution system loss minimisation (utility)	The achieved minimised cost taken as household-level desired cost as the constraint for the second stage optimization at utility level
Javadi et al. (2022)	Cost minimisation (utility)	Taking into account the mismatch between shifted amount of load to represent the discomfort index as a constraint for the objective function
Shafie-Khah and Siano (2017)	Cost minimisation (household)	Taking into account the DR’s effect on appliances to form the satisfaction index as a constraint for the objective function
Lu, L”u, et al. (2020)	Cost minimisation (household)	Taking into account users’ behaviours through categorising patterns to form constraints for objective function

Generally, there are two approaches through which HEMS model could incorporate the considerations of value(s) of well-being: that (a) the defined value of well-being as an objective assigned to HEMS model, or that (b) the value of well-being to be formed as constraint(s) for the optimisation.

To coordinate values

In the case of the well-being to be assigned as an objective, the interpretation in literal is, for example, HEMS is to ”minimise discomfort”. Such approach emphasises more on the issue of coordinating values and HEMS role to serve the coordination. Is would be either that HEMS is decisive in generating the solution with weights assigned for judging the values, or that HEMS is responsive that allows changes in weights of values based on its learning process.

Investment from both technology or knowledge aspect could facilitate the coordination but in different ways. For instance, (Javadi et al., 2020) proposed a HEMS model competent of considering the well-being while solving optimisation. In their model, weights were assigned in advance while the issue of determining appropriate weights is left for further studies. In general, the facilitation of coordination by HEMS could be improved through (1) knowledge investment: in formulating specific problem for HEMS, or, in forming message delivered to users based on the coordinated results; and, (2) technology investment: that relying on is mathematical capacities.

To sustain the value to ensure the objective assigned

In another case of forming the value of well-being as a constraint, the interpretation in plain is like that ”comfort is maintained” by HEMS at a certain level in solving the optimisation problem. The view focuses more on the purpose of maintaining such value to contribute to the objective and the HEMS role to support the process. The purpose would be like to ensure efficiency through avoiding potential adverse impact, or, to contribute to more efficiency through benefiting the higher level objective (such as encouraging participation in DR programmes). To facilitate the HEMS capacity to sustain the value to achieve the objective, knowledge required for investing in forming the constraint, assumptions and theoretical base.

In short, regardless of the objectives discussed that HEMS could be assigned, the modelling approaches suggests the role of HEMS more explicitly.

Relationships development

While the HEMS modelling approach provides the premise for developing connections, as the time goes, elements involved are constantly affecting the household energy use pattern through interacting within the network. The effects exerted to the network may lead to changes of element’s status, either that the element develops new attachments, reforms their relationship, enhances or reduces the strength of their affiliations to others; or that the element disconnects to the original network. To evaluate the role of HEMS in such changing network from a justifiable perspective, the changes could be comprehended through specifying the dependence between HEMS and connected elements.

The elaboration of dependence is to identify meaningful attachments formed between HEMS and involved elements. In specific, while HEMS modelling approach determines the development of communication channels to users, the meanings of HEMS is defined by intentional users of HEMS. As a result, the review focuses on the subjects’ perspectives to interpret their usage of HEMS, which is just an adverse way taken to elaborate the relationships development comparing to the perspective of HEMS modelling approach.

The understanding suggests the diverse meanings of HEMS for different subjects, a quality that support the potential of HEMS being ”interpretive flexibility” as a boundary object if the relationships are managed appropriately. While meaningful attachments could lead to constructive pathways towards the objectives, HEMS should sustain such diverse interpretations and facilitate the development of these attachments.

The elaboration of different-type elements’ attaching to the HEMS, with insights into functions performed, demonstrates pieces of desired components that possibly contribute the development of constructive pathways towards more energy efficiency. (Table 6.5)

Table 6.5 Specific attachments between HEMS technologies and other elements

Subject	Meaningful attachments	Reference
users	to access to/gain ”feedback” (provided by energy monitor)	Nilsson et al. (2018b); Schwartz et al. (2015)
household	to receive information of demand response event	Munankarmi et al. (2021)
local PV generation system	to access to controllable loads	Barbato et al. (2014)
power provider: time-varying tariff	to deliver message to user	Munankarmi et al. (2021)
household or community scale energy systems	(with smart meters) to manage and process measured data, to display the data/information	Barbato et al. (2014); Schwartz et al. (2015)
controllable home appliances	(with smart plugs) to consult the hub for household energy load information and adopt energy management strategy	Schwartz et al. (2015)
utilities: demand response provider	to deliver information to household ends	Shafie-Khah and Siano (2017)

6.4 Collective works

The adoption stage is framed by the objective and the current stage. In reference papers, objectives of achieving improvements in energy efficiency with the introduction of the HEMS is assumed, possible scenarios of adopting HEMS are expected to be existing in between the optimised scenario and the current stage. Therefore, the elaboration of elements involved are dependent on the specific stage discussed taking into account the given objective.

The novelty could be what emerge when the current elements respond to the introductions of technologies. Specifically, the involved elements could be developing the attachments to HEMS, building up their ways of interacting with HEMS, a process of defining the meanings of technologies to themselves. The process is, therefore, embodied by the development of connectivities and relationships between HEMS technologies and involved elements.

The optimised scenario is determined by the improvement of the energy efficiency, a representation of the moment subject to the involved elements, attachments and their relationships, reflecting the efforts invested and suggesting the possible near-future scenario. The optimised degree achieved is defined by the improved energy use pattern managed by a particular group of elements. On the other hand, the optimal status is achieved while the improvement of the efficiency contributed by the particularly managed pattern is assessed.

While different optimised scenarios are assessed, the elaboration of the context and the understanding of possible attributes are contributing to the justification of constructive pathways. As illustrated in Table 6.6, research could in various ways assess attributes to the optimised scenario, depending on the scope of the issue. Relevant studies shows the potential of identifying constructive pathways subject to the assessed optimised scenario, where efforts have been invested in a manner contributing to the adoption of HEMS.

Table 6.6 Studies on identifying different aspects of constructive pathways

Ref	Efficiency	Objective measured	Collective works
Pfeiffer et al. (2020)	optimised household energy use possibly benefiting the grid	the increased system flexibility: the amount of extra shiftable loads for customers or energy suppliers to use connected to the group	the particular pattern managed by users
Ren et al. (2022)	optimised household energy use taking into account users' well-being	reduced cost: the reduction of the costs	the enhanced modelling approach and the particular pattern managed by users
Yanxue et al. (2022)	optimised household energy use	reduced cost: the reduction of the costs perceived by users	users with changed awareness
Shin et al. (2018)	optimised household energy use taking into account users' well-being	reduced cost: the changed electricity costs	the particular status of user
Javadi et al. (2020)	optimised household energy use	reduced cost: the reduction of users' electricity bill	the energy use pattern managed by HEMS
Jafari et al. (2018)	optimised household energy use taking into account users' well-being	reduced cost: the reduction of the users' energy cost	the enhanced modelling approach and the particular pattern managed by users
Schwartz et al. (2015)	optimised household energy use	reduced energy consumption: the reduction of the household's annually energy consumption	the particular pattern managed by users while these users' characteristics are recognised
Nilsson et al. (2018b)	optimised household energy use	reduced energy use: the change of the electricity use	users with changed awareness and attitude
Shafie-Khah and Siano (2017)	optimised household energy use taking into account users' well-being	reduced energy cost: the reduction of the consumers' energy cost	the enhanced modelling approach and the particular pattern managed by users
Alıç and Filik (2021)	optimised household energy use taking into account users' well-being	reduced energy cost: the reduction of the consumers' energy cost	the enhanced modelling approach and the particular pattern managed by users

Table 6.6 Identifying constructive pathways

Ref	Efficiency	Objective measured	Collective works
Li et al. (2019)	optimised household energy use taking into account users' well-being	reduced energy cost: the reduction of the consumers' energy cost	the enhanced modelling approach and the particular pattern managed by users

6.5 Social worlds and boundaries

To deliver desired scenarios, efforts should be made in the way facilitating constructive pathways. Nevertheless, involved elements could move in directions deviating desired scenarios, which suggests the sources of inefficiency conflicting to the adoption of HEMS. In other words, conflicting situations are embodied as the mismatch between the projected pathway of the element(s) and the desired pathway.

Social worlds become recognisable within the conflicting moment. A social world represents an alliance composed of one or more element(s) whose projected direction at a moment does not match the desired pathway towards the prospected scenario. The boundary of the social world is therefore recognisable within a context where conflicts emerge. The boundary is also managed by particular characteristics possessed by the social world. To overcome the sources of inefficiency, the recognition of boundaries is a basis for evaluating necessary boundary works and building the collective work.

Barriers

The HEMS development process often gives rise to a commonly discussed situation of conflicting objectives (Alıç & Filik, 2021). This becomes particularly problematic when HEMS is introduced "without saying" (Schwartz et al., 2015). As discussed earlier, HEMS aims to achieve energy efficiency through various means, including benefiting energy grid management, optimizing household energy management, and optimizing household energy use while maintaining users' well-being. These multiple objectives can lead to a responsive and multitasking HEMS system. However, this situation also raises the possibility that HEMS may generate inefficient solutions due to conflicting objectives.

Inherent barriers: conflicting interests

Conflicts between users' comfort and efficient energy management are often considered inherent. For instance, there may be a conflict between users' comfort and the amount of their energy bills (Javadi et al., 2020). Achieving a reduction in energy bills may require compromises in comfort during energy use. Moreover, conflicting objectives can also be observed at a broader level. For example, the utility company's objective of reducing peak loads may conflict with users' objective of minimizing their energy costs (Lu, Zhang, & L"u, 2020). As a result, energy management involves trade-offs among users' objectives and the interests of other stakeholders.

Conflicts Arising from Specific HEMS Elements

When HEMS is assigned to achieve specific objectives, such as minimizing energy bills or maintaining users' comfort, conflicts can become amplified. For instance, Pfeiffer et al. (2020) suggest that HEMS may provide energy consumption feedback that does not align with users' energy use objectives. Similarly, Lu, L"u, et al. (2020) mention in their study that scheduled operations of HEMS may conflict with users' comfort preferences. Furthermore, Javadi et al. (2022) consider the rewarding scheme of HEMS and users' comfort as conflicting objectives. Therefore, conflicts between different values can arise when HEMS attempts to respond to conflicting objectives.

Users' deviating assumed usage of HEMS; Conflicts Resulting from Users' Deviation from Intended Use of HEMS

Another related but distinct situation arises when users employ HEMS in a manner that deviates from its intended use. In such cases, HEMS may not effectively perform its functions, and users' behaviours may not align with the collective effort to achieve objectives. For instance, users' control over the system may override the default model, thereby undermining its intended effectiveness (Sintov & Schultz, 2017). This can be interpreted as inadequate user inputs into the HEMS, resulting in conflicts between the observed patterns and expectations. Alternatively, conflicts may arise due to differing values held by individual or multiple users. In some cases, prioritized values may outweigh aspirations for energy use reduction in a specific context, even if energy management awareness is present (Nilsson et al., 2018b).

Alliance and characteristics

In accordance with conflicting situations, different social worlds could be recognised. The discussion of alliances involved and their characteristics reveals several points in Table 6.7.

In the case of conflicting interests, there could be certain individuals who have lifestyles that are challenging to change, posing implementation difficulties for HEMS (Schwartz et al., 2015). When it comes to conflicts between users' comfort and efficient energy management, there can be a conflict between users' comfort and the amount of their energy bills or between objectives of utility companies, such as reducing peak loads and users' objectives of minimizing their energy costs. Javadi et al. (2020) suggests that in this kind of case, prosumers, whose consumption patterns significantly impact costs, play a crucial role in cost management.

Regarding conflicts between user preferences and HEMS objectives such as providing energy feedback, scheduling and rewarding scheme, alliances usually have particular characteristics. Pfeiffer et al. (2020) identifies that some users are skeptical and do not accept HEMS, questioning its effectiveness, leading to ineffectiveness of feedback provided by HEMS. Another example is users' uncertain behaviour and deviations from scheduling patterns introduce challenges in achieving consistency and optimal energy management (Lu, L"u, et al., 2020).

Conversely, conflicts could also derive from users' deviating the expected use while deviating HEMS objective. For instance, experienced users exhibit a heightened sense of control over HEMS, sometimes overriding defaults to prioritize their own preferences (Sintov & Schultz, 2017). Nilsson et al. (2018b) discusses in their study another case that differences in values and attitudes towards energy use among household members can lead to conflicts, particularly regarding comfort and well-being.

Table 6.7 Recognition of social worlds

Conflicting situation	Alliance	Characteristics	reference
Conflicting interests • Users' comfort vs. energy bills • Utility company objectives vs. users' energy costs	• Individuals with lifestyles that are not easily changed • Prosumers whose consumption patterns have a significant cost impact	• These individuals have specific lifestyles that present challenges in adapting to or implementing changes, including changes related to energy use • These users' energy consumption patterns result in notable financial implications, either in terms of savings or expenses	Javadi et al. (2020); Schwartz et al. (2015)
Conflicts Arising from Specific HEMS Objectives • Energy consumption feedback vs. users' energy use objectives • Scheduling vs. users' comfort • Rewarding scheme conflicts vs. users' comfort	• Skeptical users who do not accept HEMS • Users with uncertain behaviour that deviates from predetermined scheduling patterns	• These users are resistant to adopting HEMS and may have doubts or concerns about its effectiveness or benefits • These users display inconsistent or unpredictable behaviours that do not align with the expected schedule, leading to conflicts or deviations from the intended HEMS operation	Lu, L"u, et al. (2020); Pfeiffer et al. (2020)
Conflicts Resulting from Users' Deviation from Intended Use of HEMS • Users' control vs. default model effectiveness • Conflicts arising from differing user values	• Experienced users who have an enhanced perception of control over HEMS • Household members with differing values and attitudes towards energy use	• These users possess a higher level of control over the system, often focusing on self-directed aspects of control that override default settings • Within a household, there are varying perspectives and priorities regarding energy use, including behaviors related to comfort and well-being	Nilsson et al. (2018b); Sintov and Schultz (2017)

6.6 Boundary works performed by HEMS

This study focused on investigating the pivotal roles of HEMS in enhancing energy efficiency efforts. The effectiveness of HEMS in driving energy efficiency improvements largely depends on a comprehensive understanding of its functions and capabilities. By focusing on areas where HEMS has direct affiliations, its potential to exert influence can be maximized.

Collective works among users is a crucial aspect of achieving energy efficiency goals. Recognizing the inherent differences and random variations among users, collaboration becomes essential (Barbato et al., 2014). Drawing on the concept of boundary objects, proposed by Carlile (2004), technical solutions serve as pragmatic boundaries that enable the iterative processes of transferring, translating, and transforming knowledge and practices which contributes to collective works.

Transfer: Delivery

In the transfer phase, effective delivery of information is crucial to ensure users' understanding and acceptance of HEMS. It is essential to provide qualified information that users can trust and comprehend to avoid skepticism and promote HEMS adoption (Schwartz et al., 2015). Misleading or misinterpreted information can lead to users' skepticism and reduced usage of HEMS. To address this, HEMS should ensure the delivery of accurate and reliable information.

HEMS also plays a vital role in providing solutions to users. By offering energy-saving measures and increasing awareness and knowledge about energy conservation, HEMS can empower users to make informed decisions (Schwartz et al., 2015). For instance, providing practical tips and advice on energy-saving measures can enhance users' awareness and knowledge in this area. Additionally, HEMS can deliver feedback on users' historical energy use, reliable metrics, and appliance-level energy consumption information to guide practical actions (Nilsson et al., 2018b). These elements contribute to the translation of information into actionable steps for users.

Translate: Information Process

The translation phase focuses on the effective processing and utilization of information within HEMS. One aspect is the increased awareness among users regarding energy consumption behaviours. This awareness is fostered through feedback provided by HEMS, enabling users to monitor and understand their energy use patterns (Nilsson et al., 2018b). Feedback allows users to recognize the impact of their energy consumption choices and facilitates behavioural change.

Cooperation among users is another important aspect of translation. HEMS can facilitate collaboration and coordination among different user groups, known as demand groups, to improve electricity grid efficiency (Barbato et al., 2014). By promoting collective action, HEMS encourages users to actively participate in energy management practices and contribute to overall grid performance.

Furthermore, the translation phase involves incorporating user-specific information into optimization models. HEMS takes into account users' satisfaction, preferences, discomfort, convenience, and energy use patterns to tailor its operations and optimize outcomes (Alıç & Filik, 2021; Aloise-Young et al., 2021; Jamil et al., 2019; Li et al., 2019; Ren et al., 2022; Shafie-Khah & Siano, 2017; Shin et al., 2018). For example, simulation models consider users' habits to ensure satisfaction while sustaining cost reduction (Ren et al., 2022). HEMS also matches energy plans with users' usage patterns to provide convenience (Shin et al., 2018). Incorporating users' desired costs and considering factors such as response fatigue index, which reflects users' comfort and satisfaction levels, further enhances the optimization process (Jafari et al., 2018; Shafie-Khah & Siano, 2017).

Transform: Sustaining the Alliance and Changing Directions

In the transformation phase, HEMS aims to sustain the alliance between users and the system while driving meaningful changes in energy management practices. Increasing awareness remains a key element in sustaining the alliance (Nilsson et al., 2018b). Studies have shown that raising users' awareness and attitudes towards the value of energy-saving measures and the impact of their energy consumption behaviours can lead to behavioural changes (Javadi et al., 2020; Schwartz et al., 2015; Yanxue et al., 2022). By providing elements that contribute to users' actions, such as incentivising self-generation and energy savings, offering dynamic energy prices, and increasing awareness about energy-saving measures, HEMS empowers users to actively participate in sustainable energy practices (Barbato et al., 2014; Javadi et al., 2020; Nilsson et al., 2018b; Schwartz et al., 2015; Yanxue et al., 2022).

Furthermore, HEMS plays a role in changing the direction of energy management practices. By enabling cooperation among users and considering their satisfaction, preferences, and energy use patterns, HEMS contributes to improving electricity grid efficiency and promoting a more sustainable energy future (Barbato et al., 2014; Shafie-Khah & Siano, 2017). The integration of user-specific information into optimization models ensures personalized solutions that align with users' needs and priorities while optimizing energy consumption and cost reduction (Alıç & Filik, 2021; Aloise-Young et al., 2021; Jamil et al., 2019; Li et al., 2019; Ren et al., 2022; Shafie-Khah & Siano, 2017; Shin et al., 2018).

In summary, the transfer, translation, and transformation processes within HEMS involve effective delivery and translation of information, as well as the sustained alliance between users and the system. By providing qualified information, delivering solutions, and incorporating user-specific information into optimization models, HEMS facilitates the transition towards sustainable energy management practices. Furthermore, research suggest that HEMS encourages cooperation among users, increases awareness, and drives changes in energy behaviours, contributing to a more efficient energy consumption pattern.

6.7 Evaluating the potential role of HEMS in achieving energy efficiency

Based on the elaborations on efficiency, objectives of HEMS and elements involved in the adoption of HEMS, this study proposed an evaluation framework through the review of meaning creations, collective works formation, social worlds and boundaries and boundary works performed by HEMS. The evaluation framework is consisting of five aspects concluded in Table 6.8.

1. Evaluating the modelling approach

This study first reviewed how does the value of well-being is interpreted by HEMS, which suggests the extent that those user-induced factors is allowed to interact with HEMS. Based on the understanding, knowledge could be invested in relevant social knowledge fields for specifying problem assigned to HEMS when addressing well-being.

Secondly, this study reviewed how do HEMSs with different modelling approaches address the value of well-being, which are categorised into (a) coordination which focuses on coordination through trading of values, or (b) processing the value which forming the value as attribute(s) to contributing to the objective. Accordingly, knowledge could be developed in different ways to support the justification of the HEMS role.

2. Evaluating meaningful relationships

This study reviewed the intentional usage of HEMS by connected elements, which suggests meaningful attachments between HEMS, users and other elements involved in the network, elaborating the specific interactions between HEMS and other elements.

3. Evaluating constructive pathways

This study reviewed the efficiency with elaborations of objectives assessed while recognizing collective works managed. Knowledge investment is required for forming collective works constructive to development of optimised scenarios in pursuit of the prospected efficiency.

4. Evaluating barriers and knowledge boundaries

This study reviewed the conflicts emerge, the representative alliances and their characteristics to elaborate the potential knowledge boundaries. Accordingly, this study elaborated the conflicts exist or emerge within the adoption of HEMS, which suggests the knowledge boundaries that require efforts input to overcome:

- Conflicting interests
- Conflicts arising from specific HEMS objectives
- Conflicts resulting from users' deviation from intended use of HEMS

5. Evaluating HEMS role in crossing knowledge boundaries

This study reviewed the influence induced by HEMS adoption which exerted the changes of relationships especially between users and HEMS. Such exertions are elaborated as transfer, translate and transform to elaborate boundary works performed by HEMS that enable the formulation of collective works.

Table 6.8 Evaluating the role of HEMS in achieving energy efficiency

Evaluation aspects	Reflections	Suggestions on knowledge development
modelling approach	How does the value of well-being is interpreted by the proposed HEMS.	Knowledge required in relevant social knowledge fields for specifying problem assigned to HEMS when addressing well-being.
	How do HEMSs with different modelling approaches address the value of well-being. In general, the value of well-being is treated (a) as an objective or (b) as a constraint.	(a) As an objective: knowledge required in formulating specific problem for HEMS while HEMS is decisive in providing the solution, or, in forming message delivered to users based on the coordinated results while HEMS is more responsive to user-induced factors. (b) As a constraint: knowledge required for investing in theoretical bases for understanding or forming the casual relationships.
meaningful relationships	The intentional usage of HEMS by connected elements.	Knowledge required to justify the relationships.
constructive pathways	The efficiency and the elaboration of objectives assessed with recognition of collective works managed.	Knowledge required for forming collective works constructive to development of optimised scenarios in pursuit of the prospected efficiency.

Table 6.8 Evaluating the role of HEMS in achieving energy efficiency

Evaluation aspects	Reflections	Suggestions on knowledge development
barriers and knowledge boundaries	Conflicts exist or emerge, representative alliances and their characteristics to elaborate the potential knowledge boundaries. Conflicts may be categorised into: (a) Conflicting interests (b) Conflicts arising from specific HEMS objectives (c) Conflicts resulting from users' deviation from intended use of HEMS.	Knowledge required for addressing conflicting issues through targeting particular knowledge possessed by recognised social worlds.
HEMS role in crossing knowledge boundaries	The exertions induced by HEMS adoption, elaborated as transfer, translate and transform, which lead to the changes of relationships especially between users and HEMS.	Knowledge required to put into developing, sustaining and facilitating the boundary works performed by HEMS.

7

Case discussion

7.1 Overview of the case

HEMS objectives in Taiwan

The HEMS adoption is to benefit mainly two aspects of energy efficiency in Taiwan: optimising household energy use and contributing to the grid management. In Taiwan, the adoption of HEMS is considered one of the solutions materialising the development of smart homes. Therefore, projects relevant to the adoption of HEMS are provided following the policy framework. According to Cho et al. (2019), technically-wise, the HEMS development focuses on contributing to the energy management on three aspects: (1) facilitating the demand side management, (2) supporting the self-consumption (increasing self-efficiency), and (3) providing the basis for the interconnection of distributed energy generation sources.

Components of HEMS products in Taiwan

As HEMS projects at the moment are mostly Proof of Concept (POC) projects, HEMS products are still under prototyping and the components are tailored to each of the pilot projects. Generally, as technical solutions, HEMS have been designed with capacity of optimising the appliances and devices' energy flow and achieve the energy savings. Therefore, the HEMS technology and services are provided with three main functions, including real-time monitoring, predicting the electricity supply and demand, and the remote control for optimising energy consumption (Cho et al., 2019). Accordingly, HEMS' exact components are determined and given based on the context of the experimentation projects.

7.2 Elements involved in the context

In the issues scope of the HEMS adoption, elements involved are recognised and categorised as human elements directly involved, important human elements indirectly involved, technical elements necessary for HEMS and technical elements supplement to HEMS.

Human elements directly involved

Human elements directly involved are recognised as determining roles who are directly leading to the adoption of HEMS. The main role is the HEMS service provider (i.e., NextDrive Corp., NextDrive). They provide product services covering Route B hardware equipment to Route B application software, with a focus on the Route B module designed according to Taipower's specifications and HEMS value-added services. NextDrive is also an IoT service provider and is involved in Taipower's infrastructure deployment POC projects, such as the Route B application end experiment.

The other leading role is the electricity supplier. In Taiwan, there is only one electricity company, i.e., Taiwan Power Company (Taipower), which is responsible for the deployment of Advanced Metering Infrastructure (AMI) as the basis for the application of HEMS. They are also leading a bunch of Proof of Concept (POC) projects for the development of smart-grid-relevant technologies, including the establishment of Route B modules (i.e., parts of the hardware of HEMS).

Thirdly, household occupants play another critical in determining the installation and the usage of HEMS. As opposed to the aforementioned HEMS provider and electricity supplier, household occupants do not inherently play specific roles in the adoption of HEMS. Instead, they are involved in the issue in diverse ways subject to their own status, affected by both external and mental factors. From the perspective of seeing them as potential uses of HEMS, occupants could be categorised into active roles of adopting HEMS, passive roles prone to the HEMS applications, and passive roles less interested in HEMS.

Important human elements indirectly involved

Important human elements indirectly involved are those relevant roles whose work could substantially affect the adoption of HEMS while their efforts are not deliberately put into the development and the adoption of HEMS. The most significant role is the government. To be specific, the Ministry of Economic Affairs (MOEA) is the representative of the government in this issue, who is the authority in charge of the development in energy sector. Currently, MOEA is leading the policy of smart grid development, incorporating the Taipowers' deployment of AMI and key technologies. Accordingly, plans are outlined and public funded are invested to relevant agendas.

Building constructor could sometimes be involved, which is somehow coincidently. Construction may includes energy management systems in their products (i.e., housing buildings). Such systems are usually Building Energy Management Systems (BEMS), which may provide ”energy visibility”, a function equivalent to what HEMS could provide. However, BEMS are not a product capable of replacing HEMS since its application scale is one building, possible composed of one or more household units. In contrast, HEMS is applied to household units. Consequently, BEMS' overlapping with HEMS is subject to housing types. While BEMS is installed in multi-family housing buildings or community (e.g., apartment complex), BEMS' control area could reach until the boundary of public area. On the other hand, BEMS could coincidently be overlapped with HEMS while which is applied to single-family houses (e.g., town houses). Nevertheless, in practice, constructors are less likely to provide such kind of houses. The reason is constructors are not obliged to provide HEMS accompanied to their products. The situation emphasises the indirect role of constructors in this issue, at least at the moment. As constructors tend to meet the requirements through cost-effective ways, the components of their products are subject to the objective and available options in the market. In this case, The Building Codes in Taiwan regulate energy efficiency at building level, the constructor may choose to install BEMS as a solution to enhance energy efficiency. In contrast, HEMS is either not an option in the market nor an necessity.

Residents' committee is another important role who could sometimes be involved, especially in the case of apartment complex. The residents' committee is distinct from residents by their different roles in affecting the adoption of HEMS. The residents' committee involvement is derived from the practical matter, which is that in apartment complex, the household's own meter is usually installed in public area where any changes made are subject to the approval of residents' committee. Therefore, in such kind of cases, there would be residents' committee who could affect the installation of HEMS thought not directly making decision for individual household on adopting HEMS.

Technical elements (necessity of HEMS)

The necessary technical elements of HEMS include the infrastructure and HEMS hardware part. Specifically, the critical infrastructure is the aforementioned AMI, which is the digitalised meters under development, substituting traditional mechanical meters for each of the households. As the HEMS is one of the application ends of AMI, the HEMS discussed in this issue could only function as long as the infrastructure is prepared. The HEMS hardware, i.e., Route B module, is another necessity. The Route B module is provided by HEMS provider while it is required to be matched with AMI. Therefore, Route B module has been designed and tested with AMI, usually through collaborative projects where the HEMS provider and the electricity supplier are both involvement. As opposed to the hardware of HEMS, the software part is realised in a form applications. Mature technologies in the development of software applications already exist (for instance, NextDrive's HEMS product in Japan include applications applicable for the design of Taiwan's HEMS product). In other words, once the AMI is deployed and Route B module is ready, the HEMS software could easily be attached upon the infrastructure.

Technical elements (supplement to HEMS)

There are several technical elements which are critical in the development of HEMS but are not developed exclusively for the HEMS. Technically speaking, HEMS could work (probably with limited functions) without such technical elements. The most significant ones are the communication standards, which are essential for the realisation of smart gird, through enabling information flows in between the networks of objects. In Taiwan, these communication standards are under developments simultaneously with the infrastructure development. There are important public-led projects run for testing the smart home communication standard, especially a technique TaiSEIA, and for the smart grid communication standard, a technique developed based on OpenADR techniques. The former is critical to allow the energy management of appliances in smart home unit and the latter is to enable the secure and stable communication between household units and the grid. The development of these techniques could consequently derive multiple stakeholders, namely, the government, non government organisations (associations), energy services providers and the electricity suppliers. The supplement elements could be critical while being determining to the added-value applications of HEMS and to the grid-to-grid communications.

7.3 Evaluating constructive pathways

Desired scenarios

In the case of Taiwan, due to the early stage of testing HEMS product, optimised scenarios are merely justified. To be specific, it is not systematically assessed that whether (and to what extent) adopting HEMS could lead to improvement in energy efficiency. Nevertheless, desired scenarios could still be interpreted from the objectives of HEMS. It is because efforts tend to be put into achieving objectives although the energy efficiency is presumed.

Based on the understanding of HEMS objectives in Taiwan, desired scenarios are subject to household level, micro-grid area and the grid scale. From the perspective of the broad scale, HEMS is to allow the communication between Taipower and low-voltage households to implement the demand response programmes. It it suggested that the desired scenario to realise the vision is that the grid management is improved through incorporating low-voltage participants in demand response programmes with the adoption of HEMS as a communication platform. For the development of smart micro-grid, the desired scenario is that HEMS to be deployed and connected to local generation (i.e., PV), energy storage system and loads as a hub to facilitate the local energy balance. In such view, the optimised scenario is determined through assessing the micro-grid energy balance with HEMS which is capable of regulating supply and demand sources.

The smaller-scale focus is on household level energy use balance while being subject to the grid management. In the vision of smart homes, HEMS allows users to control and regulate loads considering the information received (through HEMS). In such case, incorporating the tariff instruments could better lead to the energy use pattern that fit to the requirements of the grid management from power supplier. Consequently, different desired scenarios may coincide, but not necessarily due to the different involvement of elements and efforts invested to approach the objectives.

Collective works

At the moment, little knowledge in practice could hardly support the identification of constructive pathways in achieving optimised scenario(s). During such exploring stage, possible pathways are mostly guided by desired scenarios. On the other hand, constructive pathways may exist in the current exploring space once the optimised scenario is assessed.

To better facilitate the adoption process, possible attributes to constructive could be discussed at the moment through the recognition of collective works. Collective works are observed in a manner that they are (were) contributing to the development of desired scenarios and approaching objectives of the HEMS adoption in Taiwan.

Taipower to apply DR programme to low-voltage households

Under the objective of facilitating the application of DR programme to low-voltage households, collective works are embodied as the joint efforts put into facilitating the broad scale adoption of HEMS. Recognisable joint efforts at the moment are exerted mainly by Taipower and NextDrive who work collaboratively and deliberately on developing the HEMS module and on solving problems they have been, or may be faced with. For instance, they established and optimised the process of "obtaining user consent to install Route B modules:"

> *... cooperating with us, if there are processes related to Route B, then they (Taipower) can provide processes to apply.*

Furthermore, due to the centralised electricity management, the development of smart-grid-related product would require the Taipower's involvement. NextDrive recognised Taipower's significant role in driving this collaborative work and how exactly the collective work could be managed by the establishment of partnership, i.e., signing a Memorandum of Understanding (MOU):

> *... because they (Taipower) were willing to collaborate. RouteB is closely related to their electric meter and also the key. As for these two matters, how exactly we*

should proceed is defined within this MOU collaboration. They take care of everything on their end, and we handle everything on our end. We are experimenting with how HEMS vendors and the power industry can collaborate in Taiwan. Therefore, they are fully responsible for all the operations on their side, while we handle all the aspects on our side, including promotion, recruitment, product development, equipment investment, and installation – everything is set up this way.

Through MOU, both parties can exchange practical cooperation in promoting their respective businesses and then provide feedback to their own work promotion.

More efforts are expected to be invested in building such collective work to approach the objective, either through enhancing the collaborations or through including more participants. Some potential contributors to the collective work could be discussed.

For instance, NextDrive recognised that the fact users have become accustomed to incorporating HEMS as one of the functions in their daily lives could serve as a signal indicating that the market is prepared to embrace HEMS:
The so-called maturity is when almost every household has become accustomed to HEMS as one of the functions in their daily life. At this point, when TaiPower needs to perform dispatch, send a signal or something similar, they are likely willing to comply.

The so-called maturity is when almost every household has become accustomed to HEMS as one of the functions in their daily life. At this point, when Taipower needs to perform dispatch, send a signal or something similar, they are likely willing to comply.

In addition, customers who perceive value of HEMS could probably drive market establishment, and the market drives the development and application of HEMS.

A new market, if it's going to be able to run, it must ultimately be driven by the market itself, so that's how it's going to be able to run. The meaning of being driven by the market is that customers feel that there's value.

Furthermore, according to the trial of 1% Energy Actor Programme, though not examined through a rigorous studies, active participants in demand response have achieved overall reduction in energy use in the:

This time, after recruiting only 20 households, it ended. It's temporarily within this group to use a single-time game. And then, among these 20 households, indeed, there are some reductions; there's about 70 to 75% reduction.

Smart micro-grid to balance local electricity supply and demand

There is no recognisable collective work that serves directly to such object although the vision is assumed by energy provider and energy service provider. The main reason is probably that the realisation of smart micro-girds requires more participants from sectors in addition to the grid development. Specifically, three subsystems of the smart micro-grid should be prepared, namely, local generation system (sources of renewables), energy storage system (ESS), household load system (including appliances and EV chargers). The development of each of the subsystems could source back to different leading roles. However, due to the ”inclusiveness” of the issues subject to adopting HEMS for micro-grid development, there are recognisable collective works for different objectives that may coincidently benefiting the adoption of HEMS.

One of the benefiting work is the development of smart home relevant technologies, especially the expansion of smart appliances market and the development of communication standards led by the energy market. The smart appliances network provides basis allowing the controlling capability through the HEMS as a hub. The other case is the promotion of private solar generation through encouraging the installation of PVs. The effort is not inherently supporting the micro-grid but invested for amplifying the capacity of renewable generation as a whole. Therefore, the initially locally-generated solar energy has been sold to Taipower for centralised management. The local generation system began receiving contributions as the consciousness of ”self generation for self use” grows, which is just the core concept of micro-grid management. The trend, along with the development of renewable-fuelled appliances, such as solar water heatings, consequently providing another basis for the application of HEMS.

From another perspective, the preparation of HEMS taking into account these subsystems that are supplement to HEMS application for smart micro-grids, is another approach of driving the collective works for developing smart micro-gird. Deliberate efforts invested into the existing efforts (parallel to HEMS adoption) is possibly eventually generating the co-benefit.

Similar to what is perceived constructive for achieving the utility’s energy management objective, customers who perceive the value of adopting HEMS could facilitate market establishment. Accordingly, the market drives the development and application of HEMS.

Household to manage the energy use pattern at their best interests using HEMS while the pattern also fit to the grid supply

The objective is particularly managed at household level while subject to both the households’ engagement and the grid management. In other word, this desired scenario could be seen as the (advanced) scenario based on the first one, that is, the users could achieve their best interest while fitting, consciously or not, to the needs of grid management.

Again, customers who perceive the value of adopting could benefit market development while the market also drives the development and application of HEMS. In addition, it is obvious that users who are willing to adopt smart homes are more likely to use HEMS.

Besides, the trial project not only help HEMS companies find early adopters but increases the interest of participants in HEMS, targeting potential HEMS users and HEMS product/service consumers. For example, NextDrive identified some interested users of HEMS in their 1% Energy Actor Programme:

> *Indeed, there are some entities that after being pushed through, they’re very interested, and this also represents that they agree with this kind of concept. It’s about being able to do their own energy management well, to control their own energy. They had never thought about it before, but when they know it’s possible, they’re interested. ...... But there’s also a group of people who are already ahead like*

this. So, what this group of people is like, this is something that we really want to know the most in this project this time.

Collective works reflect the efforts invested into approaching specific objective(s), i.e., achieving the desired scenarios. Once the objective(s) is assessed, the constructive pathways and their potential attributes could further be evaluated, a justification process that could be driven.

7.4 Evaluating barriers and knowledge boundaries

In contrast, efforts may not be well invested into constructive pathways once conflicts emerge against desired scenarios. Generally speaking, conflicts emerge in two situations taking into account the understanding of existing collective work(s): (1) between the existing collective work and potential participant(s) and (2) within the existing collective work.

Conflicts could emerge at the moment when efforts are invested in a way contributing to the expansion of existing collective work, that an effort either intends to include more element(s) into or to take part in the particular collective work. In addition, conflicts could emerge within the existing collective work when the connected network is no longer able to leverage the collaborative efforts towards the desired scenario, driven by either internal or external factors.

Conflicts against desired scenarios

Among types of conflicts that could be discussed relevant to the adoption of HEMS, including conflicts emerge inherently from conflicting interests, conflicts arising from specific HEMS functions and resulting from users' undesired behaviours during the adoption of HEMS, conflicting interests is more closely related to the case of Taiwan due to limited knowledge in HEMS products in real life.

To follow up the context of the issue, this study discussed conflicts in accordance with three desired scenarios of adopting HEMS elaborated in previous sections.

Conflicts to the introduction of DR programme for low-voltage households

Against the desired scenario, the conflict between the utility's objective and potential participants is expected. Such conflict is located within a broader context, which is that Taipower intends to include more participants including HEMS providers and potential DR participants. However, due to the lack of incentives, the collective work to be managed by those participants can merely be realised.

Another conflict emerging relevant to conflicting interests is that when the reluctance to install HEMS overtake the willingness. In some of the cases, potential user may not be reluctant to adopting HEMS initially. However, the installation of HEMS could involve time consuming and bothering processes. Typically, complex process could reduce potential users' willingness to install HEMS.

Conflicts resulting from users' undesired behaviours could also be recognised. It is learned from the experience of 1% Energy Action project that participants of DR programme could be behaving the way deviating the expectation which is committed by the participant. This means the DR participant may not realise the efficient energy use pattern benefiting the grid although using HEMS. The underlying reasons could be diverse. For instance, it could be just ”forgotten to fulfil the commitment”.

Conflicts to the development of smart micro grids

Under the desired scenario, one of the conflicts observed is the conflicting objectives relevant to energy management between potential users and HEMS developing side. It is leaned from NextDrive’s experience that there are interested people as individuals who approaches HEMS company to inquire the HEMS product. However, the company did not have a commercialised HEMS product in the market yet, causing the situation that potential HEMS users willing to install HEMS but HEMS products not existing or not prepared. The mismatch between potential users’ expectation on energy management using HEMS and which of HEMS provider could possibly impede the development of HEMS.

Another situation relevant to conflicting interests is the conflict between existing prosumer’s energy generation and usage pattern and the HEMS objective of being connected to local generation.In some of the cases in real life, renewable may not be stored or consumed for local use. Instead, local generation may be sold to the power company, causing the circumstance that local generator may be leaving the collective work.

The conflicting interests derive from complex installation process could be recognised under this desired scenario as well. In the case of developing micro grids, the installation of HEMS could involves more than the installations of HEMS components but the accommodation of HEMS application into the broader system. Therefore, complex processes could reduce potential users’ willingness of installing HEMS, suggesting the conflicting situation when potential users does not see the time and efforts put as cost-effective investment of HEMS for energy management.

There could be the case of users’ deviation from the use of HEMS that leads to conflicting situation. It usually occurs when HEMS functions do not fit users’ needs. In the case of Taiwan, a situation is identified that HEMS users would possibly expect more usage of HEMS while HEMS is not prepared currently. The situation is particularly related to the early stage of developing HEMS which results in prototyped HEMS products with basic and limited functions.

Conflicts to the management of households’ cost-efficient energy use

Conflicts emerge within the desired scenario are relevant to conflicts discussed in previous sub-sections. Specifically, conflicts arise from conflicting interests include that potential HEMS users willing to install HEMS but HEMS products not existing or not prepared, participants of DR programme not behaving the way benefiting the grid and that complex processes may reduce the willingness of installing HEMS, leading to the situation that investments required could not rationalise users’ energy management intends. Additionally, conflicts arising from users deviation could also be recognised that users of HEMS may expect more usage of HEMS while HEMS not prepared.

7.5 Evaluating potential role of HEMS in crossing knowledge boundaries

The Table 7.1 presents an evaluation of HEMS in the context of conflicting interests and conflicts arising from users' deviation. As the same time, relevant scenarios are highlighted where HEMS can perform boundary work through the processes of transferring, translating, and transforming.

Table 7.1 Evaluating potential roles of HEMS

Conflicts	Context	Relevant scenarios	HEMS roles
conflicting interests	Taipower intends to include more participants including HEMS providers and potential DR participants.	introduction of DR programme for low-voltage households	facilitates participation of HEMS providers and potential DR participants
conflicting interests	Potential HEMS users willing to install HEMS but HEMS products not existing or not prepared.	development of smart micro grids; management of households' cost-efficient energy use	contributes to the development of HEMS products to meet user demand
conflicting interests	In some of the cases in real life, renewable may not be stored or consumed for local use.	development of smart micro grids	enables the integration and utilisation of renewable energy sources within smart micro grids
conflicts arising from users' deviation	Participants of DR programme could be behaving the way deviating the expectation which is committed by the participant.	introduction of DR programme for low-voltage households; management of households' cost-efficient energy use	supports the management of households' energy use and facilitates adherence to DR program commitments
conflicting interests	complex process could reduce potential users' willingness to install HEMS.	introduction of DR programme for low-voltage households; development of smart micro grids; management of households' cost-efficient energy use	simplifies the installation and operation process of HEMS to increase user adoption
conflicts arising from users' deviation	users of HEMS may expect more usage of HEMS while HEMS not prepared.	development of smart micro grids; management of households' cost-efficient energy use	enhances the availability and readiness of HEMS to meet user expectations

Transfer: Delivery

In the context of Taiwan, NextDrive underscored the role of HEMS as a conduit for transferring knowledge and delivering information related to energy usage, an added-value application believed to catalyze behavioral changes among users:

> *Energy visualization means that after you see your electricity usage ... your behavior will change accordingly. So, this matter of energy visualization leads to energy management.*

Another substantial effort lies in furnishing real-time information about energy consumption, which significantly piqued interest and awareness in HEMS:

> *Indeed, some entities are very interested after being promoted, and this also signifies their agreement with such a concept. It's about being able to manage their energy well, to control their energy. They had never thought about it before, but when they found out it's possible, they're interested.*

This transmission of information is believed to empower users to monitor their energy consumption patterns and make informed decisions to optimise their energy usage.

Consequently, while HEMS can certainly serve as an intermediary for transferring information, its ultimate purpose lies not merely in information delivery, but rather in fostering endeavors that could culminate in the development of desired scenarios.
As an example, the HEMS application of Route B operates as a conduit for communication between electricity companies and households:

> *So, what's the purpose of HEMS? When your household is separate, you have the ability to regulate, like if the electricity industry wants to work on low voltage, I can communicate with households.*

This two-way exchange of information empowers households to actively engage with their energy usage data, nurturing a deeper understanding of their consumption patterns:

> *I think DR is the most apparent point where we start to interact with it (HEMS).*

Through the implementation of demand response experiments, HEMS offers households valuable opportunities to interact with their energy data and make well-informed decisions about their energy usage.

Translate: Information Process

NextDrive underscored that users actively participating in demand response programs, facilitated by HEMS, have achieved noteworthy reductions in their energy consumption:

> *Among these 20 households, there are indeed reductions, approximately about 70-75% have reductions.*

This tangible reduction in energy usage through active demand response participation highlights HEMS' role as a translator of knowledge, converting energy data into actionable insights that empower users to make more informed decisions about their consumption behaviours. By engaging users in real-time energy management, HEMS becomes the conduit through which energy-related information is translated into tangible behaviour changes.

Nevertheless, the extent to which energy visibility contributes to these energy-saving behaviours remains unclear. Further research is warranted to ascertain the specific influence of energy visibility on behaviour change and energy conservation.

Moreover, by collecting data from early participants, the industry gains the ability to analyze their characteristics and energy usage profiles, thereby obtaining insights into user behaviors and preferences:

We want to try and see, find out what early users might look like.

This process of collecting and analysing user data further highlights HEMS' role in converting raw data into meaningful patterns and trends that inform the industry about user behaviours and preferences.

This data-driven approach empowers the industry to identify and rectify product glitches, ensuring the continual enhancement of HEMS functionalities. It highlights how HEMS not only translates energy data into actionable insights for users but also translates user feedback and product performance data into improvements, resulting in a dynamic and evolving energy management solution.

After this promotion, I will see several issues, including bugs within our product development process that we've identified. So, including product issues, we've caught them, and including the target customers.

This iterative improvement cycle, driven by the translation of user data and feedback, reinforces HEMS' pivotal role as a knowledge translator, bridging the gap between energy data and user behaviour, while also facilitating communication between users and the industry for mutual benefit.

Transform: Sustaining the Alliance and Changing Direction

HEMS experiments not only play a pivotal role in shaping the design of HEMS products and services but also yield invaluable insights for the industry. By meticulously analysing data from early participants, the industry gains the capacity to enhance and fine-tune HEMS functionalities, aligning them more precisely with user needs and expectations.

This interactive capability to engage with energy usage data empowers households to proactively oversee their energy consumption, fostering a profound impact on behaviour change and energy conservation. As users develop a heightened understanding of their energy consumption patterns, they are better poised to make informed decisions and proactively adapt their behaviours to align with their energy management goals. In this way, HEMS not only transfers and translates knowledge but also takes significant strides towards transforming how users interact with and manage their energy consumption. (Figure 7.1)

This dynamic process of refining HEMS functionalities is a prime example of its transformative role – one that builds upon the initial foundations of data transfer and translation, thus suggesting the potential for further transformative impact. While the cases in Taiwan have primarily supported the elaboration of transferring and translating knowledge, the notion of HEMS actively transforming user behaviour remains an avenue ripe for exploration and holds great potential.

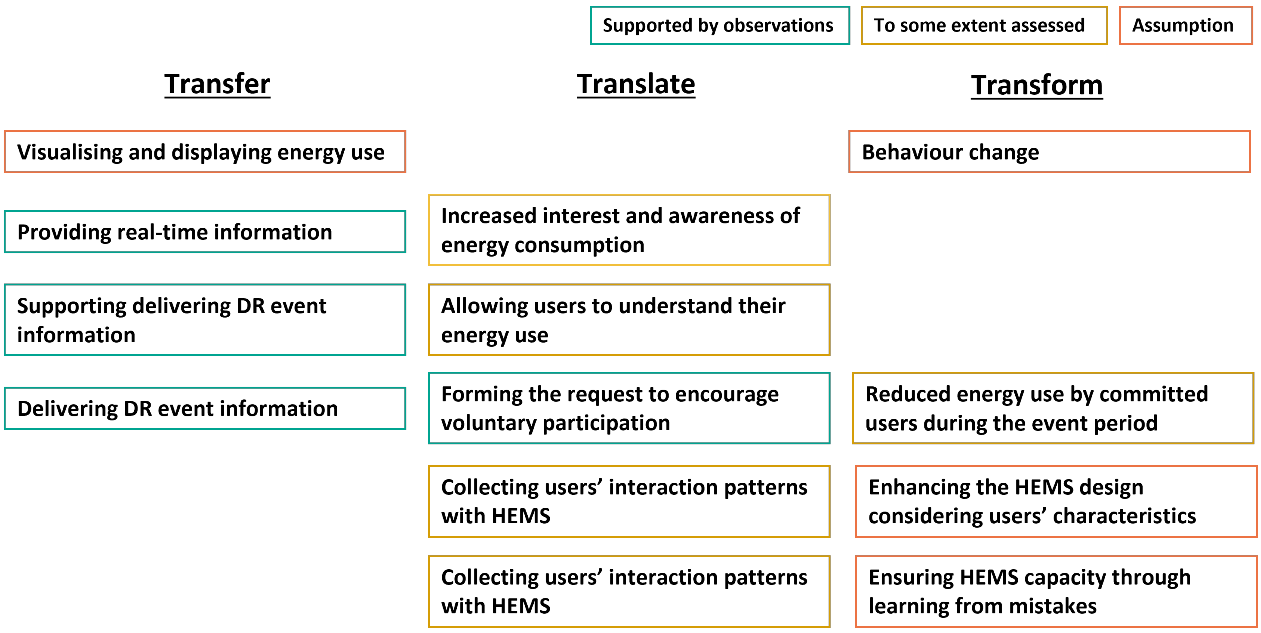

Figure 7.1: Evaluating the role of HEMS in crossing knowledge boundaries

8 Conclusions

This study dived into the potential role of HEMS to support the market development in Taiwan, with an emphasis on its potential of achieving energy efficiency improvement. To tackle this issue, a robust framework was proposed through reviewing the knowledge developed in relevant studies, aimed at comprehensively evaluating the viability of HEMS adoption within a complex context. This framework facilitated a multi-faceted analysis that encompassed understanding adoption efforts, exploring potential development pathways, identifying barriers, and reflecting on the multifaceted roles that HEMS could undertake. By employing this comprehensive framework, decision-makers were empowered to assess HEMS' roles effectively, considering cost implications with regard to both technology and knowledge development.

To respond to the question of how to evaluate the role of HEMS with respect to its sufficiency in meeting energy efficiency goals, the study embarked on an examination of the intricate properties entailed in HEMS adoption. The study revealed that HEMS adoption encompassed a diverse array of knowledge sources, dependency on system development, and a continuous influx of novel information throughout the adoption process. These complex properties presented challenges in assessing various adoption scenarios and identifying cost-effective pathways. Consequently, the study suggested that adopting HEMS should be regarded as an investment in the development of knowledge, recognising its complex nature while addressing informational and behavioural barriers.

The subsequent exploration, aimed at identifying the justifiable characteristics of adequately designed HEMS, shed light on the barriers that must be navigated to bridge the energy efficiency gap. These barriers encompassed the absence of prepared or existing HEMS products, conflicting stakeholder interests, and deviations from anticipated user behaviours. HEMS aimed to target occupants' energy inefficiencies while aligning with their preference for energy-efficient appliances. The study uncovered the emergence of conflicts and barriers during the adoption process, rooted in knowledge boundaries and social dynamics. Understanding these challenges was deemed pivotal in effectively addressing the intricate dimensions of HEMS adoption.

Through the case discussion, this study further investigated into the role of HEMS unearthed its capacity to function as boundary objects to approach particular desired scenarios of adopting HEMS in Taiwan. By acting as intermediaries between electricity companies and households, HEMS facilitated interaction and data sharing. This bolstered energy visibility, fostering awareness and potentially driving behavioural change alongside an elevated interest in energy consumption. The study highlighted HEMS experiments' contribution to enhancing product and service quality through valuable data collection and bug correction. As boundary objects, HEMS could play an indispensable part in conflict resolution, accommodating user preferences, and integrating information into optimisation models to heighten electricity grid efficiency.

In summary, this study's insights into the complex properties of HEMS adoption, identification of barriers, and delineation of its role as a boundary object collectively enrich the understanding of the adoption process. These understanding allows decision makers in market development to steer their efforts towards fostering appropriate assessment of HEMS adoption.

However, it is essential to acknowledge a key limitation of this study. The development of the evaluation framework was rooted in information collected from a systematic literature review, which, while comprehensive, introduces the possibility of inherent bias within the selected sources. The reliance on existing literature, although advantageous for establishing a strong foundation, may inadvertently introduce certain viewpoints or perspectives that could influence the design of the framework and subsequent findings. Recognising this potential limitation, future research could explore ways to mitigate bias by, for instance, incorporating a broader range of primary data sources and engaging with diverse stakeholders to ensure a more well-rounded and unbiased framework development process.

In addition, as with any research endeavour, limitations exist that warrant acknowledgement. The research design employed a comprehensive framework to address the research questions regarding HEMS adoption. The framework facilitated a holistic exploration of HEMS adoption scenarios, barriers, and roles in complex contexts. However, the reliance on qualitative analysis might have limited the ability to quantify the impact of adopting HEMS.

Moreover, the study might have gained further depth through the incorporation of a mixed-methods approach, seamlessly blending qualitative insights with quantitative data. Such an approach would have fortified the comprehension of HEMS' role by offering a more comprehensive and multi-dimensional perspective. It's important to note, however, that quantifying efficiency is contingent upon contextual factors, which can introduce challenges in ensuring consistent evaluations. Future endeavours could focus on refining a systematic methodology for collecting quantifiable information, while adeptly accounting for the intricate contextual nuances.

In conclusion, this study incorporated the concept of boundary object to explore the potential role of HEMS in achieving energy efficiency through investigating the complexities of HEMS adoption, knowledge barriers, collective works and the role of HEMS as boundary objects. Acknowledging the limitations of the study, future research could build upon these insights to deepen the understanding of HEMS adoption.

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Appendices

A

List of related papers

Table A.1 List of related papers: reviews on Title and Abstract

ID	Authors	Year	Article Title	Related?	Field	Review results	rvID
1	Pfeiffer, C; Puchegger, M; Maier, C; Tomaschitz, IV; Kremsner, TP; Gnam, L	2021	A Case Study of Socially-Accepted Potentials for the Use of End User Flexibility by Home Energy Management Systems	v	Title	keyword(s) or key concepts mentioned in title	1
2	Kong, XY; Zhang, SQ; Sun, BW; Yang, Q; Li, SP; Zhu, SJ	2020	Research on Home Energy Management Method for Demand Response Based on Chance-Constrained Programming	x	Abstract	the study focuses on technology development	-
3	Jia, KQ; Guo, G; Xiao, JC; Zhou, H; Wang, ZH; He, GY	2019	Data compression approach for the home energy management system	x	Abstract	the study focuses on technology development	-
4	Ghazvini, MAF; Soares, J; Abrishambaf, O; Castro, R; Vale, Z	2017	Demand response implementation in smart households	v	Abstract	the study focuses on technology development while the important role of HEMS to enable consumers' participating in DR is recognised	2
5	Guo, YM; Zhang, ZF; Guo, YJ	2022	SecFHome: Secure remote authentication in fog-enabled smart home environment	x	Abstract	the study focuses on technology development	-
6	Ren, MF; Liu, XF; Yang, ZL; Zhang, JH; Guo, YJ; Jia, YB	2022	A novel forecasting based scheduling method for household energy management system based on deep reinforcement learning	v	Abstract	"" the user costs are effectively reduced while the user satisfaction is maintained utilizing the proposed method""	3

Table A.1 List of related papers: reviews on Title and Abstract

ID	Authors	Year	Article Title	Related?	Field	Review results	rvID
7	Eom, S; Zhou, HZ; Kaur, U; Voyles, RM; Kusuma, D	2022	TupperwareEarth: Bringing Intelligent User Assistance to the Internet of Kitchen Things	x	Abstract	the study examines the product of a specific company, which is deviating from general cases	-
8	Li, YX; Zhang, XY; Gao, WJ; Qiao, JL	2022	Lessons Learnt From the Residential Zero Carbon District Demonstration Project, Governance Practice, Customer Response, and Zero-energy House Operation in Japan	v	Abstract	""recognizes how the residential consumers engaged and perceive delivered energy saving and cost reduction issues""	4
9	Mohammad, F; Ahmed, MA; Kim, YC	2021	Efficient Energy Management Based on Convolutional Long Short-Term Memory Network for Smart Power Distribution System	x	Abstract	the study focuses on technology development	-
10	Mohammadi, F; Faghihi, F; Kazemi, A; Salemi, AH	2021	A risk-based energy management system design for grid-connected smart homes	x	Abstract	the study focuses on technology development	-
11	Monyei, CG; Adewumi, AO	2018	Integration of demand side and supply side energy management resources for optimal scheduling of demand response loads - South Africa in focus	v	Abstract	""… is proposed to provide a platform for incorporating the demands and constraints of consumers… and suppliers""	5
12	Ul Haq, E; Lyu, C; Xie, P; Yan, S; Ahmad, F; Jia, YW	2022	Implementation of home energy management system based on reinforcement learning	x	Abstract	the study focuses on technology development	-
13	Mahmoudi, M; Afsharchi, M; Khodayifar, S	2020	Demand Response Management in Smart Homes Using Robust Optimization	v	Abstract	the study focuses on technology development while the user's satisfaction is taken into account	6

Table A.1 List of related papers: reviews on Title and Abstract

ID	Authors	Year	Article Title	Related?	Field	Review results	rvID
14	Sintov, ND; Schultz, PW	2017	Adjustable Green Defaults Can Help Make Smart Homes More Sustainable	v	Abstract	the study reviews behavioural knowledge in smart home technologies	7
15	Honold, J; Kandler, C; Wimmer, P; Schropp, B; Reichle, R; Grone, M; Bunemann, M; Klein, J; Kufner, M	2017	Distributed integrated energy management systems in residential buildings	x	Abstract	the study discusses the technical system	-
16	Shin, JS; Bae, IS; Kim, JO	2018	Impact of User Convenience on Appliance Scheduling of a Home Energy Management System	v	Title	keyword(s) or key concepts mentioned in title/ the study focuses on model development while putting effort in incorporating users' convenience knowledge (in a manner improving the flexibility of modelling method). The study also concludes its approach's potential in enhancing user's engagement	8
17	Dinh, HT; Lee, KH; Kim, D	2022	Supervised-learning-based hour-ahead demand response for a behavior-based home energy management system approximating MILP optimization	x	Abstract	the study focuses on technology	-
18	Javadi, MS; Gough, M; Lotfi, M; Nezhad, AE; Santos, SF; Catalao, JPS	2020	Optimal self-scheduling of home energy management system in the presence of photovoltaic power generation and batteries	v	Abstract	the study focuses on technology development while recognising its effect on users participation	9

Table A.1 List of related papers: reviews on Title and Abstract

ID	Authors	Year	Article Title	Related?	Field	Review results	rvID
19	Galvan, E; Mandal, P; Chakraborty, S; Senjyu, T	2019	Efficient Energy-Management System Using A Hybrid Transactive-Model Predictive Control Mechanism for Prosumer-Centric Networked Microgrids	x	Abstract	the study focuses on technology development	-
20	Munankarmi, P; Maguire, J; Balamurugan, SP; Blonsky, M; Roberts, D; Jin, X	2021	Community-scale interaction of energy efficiency and demand flexibility in residential buildings	v	Title	keyword(s) or key concepts mentioned in title; this study discusses the HEMS influence on different scale (customers and community scales)	10
21	Jamil, A; Alghamdi, TA; Khan, ZA; Javaid, S; Haseeb, A; Wadud, Z; Javaid, N	2019	An Innovative Home Energy Management Model with Coordination among Appliances using Game Theory	v	Abstract	””coordination among appliances has helped in increasing the user comfort by reducing the waiting time of appliances””	11
22	Kwon, Y; Kim, T; Baek, K; Kim, J	2020	Multi-Objective Optimization of Home Appliances and Electric Vehicle Considering Customer’s Benefits and Offsite Shared Photovoltaic Curtailment	v	Title	keyword(s) or key concepts mentioned in title	12
23	Lai, BC; Chiu, WY; Tsai, YP	2022	Multiagent Reinforcement Learning for Community Energy Management to Mitigate Peak Rebounds Under Renewable Energy Uncertainty	x	Abstract	the study focuses on technology development	-
24	Wang, ZY; Sun, M; Gao, CX; Wang, X; Ampimah, BC	2021	A new interactive real-time pricing mechanism of demand response based on an evaluation model	x	Abstract	the study focuses on technology development	-
25	Jafari, F; Samet, H; Seifi, AR; Rastegar, M	2018	Developing a two-step method to implement residential demand response programmes in multi-carrier energy systems	v	Abstract	the study focuses on technology development while taking into account user participation	13

Table A.1 List of related papers: reviews on Title and Abstract

ID	Authors	Year	Article Title	Related?	Field	Review results	rvID
26	Iqbal, MM; Sajjad, MIA; Amin, S; Haroon, SS; Liaqat, R; Khan, MFN; Waseem, M; Shah, MA	2019	Optimal Scheduling of Residential Home Appliances by Considering Energy Storage and Stochastically Modelled Photovoltaics in a Grid Exchange Environment Using Hybrid Grey Wolf Genetic Algorithm Optimizer	x	Abstract	the study focuses on technology development	-
27	Barbato, A; Capone, A; Carello, G; Delfanti, M; Falabretti, D; Merlo, M	2014	A framework for home energy management and its experimental validation	v	Abstract	the study focuses on technology while taking into account users' perspectives	14
28	Schwartz, T; Stevens, G; Jakobi, T; Denef, S; Ramirez, L; Wulf, V; Randall, D	2015	What People Do with Consumption Feedback: A Long-Term Living Lab Study of a Home Energy Management System	v	Title	keyword(s) or key concepts mentioned in title	15
29	Prakash, J; Naidu, SH; Aziz, IA; Jaafar, J	2021	Reward-based residential wireless sensor optimization approach for appliance monitoring	x	Abstract	the study focuses on technology	-
30	Javadi, MS; Gough, M; Nezhad, AE; Santos, SF; Shafie-khah, M; Catalao, JPS	2022	Pool trading model within a local energy community considering flexible loads, photovoltaic generation and energy storage systems	v	Abstract	""through cooperation, end-users in the local energy community market can reduce the total electricity bill""	16
31	Chavali, P; Yang, P; Nehorai, A	2014	A Distributed Algorithm of Appliance Scheduling for Home Energy Management System	x	Abstract	the study focuses on technology	-
32	Langer, L; Volling, T	2020	An optimal home energy management system for modulating heat pumps and photovoltaic systems	x	Abstract	the study focuses on technology development	-
33	Luo, FJ; Dong, ZY; Xu, Z; Kong, WC; Wang, F	2018	Distributed residential energy resource scheduling with renewable uncertainties	x	Abstract	the study focuses on technology development	-

Table A.1 List of related papers: reviews on Title and Abstract

ID	Authors	Year	Article Title	Related?	Field	Review results	rvID
34	Xu, ZH; Gao, Y; Hussain, M; Cheng, PH	2020	Demand Side Management for Smart Grid Based on Smart Home Appliances with Renewable Energy Sources and an Energy Storage System	x	Abstract	””our proposed model not only enhances users' utility but also reduces energy consumption cost””	-
35	Ni, Z; Das, A	2018	A New Incentive-Based Optimization Scheme for Residential Community with Financial Trade-Offs	v	Abstract	the study proposes an incentive-based modelling apporach taking into account the users' interaction with HEMS	17
36	Alkatheiri, MS; Alqarni, MA; Chauhdary, SH	2021	Cyber security framework for smart home energy management systems	x	Abstract	the study focuses on technology	-
37	Nilsson, A; Wester, M; Lazarevic, D; Brandt, N	2018	Smart homes, homes, home energy management systems and real-time feedback: Lessons for influencing household energy consumption from a Swedish field study	v	Title	keyword(s) or key concepts mentioned in title	18
38	Shafie-Khah, M; Siano, P	2018	A Stochastic Home Energy Management System Considering Satisfaction Cost and Response Fatigue	v	Abstract	the study focuses on technology development while taking into account consumers' needs	19
39	Faqiry, MN; Wang, L; Wu, HY	2019	HEMS-enabled transactive flexibility in real-time operation of three-phase unbalanced distribution systems	x	Abstract	the study focuses on technology development	-
40	Aki, H; Iitaka, H; Tamura, I; Kegasa, A; Hayakawa, H; Ishikawa, Y; Yamamoto, S; Sugimoto, I	2018	Analysis of measured data on energy demand and activity patterns in residential dwellings in Japan	x	Abstract	the subject is a bit delineating this study	-

Table A.1 List of related papers: reviews on Title and Abstract

ID	Authors	Year	Article Title	Related?	Field	Review results	rvID
41	Gazafroudi, AS; Shafie-khah, M; Heydarian-Forushani, E; Hajizadeh, A; Heidari, A; Corchado, JM; Catalao, JPS	2019	Two-stage stochastic model for the price-based domestic energy management problem	x	Abstract	the study focuses on technology development	-
42	Martinez-Pabon, M; Eyeleigh, T; Tanju, B	2018	Optimizing residential energy management using an autonomous scheduler system	x	Abstract	the study focuses on technology development	-
43	Aloise-Young, PA; Lurbe, S; Isley, S; Kadavil, R; Suryanarayanan, S; Christensen, D	2021	Dirty dishes or dirty laundry? Comparing two methods for quantifying American consumers' preferences for load management in a smart home	v	Abstract	""to compare two approaches for collecting and modeling consumers' load management preferences""	20
44	Lu, Q; Lu, SK; Leng, YJ; Zhang, ZX	2020	Optimal household energy management based on smart residential energy hub considering uncertain behaviors	v	Title	keyword(s) or key concepts mentioned in title	21
45	Lu, Q; Zhang, ZX; Lu, SK	2020	Home energy management in smart households: Optimal appliance scheduling model with photovoltaic energy storage system	v	Abstract	the study focuses on technology development taking into account users traits	22
46	Mohammadi, F; Faghihi, F; Kazemi, A; Salemi, AH	2022	The effect of multi-uncertainties on battery energy storage system sizing in smart homes	x	Abstract	the study focuses on technology development	-
47	Alilou, M; Tousi, B; Shayeghi, H	2021	Multi-objective energy management of smart homes considering uncertainty in wind power forecasting	x	Abstract	the study focuses on technology development	-
48	Alic, O; Filik, UB	2021	A multi-objective home energy management system for explicit cost-comfort analysis considering appliance category-based discomfort models and demand response programs	v	Abstract	""it is revealed that a residential consumer can make an explicit cost-comfort analysis""	23

Table A.1 List of related papers: reviews on Title and Abstract

ID	Authors	Year	Article Title	Related?	Field	Review results	rvID
49	Liemthong, R; Srithapon, C; Ghosh, PK; Chatthaworn, R	2022	Home Energy Management Strategy-Based Meta-Heuristic Optimization for Electrical Energy Cost Minimization Considering TOU Tariffs	x	Abstract	the study focuses on technology development	-
50	Le, MH; Ploix, S	2018	Sensibility and Uncertainties Analysis method dedicated to home energy management problem	x	Abstract	investigating the uncertainties but may not be able to provide knowledge for this study	-
51	Li, SL; Yang, JJ; Song, WZ; Chen, A	2019	A Real-Time Electricity Scheduling for Residential Home Energy Management	x	Abstract	the study focuses on technology development	-
52	Alilou, M; Tousi, B; Shayeghi, H	2020	Multi-objective unit and load commitment in smart homes considering uncertainties	x	Abstract	the study focuses on technology development	-
53	Goncalves, I; Gomes, A; Antunes, CH	2019	Optimizing the management of smart home energy resources under different power cost scenarios	v	Abstract	the transition process may be recognised from this study	24
54	Li, KP; Zhang, P; Li, G; Wang, F; Mi, ZQ; Chen, HY	2019	Day-Ahead Optimal Joint Scheduling Model of Electric and Natural Gas Appliances for Home Integrated Energy Management	v	Abstract	”” can save the total energy costs up to 30% for customers whilst ensuring their satisfaction levels””	25
55	Tushar, MHK; Zeineddine, AW; Assi, C	2018	Demand-Side Management by Regulating Charging and Discharging of the EV, ESS, and Utilizing Renewable Energy	v	Abstract	the study focuses on technology development while stakeholders involvement are discussed	26
56	Chen, SJ; Chiu, WY; Liu, WJ	2021	User Preference-Based Demand Response for Smart Home Energy Management Using Multiobjective Reinforcement Learning	x	Abstract	the study focuses on technology development	-
57	Elkazaz, M; Sumner, M; Pholboon, S; Davies, R; Thomas, D	2020	Performance Assessment of an Energy Management System for a Home Microgrid with PV Generation	x	Abstract	the study focuses on technology development	-

Table A.1 List of related papers: reviews on Title and Abstract

ID	Authors	Year	Article Title	Related?	Field	Review results	rvID
58	Minhas, DM; Frey, G	2020	Modeling and Optimizing Energy Supply and Demand in Home Area Power Network (HAPN)	x	Abstract	the study focuses on technology development	-
59	Najafi-Ghalelou, A; Nojavan, S; Zare, K	2018	Heating and power hub models for robust performance of smart building using information gap decision theory	x	Abstract	the study focuses on technology development	-
60	Rehman, S; Habib, HUR; Wang, SR; Buker, MS; Alhems, LM; Al Garni, HZ	2020	Optimal Design and Model Predictive Control of Standalone HRES: A Real Case Study for Residential Demand Side Management	x	Abstract	the study focuses on technology development	-

B

Lists of keywords and synonyms

Table B.1 Lists of keywords and synonyms

Components			**Interchangeable terms**
Terms representing HEMS			HEMS, demand-side management system, demand-side management unit, demand-side management controller, energy management system, energy management unit, energy management controller, optimised energy management system, optimised energy management unit, optimised energy management controller, optimized energy management system, optimized energy management unit, optimized energy management controller, smart energy management system, smart energy management unit, smart energy management controller, demand-side control*, demand-side schedul*, energy consumption control*, energy consumption schedul*, energy control*, energy schedul*, smart control*, smart schedul*, smart home control*, smart home schedul*, power control*, power schedul*, smart device, smart devices, home automation system, MavHome, load manager, energy box, gateway system
Limited to residential units			home*, house*, residen*
Efficiency of HEMS	*Option1*	*Element1*	reduc*, decreas*, minim?*, optimi?*, efficient, lower*, shift*
		Element1	energy, electricity, peak, use, waste, consump*, load*, cost*, demand*, power
	Option1	*Element1*	improv*, optimi?*, increas*, high*, more*, benefit*
		Element1	efficiency
Boundary objects			boundary object, boundary objects, boundary work, boundary organizations, boundary organisations
Human elements			resident*, occupant*, consumer*, user*, operator*, governor*

C

Interview guide

Interviewee: Marketing Manager of NexDrive Company
Duration: 1 hour
Interview type: Semi-structure interview
Original language: Mandarin
Questions:

Part I: The company's role in HEMS development: relationships (collaborations/interactions) with the government, power company, other energy service providers, and users, etc.

1. Who are the participants involved in the development and adoption of HEMS in Taiwan, what is your company's role, and what are the relationships between your company and other participants?
2. This study assumes that the adoption of HEMS may involve complex properties, including differences in knowledge, self-dependency (path dependence), and novelty. In the case of Taiwan, do you consider the development and adoption of HEMS to involve the aforementioned complex properties?

Part II: DextDrive company's strategy in designing and providing HEMS products and services to respond to the uncertainty involved in the process, such as diverse user needs, behaviors, and preferences.

3. Referring to the "Research on HEMS Application Services and Business Models" proposed by your company, which includes nine dimensions: target customers, channels, value propositions, customer relationships, key resources, key activities, key partners, revenue streams, and cost structure. Does this also involve issues of uncertainty?
4. Related research has pointed out that diverse user needs are one of the uncertain factors involved in the effectiveness of HEMS in energy efficiency improvement. What is your company's strategy for responding to this issue when launching HEMS products and services?

Part III: Experience with current products and services offered, such as the "1% Energy Action Plan" project launched by NextDrive company.

5. Have there been any difficulties in adopting (launching) HEMS products and services? If so, what are the main challenges?
6. In times of difficulty, how would you describe the relationships between the roles involved, such as whether there are conflicting groups or whether the roles form an alliance? If so, what are the key role relationships that may need to be addressed?
7. Have the effects of HEMS on energy savings and energy management efficiency been evaluated? Does the result meet your expectations?

8. Does current experience reflect the possibility of further improving energy efficiency or other potential? If so, please describe how current experience shows how HEMS contributes to energy efficiency or reflects other potential.
9. This study believes that the application of HEMS can promote a positive cycle process of energy saving and energy management efficiency improvement. Do you think that HEMS can perform such function(s)? Or do you think that HEMS performs its function(s) differently?
10. In the process of introducing HEMS (before, during, and after), have the relationships between HEMS and relevant participants changed?