ERA-Net Smart Grids Plus project CESEPS
Co-Evolution of Smart Energy Products and Services

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CESEPS
Co-Evolution of Smart Energy Products and Services

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ABSTRACT

To develop a viable market for residential smart energy systems, the (re)design of innovative product-service combinations in smart grids must be more responsive to the demands of various stakeholders. In this research project, entitled CESEPS, we have therefore explored smart energy systems from an interdisciplinary perspective with a focus on quantifying local production of sustainable electricity eventually in combination with storage, capturing stakeholders practices in smart grid pilots, evaluations of various forms of e-mobility, forecasting of the performance of smart energy systems by (co-)simulation and the design and development of smart energy products and services. This has been done in the Netherlands and Austria and involved evaluations of existing residential smart grid pilots in these two countries as well as the design, simulation and testing of smart grid products.
For the individual work packages (WPs) we draw the following conclusions:

WP2 on Marketplaces: National regulations, policy and market incentives play a major role in inertia around implementation of mature smart grid solutions in both Austria and the Netherlands. Therefore based on our research we advise to pay more attention to reducing cross border barriers in Europe around energy regulations and energy policy. This will involve multiple stakeholders.
WP3 on Stakeholders: Public organizations and grid operators, play a more dominant role than energy companies in smart grid development, but the expectations of DSOs and consultants about a flexibility market have so far remained unfulfilled. End users are very interested in renewable energy but in order to develop successful smart grid environments, we shouldn't address users not just as energy consumers, but also as managers of local energy systems, meaning they would gain decision making power, to learn about their role as empowered co-providers.
WP4 on Technologies and Methods: Based on the research conducted in this project we can conclude that from a technical point of view the new smart energy systems which have been applied in various pilots perform well and reliably and can therefore be used as expected for distributed power generation as well as demand side management. Hence they can contribute to self-sufficient renewable energy systems.
WP5 on Smart Energy Products and Services: Smart energy products and services should provide the feeling to end users of being part of the renewable energy systems rather than having an interaction with black box technologies.

General recommendation: the renewable energy transition is a multidisciplinary problem with various stakeholders, with considerable dependencies on geography and regulations, which require complex and complete solutions in order to become feasible and widespread applicable. Therefore, we would recommend that multidisciplinary approaches such as the three layer model will become more established in the development of smart grid environments.

Naturally in this short abstract we can't cover a project which was executed by 22 researchers in the period of 2016 to 2019, therefore we hope that you will enjoy reading the full report.

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Abbreviations and Acronyms

Abbreviations & Acronyms	Meaning
AC	Alternating Current
AFC	Alkaline Fuel Cell
BESS	Battery Energy Storage Systems
BRPs	Balance Responsible Parties
CaPP	Car as Power Plant
CDH	Central Data Hub Model
CDSM	Centralized Demand Side Management
CESEPS	Co-Evolution of Smart Energy Products and Services
CHP	Combined Heat and Power
CPP	Critical Peak Pricing
CTA	Constructive Technology Assessment
DHW	Domestic Hot Water
DAM	Data Access-Point Manager Model
DC	Direct Current
DG	Distributed Generation
DIM	Delft Innovation Model
DLC	Direct Load Control
DR	Demand Response
DR-DB	Demand Bidding DR
DRES	Distributed Renewable Energy Source
DSM	Demand Side Management
DSO	Distribution System Operator
EE	Energy Efficiency
EMCS	Energy Monitoring and Control Systems
EMS	Energy Management System
EV	Electric Vehicle
FCEV	Fuel Cell Electric Vehicle
FFT	Fossil Fuel Technology
G2V	Grid to Vehicle Services
GHG	Green House Gas
HEMS	Home Energy Management Systems
HP	Heat Pumps
HVAC	Heating, Ventilation and Air Conditioning
IBDR	Incentive-Based Demand Response
IDM	Industrial Design Method
IDS	Innovative Design and Styling
IJ	Innovation Journey
LCA	Life Cycle Assessment
LMP	Locational Marginal Price
LU	Lead User study
MCFC	Molten Carbonate Fuel Cell
MDM	Multilevel Design Model
NP	Nuclear Power
O&M	Operations and Maintenance
PAFC	Phosphoric Acid Fuel Cell
PEMFC	Polymer Electrolyte Fuel Cell
PBDR	Price-Based Demand Response
PDPD	Platform-Driven Product Development
PMC	PowerMatching City
PSP	Pecan Street Project
PV	Photovoltaic
P2G	Power-to-Gas
RDM	Risk Diagnosing Methodology
RE	Renewable Energy

RTP	Real-Time Pricing
SEPS	Smart Energy Products and Services
SG	Smart Grid
SOC	State of Charge
SOFC	Solid Oxide Fuel Cell
SOFCR	Solid Oxide Fuel Cells Operating as Reformer
TCL	Thermostatic Controlled Loads
ToD	Time of Day
ToU	Time-of-Use Pricing
TRM	Technology RoadMapping
VPP	Virtual Power Plants
TRIZ	Theory of inventive problem solving (Russian acronym)
TSO	Transmission System Operator
V2G	Vehicle to Grid Services

The secret of change is to focus all your energy,
not on fighting the old but on building the new[1]

[1] Quote by Socrates

1 INTRODUCTION

1.1 INTRODUCTION TO THE CESEPS PROJECT

1.1.1 Introduction

In this final report of the ERA-Net Smart Grids Plus project “CESEPS”, we explore existing smart grid environments by evaluating the performance of smart energy systems in relation to the energy products and services used as well as stakeholder processes and end-users perceptions. We do this for a significant number of realized smart grid pilots in the Netherlands and Austria. CESEPS is the acronym for the project’s full title “Co-Evolution of Smart Energy Products and Services” indicating that smart grids, smart energy systems and the products and services that are applied in them are still in development towards optimized solutions for various conditions of use.
Past studies have indicated that the needs of the energy industry must be tightly coupled to end-users in the design of new energy products and services which could support changes in household energy management.
Also the use of renewable energy in smart grid pilots can be better matched to end-users consumption patterns by products and services that stimulate demand side management. In this scope e-mobility could play a significant role in the mid-term smart grid future in realizing energy-efficient and sustainable smart grids at a local and regional level. Regarding these topics, we compare findings from the Netherlands and Austria with the aim to develop a joint framework for smart grids co-evolution. For this purpose in the project the following partners collaborated, in the Netherlands: University of Twente, Delft University of Technology, Wageningen University of Research, Utrecht University and DNV GL and in Austria:TU Graz, Austrian Institute of Technology and eseia. This final report contains the results of the Dutch team of the CESEPS project which conducted research from early 2016 until January 2019.

The integration of intermittent renewable energy sources and decentralized energy production in existing electricity grids is a technical and organizational challenge. Moreover, the means to temporarily store this energy, as well as the expected use of large numbers of new types of energy products (for example electric cars and heat pumps) will pose big engineering questions in the next 10-20 years. Smart grids are an important promising solution - at transnational, national and local levels - supporting the transition from centralized energy generation to energy systems containing more distributed, intermittent energy generation with a high penetration of renewable energy systems and flexible options to manage energy flows via advanced ICT. This paradigm shift will lead to new requirements towards increased flexibility of power systems, increased network capacity and new innovative energy products and services. This paradigm shift is supported by industry leaders such as Isabelle Kocher (CEO of Engie) who indicated that “Renewable energy is an essential part of our strategy of decarbonization, decentralization, as well as digitalization of energy” (Kocher, 2018) and Paul Polman (CEO of Unilever) we mentioned that “Renewable energy could reduce emissions but also create jobs and improve public health” (Polman, 2015).

After technical aspects, the second biggest challenge in smart grids development is to understand and influence consumer behavior in smart grids as social acceptance and a more active role of energy consumers are of great importance for the success of smart grids. Currently however the sector is strongly driven by technical developments; therefore to support a healthy market place for smart energy systems, the supply of innovative product-service combinations in smart grids must be more responsive to the demands and requirements of various stakeholders in terms of performance, costs, safety, robustness and comfort. At present a lot of uncertainty exists about what product-service combinations will be offered, and a better understanding of these issues is required. Existing smart grid pilot projects are a rich source of information regarding marketplaces for new innovative energy products and services and the adoption processes of various stakeholders, including utilities, consumers, and network operators, in these smart grid pilots. These are important factors that can contribute to the development and successful implementation of smart grids within Europe. By capturing critical stakeholders’ preferences and experiences, smart energy products and services can be developed in a more effective way than solely through technical approaches that mainly focus on increased energy performance and reduction of costs.

1.1.2 Co-evolution

To overcome these challenges we suggest a co-evolutionary approach through which technology, marketplaces, emerging user needs and their adaption, as well as needs of stakeholders in business and governance will be merged. In biology, co-evolution is the term for a long-term process by which several organisms evolve together while adapting to – and in time, changing – environments. Organisms make use of other organisms by building partnerships or by living on or in them, and have to adapt to their environments and to these relationships. These adaptations result in future generations with better features suitable for survival, often by improved mutual relationships – different organisms working better together- and sometimes these changes are that intense that the next generations will become that different that they may become different species. In applying this co-evolutionary thinking to the mid- and long-term development of smart grids we see the 'smart grid' as an environment and its energy technologies, ICT solutions, end-users, and other stakeholders as complementary organisms that have to collaborate to make the smart grid function as intended: flexible, energy-efficient, reliable and robust, sustainable, and cost-effective. In that sense the co-evolution of multiple compatible smart grid technologies are put in the context of society and product development from a process perspective.

1.1.3 Challenge and objectives

By exploring the performance of energy products and services and end users' perceptions in a significant number of existing smart grid pilots in the Netherlands and Austria, we address the main challenge of supporting the energy transition by open markets for energy products and services while facilitating the active participation of customers. Through the evaluation of existing pilots and by designing, implementing, and evaluating new pilots for the charging of e-vehicles and/or home energy management products, we will investigate in detail the effect of the increased generation from renewables in support of internal energy markets. We will investigate the complex interaction between variable decentralized renewable generation and the energy demand of various stakeholders at the levels of residential areas and national regions and we will place them in the perspective of transnational comparison. The research presented in this report is based on information originating from pilots and demonstration projects in the field of smart grids, while demonstrating applicability of the three research layers of Stakeholder/Adoption, Marketplace and Technology, which is explained in Section 1.2 . As such our project integrates the three research layers as envisioned by the ERA-Net Smart Grids Plus scope of the three-layer model.

The project's main objective is to support the development of smart energy products and services for local smart grids that better respond to the demands and concerns of all stakeholders in terms of performance, cost, reliability, safety and robustness, sustainability and energy-efficiency, and end-users' comfort. The research was therefore focused on comparative validation of technologies and concepts of existing demonstrations and the further development of new innovative energy products and services for the present and medium-term using a co-evolutionary approach.

Main project goals:

1. To develop knowledge about the role of stakeholders and end users in local smart grid pilots by gaining insights into their needs and wishes for smart energy products and services, the needed changes in their energy practices, and contextual barriers encountered.
2. To develop knowledge about the actual performance of technologies in local smart grid pilots by evaluating monitoring data from these projects and executing measurements on site. Complementary to the experimental approach, theoretical modelling of energy performance of smart grid technologies and their interaction will be established.
3. On the basis of these insights (from 1 and 2) to construct a set of specifications, designs, and implementation guidelines for the development of smart energy products and services for local smart grids that enable the development of fully functional solutions for a better smart grid environment and its elements and users.
4. It is aimed to accelerate the innovation process of smart energy products and services by informing stakeholders at intermediate points through the project and receiving their feedback to be included in the project.
5. To develop energy products and services that can be customized for individual households as well as communities, integrating the knowledge and needs of inhabitants and other stakeholders.
6. To implement some of these newly developed energy products and services on test sites of the consortium

7. To develop novel smart grid applications with and without storage with a focus on e-vehicles, demand side management, increased hosting capacity, and customer safety.
8. To validate and scale the smart energy products under various situations, including a co-simulation framework combining real and simulated components for scaling and replication.

1.1.4 Organization of the CESEPS project

On the basis of the Austrian – Dutch collaboration the project has been executed according to a Work Package structure comprising the following six Work Packages that refer to the three-layer model (see Section 1.2) of the ERA-Net Smart Grid Plus Program. These Work Packages (WP) are :

WP1: Project Management,
WP2: Marketplaces,
WP3: Stakeholders,
WP4: Technologies and Methods,
WP5: Smart Energy Products and Services, and finally
WP6: Knowledge Community.

The Austrian research team has been fully operated according this Work Package structure whereas on the contrary the Dutch research team had a semi-structured set-up and mainly contributed to WP2 to WP5 on the basis of exploratory research results. Since WP1 is closely embedded in the management activities of this project, in this section we will describe the project only from a contents-wise perspective as represented by WP 2 to WP5. In Table 1.1 it is shown which organization has been contributing to which Work Package in the CESEPS project.

WP2: Marketplaces aims at delivering input and help to synthesize smart energy products in existing and future marketplaces as well as developing new market concepts for improved consumer involvement. It comprises the following tasks: (T2.1) a meta-study on existing literature about existing Smart Grids, (T2.2) regulatory conformity to investigate required changes in regulatory frameworks to successfully deploy new services and products, (T2.3) scenarios for future marketplaces for smart energy products and services and (T2.4) the development of guidelines for Innovation processes around smart energy products and services.
WP3: Stakeholders aims at gaining knowledge about stakeholders and end-users. This Work Package focuses on three tasks (T3.1) stakeholder interviews, (T3.2) end-user studies in Smart Grid pilots and (T3.3) socio-economic assessments to evaluate the cost-benefit performance of local smart grids.
WP4: Technologies and Methods covers research on smart grid technologies and the methods to evaluate them, such as data monitoring and simulation. This Work Package contains 4 tasks, which are related to the core technologies that are topics of the research, (T4.1) grid Stability and flexibility, (T4.2) demand side management and forecasting, (T4.3) e-vehicles integration, (T4.4) data management and storage.
WP5: Smart Energy Products and Services is the Work Package that merges experiences, findings and results originating from WP2, WP3 and WP4 into activities that are aiming to support improved product development of smart energy products and services (SEPS). WP5 covers five tasks, namely (T5.1) conceptual product design of SEPS, (T5.2) the realization of an advanced co-simulation environment for SEPS in a market situation and various scenarios of use, (T5.3) a laboratory setup to test and analyze the applicability of conceptual SEPS, (T5.4) small pilots on campi and (T5.6) design guidelines for SEPS resulting from experiences in WP5.
WP6: Knowledge Community. In order to maximize the impact and reach of the project's results and achievements to the wider European Community, a dedicated networking, training, and cooperation partner, eseia, was involved to contribute greatly to the WP6 Knowledge Community. By the project a new Knowledge Community regarding residential smart grid experiences, and the development of new energy products and services had to be established. The knowledge community work package enable monitoring of progress and results, emphasizing and fostering interoperability, scalability and replicability of the results and solutions deployed on a national and European level within the ERA-Net Smart Grids Plus initiative.

Because this final report is mainly representing the findings of the Dutch team, it won't for instance report in depth about WP2 on Marketplaces. Also it won't report about WP6 which is about the Knowledge Community, however it will be mainly focused on results originating from WP3 on Stakeholders, WP4 on Technologies and WP5 about Smart Energy Products and Services.

Table 1.1 Overview of the Work Packages of the CESEPS project and the extent to which the collaborating partners contributed to specific WPs.

Work packages	UT	TUD	WUR	UU	DNV GL	TUG	AIT	eseia
WP1: Project Management	xx							x
WP2: Marketplaces							x	
WP3: Stakeholders	x		xx					x
WP4: Technologies and Methods	x	xx		x	x	xx	xx	
WP5: Smart Energy Products and Services	xx	x			x	x	x	
WP6: Knowledge Community								x

1.1.5 The structure of this report

In this chapter, in Section 1.2, the theoretical framework for this study, namely the three-layer model is presented and described. In Chapter 2, smart grids pilots are presented in the international context of this project. Also the details of the pilots are shown that were studied at a national level. The role of stakeholders and end users in local smart grid pilots is explored in Chapter 3 by gaining insights into their learning processes, the needed changes in their energy practices, and contextual barriers encountered. Chapter 4 reports on experiences with smart grid pilots, data analysis and comparison of the pilots, and research activities on demand side management, storage and hydrogen technologies. Chapter 5 will be dedicated to smart energy products and services, their design, tests in multiple environments and conditions, including co-simulation of the SEPS and end-user studies. Finally, this report will be completed by discussions and conclusions regarding the full project which are presented in Chapter 6.

1.2 Three-Layer Model for Smart Grid Environments [2]

In this section, a framework is presented for the evaluation of smart grid environment which is called the three-layer model. This three-layer model comprises three specific categories, or 'layers', namely, the stakeholder, market and technologies layers. Each layer is defined and explored herein, using an extensive literature study regarding their key elements, their descriptions and an overview of the findings from the literature. The assumption behind this study is that a solid understanding of each of the three layers and their interrelations will help in more effective assessment of residential smart grid pilots in order to better design products and services and deploy smart grid technologies in networks. Based on our review, we conclude that, in many studies, social factors associated with smart grid pilots, such as markets, social acceptance, and end-user and stakeholder demands, are most commonly defined as uncertainties and are therefore considered separately from the technical aspects of smart grids. As such, it is recommended that, in future assessments, the stakeholder and market layers should be combined with the technologies layer so as to enhance interaction between these three layers, and to be able to better evaluate residential smart energy systems in a multidisciplinary context (Reinders et al., 2018a; Reinders et al., 2018b).

1.2.1 Smart grid environments

For the successful deployment of residential smart grids, it is evident that interdisciplinary information about energy technologies, energy markets and the needs of various types of stakeholders must be identified, merged, and implemented in practice. Therefore, in this section, the results of an in-depth literature study are presented, aimed at elaborating a framework for gathering knowledge and developing understanding about residential smart energy systems. This framework, called the three-layer model, comprises three layers: stakeholders, the market, and technologies (Reinders et al., 2016). Each layer is defined below. The framework originates from the European research program, ERA-Net Smart Grids Plus, in which it is considered to provide a common context for interdisciplinary smart grid research (see Figure 1) (ERA-Net Smart Grids Plus, 2017). According to the International Energy Agency (IEA), a smart grid is defined as "an electricity network that uses digital and other advanced technologies to monitor and manage the transport of electricity from all generation sources in that (local) network to meet the varying electricity demands of end-users" (International Energy Agency, 2011).

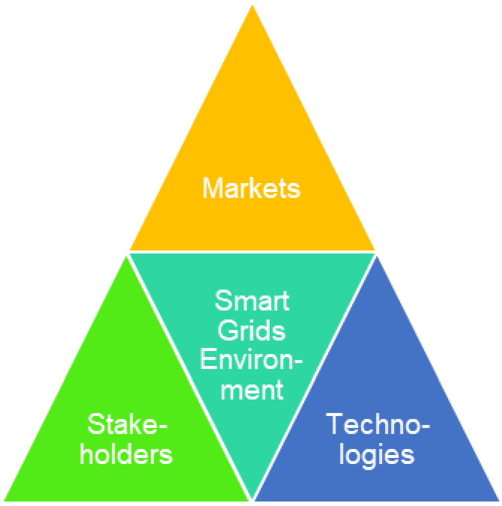


Figure 1.1. The three-layer research model for smart grids environments (adapted from ERA-Net Smart Grids Plus, 2017).

[2] A significant part of this chapter is based on our review publication and our literature study:

- Reinders, A., Übermasser, S., van Sark, W., Gercek, C., Schram, W., Obinna, U., Lehfuss, F., van Mierlo, B., Robledo, C., and van Wijk, A. (2018). An Exploration of the Three-Layer Model Including Stakeholders, Markets and Technologies for Assessments of Residential Smart Grids. Applied Sciences 8, 2363.

- Reinders, A., Hassewend, B., Obinnna, U., Markocic, E., de Respinis, M., Schram, W., van Sark, W., Gultekin, E., van Mierlo, B., van Wijk, A., et al. (2017). Literature Study on Existing Smart Grids Experiences, Report resulting from CESEPS project

In this work, we focused on the specific category of smart grid environment known as residential smart grids and their pilot projects for experimenting with diverse features. Residential smart grids are located in the low voltage grid, usually in the built environment, and involve tens to hundreds of households that are equipped with smart energy products and services.

Our definition of smart energy products and services (SEPS) includes all the products and services that have the ability to support the active participation of end users by efficiently and reliably managing their energy systems and balancing the mismatch between electricity demand and supply (Geelen et al., 2013a).

Below each layer of the model is briefly described in order to provide a general understanding for the reader.

Stakeholders layer
In this layer stakeholders cover a diverse group of entities, ranging from individual end-users, communities, network operators, and aggregators to (local) governmental organizations. Stakeholders interact with smart grids through an interest or concern. Some features of smart grids, such as demand side management (DSM) and exchange of energy with other end users (peer-to-peer trading) involve individual end-user type stakeholders of the type of individual end users, whereas other features—such as a high penetration of renewable energy at a local level, as well as electric mobility (ERA-Net Smart Grids Plus, 2017), (Geelen et al., 2013a), (Verhoef et al., 2017), (Griffiths et al., 2007) involve stakeholders which have a more organizational character such as network operators and governmental organizations.

Markets layer
This layer comprises all the financial and business-related aspects of smart grids. Energy market structures, the micro-economics of energy technologies and energy billing belong to the markets layer. Also factors such as investments, net present value (NPV), levelized costs of electricity (LCoE), electricity tariffs and pricing mechanisms, fall into this category (Metz, 2017), (Universal Smart Energy Framework, 2017).

Technologies layer
The technology layer covers all technological aspects of smart grids (Wijk et al., 2014), (Wijk et al., 2017), (Oldenbroek et al., 2017a) related to energy technologies and information and communications technology (ICT), among which, but not exclusively, smart grids' networks, distributed energy resources (DER) such as photovoltaic(PV) systems, wind turbines, micro-combined heat and power (µCHP) (Gercek, 2018) (Gercek and Reinders, 2018a), energy storage systems (Schram et al., 2018a), home energy management systems (HEMSs), DSM (Weck et al., 2017), demand shifting (Gercek and Reinders, 2018a), demand and supply forecasting algorithms, electric vehicles (EVs), EVs' charger stations, stationary fuel cells and hydrogen fuel cell electric vehicles (FCEVs) (Robledo et al., 2018a).

Flexibility

In addition to the three layers, special attention is given to 'flexibility' in this paper, as it is a main characteristic of future energy systems. It is defined as a "general concept of elasticity of resource deployment providing ancillary services for the grid stability and/or market optimisation" according to CENELEC (CEN-CENELEC-ETSI Smart Grid Coordination Group, 2012). In other words, electrical flexibility is the ability of a system to deploy its resources to respond to changes in net load, where the net load is defined as the remaining system load not served by variable generation (Lannoye et al., 2012). Because the intermittent nature of renewable energy generation may threaten the stability of the overall system, smart grids can provide the flexibility needed for the correct operation of the energy system.

Aim

The main aim of this review was to emphasize the importance of each of the three layers and the current knowledge of each layer, to show the number of research activities in the different disciplines, and make an attempt to define the key elements of residential smart grids for sustainable energy and flexibility. To this end, a thorough review of the literature was performed. Compared to other established frameworks—such as the Transactive Energy [21], the Universal Smart Energy Framework (USEF) (Universal Smart Energy Framework, 2015), and the Energy Flexibility Platform & Interface (Flexiblepower Alliance

Network, 2018) —our review approaches energy transition at the residential level, using the theoretical three-layer model framework. We take into consideration each layer and their interrelations, suggesting cooperation among disciplines and parties, from their very beginnings and into the design phase. The main advantage of our approach is that we distinguish among the various disciplines in order to allocate knowledge and barriers for each layer in residential smart grid projects. This is a different approach than most of the stochastic or techno-economical models (Marzband et al., 2018a), (Marzband et al., 2018b). In this way, we aimed to decrease the uncertainties and increase active involvement at the residential level, making stakeholders and prosumers (consumers that also generate energy) part of the energy transition, and to stimulate feedback from end-users to designers. The research approach is presented in Section 2, with insights from the literature regarding the three layers then being presented (Section 3) and discussed (Section 4). The paper is summarized in the Conclusions (Section 5).

1.2.2 Research Approach

Our research consisted of reviewing journal papers, conference papers, reports and websites of interest to smart grids in the framework of technologies, markets, and stakeholders. The term 'smart grid' was used for the first time in 1966 (Darlington et al., 1966). Caution should be taken because at that time the term 'smart grid' was related to radio wave transmissions instead of electricity grids. The first official definition of a smart grid was approved by the US Congress in 2007, and signed into law in the same year (US Energy Independence and Security Act). According to a search in Scopus, which took place in November 2018, since 2007, there have been more than 100,000 papers published mentioning the term 'smart grid'. We found it most significant to consider articles that mentioned 'smart grid' in the abstract, title or keywords in our literature study. We found around 40,000 works, 92% of them being conference papers (64%) and articles (28%). The literature study is summarized in Figure 2, and pertains to the years and different layers proposed above.

Up to 2012, the number of papers was exponentially increasing for all areas of research into smart grids. Since 2012, the increasing annual number of publications on smart grid topics has led to a massive volume of more than 4000 publications per year, represented by a linear increase between 2012 and 2015. Around 5600 publications were published in 2016, which is very similar to 2017. At the beginning of November 2018, the number of publications in 2018 had already reached 5200. Although the year has not ended yet, we did include 2018 in our results (Figure 2). Based on affiliation, most of the publications originated from the EU (37.5%), the USA (22%), China (19%), and other countries (21%). The trends are similarly exponential before 2012 for almost all regions, and for all disciplines. After 2012, the number of publications stabilized around 1000 publications per year for the USA and China, although trends in EU countries vary considerably. The Joint Research Centre of the European Commission database and reports indicate that 953 smart grid projects have been funded in the EU since 2007, by 2900 different organizations, involving 5900 participants, and with investments of around €5 billion (Gangale et al., 2017). This diversity in projects and participants, gave the EU the lead in the number of scientific publications. For the USA, the number of projects announced on government websites was limited to only 119. As such, the related budget ($4.5 billion) indicates that projects funded in the USA were mostly larger-scale projects than in the EU (Office of Electric Delivery and Energy Reliability for the SGIG, 2016). For China, pilot projects were expected to be even more concentrated, as today there are 15 smart city pilots, with an expected $7.4 billion of investments by 2020 (JUCCE, 2018).

A further analysis was needed in order to categorize papers in terms of the three layers proposed of the framework, aimed at highlighting the trends in weight of research directed towards each layer. The boundaries between the disciplines are difficult to clarify. A classification based on which journal the publication appeared, and it led to relatively very small number of papers for the market (Business, Management, and Accounting: 2.6%) and stakeholders (Social Sciences Journals: 4.2%) layers. Therefore, we searched in Scopus using the keywords that we used to define the layers. Multidisciplinary studies were taken into consideration so publications dealing with than one layer were mentioned in both corresponding layers. Therefore, the sum of the publication for each layer is greater than the total number of papers. It appears that markets and stakeholder layers' tendencies are very close to each other. A possible explanation could be that many social scientific studies on users were critical of the market layer's scientific contributions or insights, and those papers thus represent critiques. Another explanation could be that user behavior, stakeholder investments and expectancies played a major role in the market layer, considering the dependency of energy price on demand. The technologies layer showed at least 50% more publications than the other layers regardless of the year of publication.

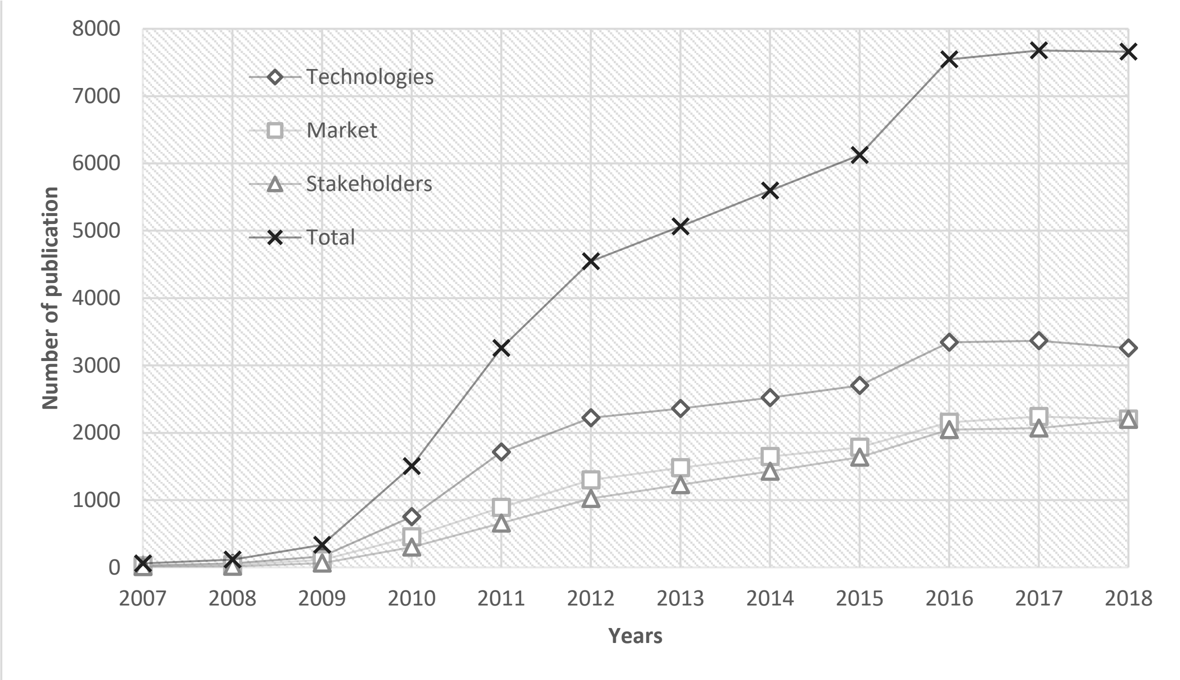


Figure 1.2. Yearly number of publications found by applying search term "smart grid" in Scopus.(November 2018)

1.2.2.1 Stakeholders layer

Looking at the stakeholders layer, the main focus is on residential customers and prosumers (Michaels and Parag, 2016), (Fell et al., 2015), (Horne et al., 2015). It was found that users, as they are described in the more recent research, not only have different labels—such as customers, consumers, prosumers and end users—but are also assumed to behave differently from each other (Geelen et al., 2013a), (Vliet et al., 2005), (Goulden et al., 2014),(Geelen, 2014). The most prevalent type reported on in the literature is the consumer, who is supposed to adapt to new developments in the energy system, such as smart grids. The prosumers are seen as users who consume and (co-)produce energy, who are sometimes also seen as potential active players on energy markets through aggregators (Naus et al., 2014),(Geelen et al., 2013b). The prosumers' most important attribute is their 'proactiveness' inside the new energy system, which differs from passive consumers, who merely have to accept or adopt smart grids, and end users. Furthermore, based on the papers that focused on user experiences, with special attention paid to demand side management, it appears that the issue of the acceptance of smart grids is widely discussed. Only a few studies built on evaluations of real life experiences based on smart grid projects (Smale et al., 2017a), (Raimi and Carrico, 2016), whilst most studies focused on future scenarios and (online) surveys (Fell et al., 2015), (Raimi and Carrico, 2016), (Buchanan et al., 2016), (Döbelt et al., 2015) (see report (Reinders et al., 2018a) for further details).

In particular, end-users' knowledge with regard to smart grids, is shown to both enhance acceptance and to create confusion (Horne et al., 2015), (Verbong et al., 2013a), (Lopes et al., 2016) . The literature review shows that from current smart grid projects and the reference framework USEF, the following other main stakeholder groups can be distinguished in smart grid environments: business customers, aggregators, balancing responsible parties, balancing service providers (BSPs), suppliers, distribution system operators (DSOs), transmission system operators (TSOs), governments, and other regulators (Table 1) (Universal Smart Energy Framework, 2017).

The role descriptions shown in Table 1 indicate stakeholders' roles and their interactions with the markets or technologies layers. Our study also shows that the future roles of other stakeholders, other than the residential customers, are foremost mentioned in policy reports with a special focus on the role of the DSOs, which are generally public organizations. Mostly, their concerns are reliability and equity among the residential energy consumers, and not the development of new markets. From these reports, it seems that uncertainties still exist with regards to market structures (monopoly versus competition), task delegation, the necessity of new (independent data handling) institutions, etc.; however, again, there is very little information about the exact roles of the stakeholders inside smart grids pilot projects, nor as facilitators of the renewable energy transition.

DSOs in the Netherlands play a major role in improving the reliability and robustness of the local grids in response to the supply of distributed renewable energy and expected peaks in demand for charging EVs. To support this statement, Dutch DSOs participated in 28 out of 31 projects with at least 15 households in each. In 12 of these pilots, they were part of the project consortium (Reinders et al., 2018a). Regarding TSOs, their role is closely related to that of the DSOs, with the duties of developing and maintaining the transmission of electricity, and balancing supply and demand across different districts. They usually have a particular interest in new DER technologies as vehicle-to-grid (V2G) in order to provide local balance and supply to decrease transmission and avoid congestion. In the Netherlands, the TSO also pilots some of the smart grids with aggregators.

Table 1.2. Stakeholders in smart grids environments and descriptions of their roles [adapted from (Universal Smart Energy Framework, 2017)]

Stakeholder Group	Description
Residential or business prosumer	A residential customer or utility business that produces electricity. Roof top PV installations and energy storage battery systems are examples of homeowner investments that allow people to do both - consume and produce energy - for use locally or export during certain parts of the day or the year.
Aggregator	A person or company combining two or more customers into a single purchasing unit to negotiate the purchase of electricity from retail electric providers, or the sale of electricity to these entities. Aggregators also combine smaller participants (as providers or customers or curtailment) to enable distributed resources to play in the larger markets.
Balancing responsible party (BRP)	A legal entity that manages a portfolio of demand and supply of electricity and has commitment to the system operator in an ENTSO-E (European Network of Transmission System Operators for Electricity) control zone to balance supply and demand in the managed portfolio on a Program Time Unit (PTU) basis according to energy programs.
Balancing service provider (BSP)	Balancing Service Provider (BSP) in the European Union Internal Electricity Market is a market participant providing Balancing Services to its Connecting Transmission System Operator (TSO), or in case of the TSO-BSP Model, to its Contracting TSO.
Supplier	A supplier provides energy to end customers, based on a contract. The energy can be from the supplier's own power plants or traded at relevant markets.
Distribution system operator (DSO)	The DSO is responsible for the safe and secure operation and management of the distribution system. DSOs are also responsible for the planning and developing of the distribution system.
Transmission system operator (TSO)	A legal entity responsible for operating, developing and maintaining the transmission system for a specific zone and, where apposite, its interconnections with other systems, and to guarantee the long-term ability of the system to meet reasonable demands for the transmission of electricity.
Government / Regulator	The regulator must strengthen competition and ensure that this does not compromise security of supply and sustainability. To act even-handedly in the interests of all market participants, regulators must be politically and financially independent.

1.2.2.2 Market Layer

From the existing literature, it can be concluded that several incentives for smart grid environments are present at the market level. Namely, aggregators can operate on the spot markets, i.e., by energy arbitrage, and on the balancing markets (Universal Smart Energy Framework, 2017), however, some market barriers are present. For example, in many European countries, it is impossible for renewable electricity generation to operate on balancing markets, while this generation is very suitable to use for downward regulation (Hu et al., 2017). Another current market inefficiency is the risk that current renewables generation incentive schemes (especially feed-in tariffs) decrease the value of newly installed renewables generation over time. Smart grids can address this by more efficiently matching supply and demand.
From a market perspective, one could argue that, when the shares of renewables in the grid increase to high levels, their inherent fluctuations would cause more volatile spot market prices and higher imbalance prices, thus providing higher incentives, and possibly business models, for smart solutions. On the

other hand, one could also argue that, before that was the case, stakeholders would need to (and will) gain experience in these smart solutions because of the pivotal role that the electricity system plays in our society. Whether the current market model is already suitable for deploying smart grids thus remains therefore a matter for discussion in forthcoming years.

1.2.2.2.1 Pricing of the Electricity and EU electricity market

Concerning the pricing of electricity, in nodal pricing (or locational marginal pricing), which is incorporated in the electricity system of the USA, prices are set at different nodes in the system (places where supply and demand meet). In zonal pricing, as used in the EU electricity markets, prices are the same across the entire zone, not taking transmission limits into account. Therefore, the criticism of zonal pricing is that it does not stimulate the optimal placement of variable renewable electricity production (Neuhoff et al., 2013), (Wang et al., 2015). For example, in Germany, much wind electricity production is located in the north, but the transmission line does not have the capacity to transfer this electricity to the south, resulting in congestion losses (Neuhoff et al., 2013), (Scharff, 2015). In 2015, 566 TWh was traded on the European Power Exchange (EPEX, including Germany, Austria, Luxembourg, France, the UK, the Netherlands, Belgium, Switzerland), while 59 TWh was traded on the intraday market, although the intraday market grew faster (26% versus 20%) (European Power Exchange, 2016).

There may be concerns about price and power fluctuations, regarding the market and technologies layers; however, flexible market scenarios, which control unwanted fluctuations, have recently been reported (Qin et al., 2017), (Jain et al., 2017). In addition, moderate fluctuations may potentially accelerate DER deployment, the design of various smart energy products and services, widen the international electricity networks' power transfer capacities and agreements as part of EPEX, meaning that one aspect viewed as unbeneficial for one layer, may come to be potentially beneficial for the future of smart grids. For such perspectives, the three-layer approach facilitates the identification of interactions between layers, and therefore permits more global and multidisciplinary approaches on smart grids and energy transitions.

1.2.2.2.2 Flexibility of the market

In terms of the dynamics in the electricity supply system, and due to system stability reasons, demand and supply need to match at any instant in time; otherwise, the system is in imbalance. In liberalized electricity systems, market mechanisms implemented to maintain the balance are increasing. In short-term markets and balancing especially, flexibilities aggregated from end-users (customers or prosumers) provide an increasing potential for smart grids. Such flexibility can be used for several use cases, such as balancing, optimizing trading costs and minimizing costs from the imbalance settlement (e.g., caused by forecast errors in renewable electricity generation) or for the customer to increase their own consumption, whereby these use cases can be associated with different roles/actors. When using the flexibility for one use case, however, several other actors may be influenced by this activation, either positively or negatively. Future markets in smart grid environments indicate an increased coordination need between several actors in regard to the integration of flexibility, and different flexibility use cases are depicted based on different roles, as shown in Figure 3.

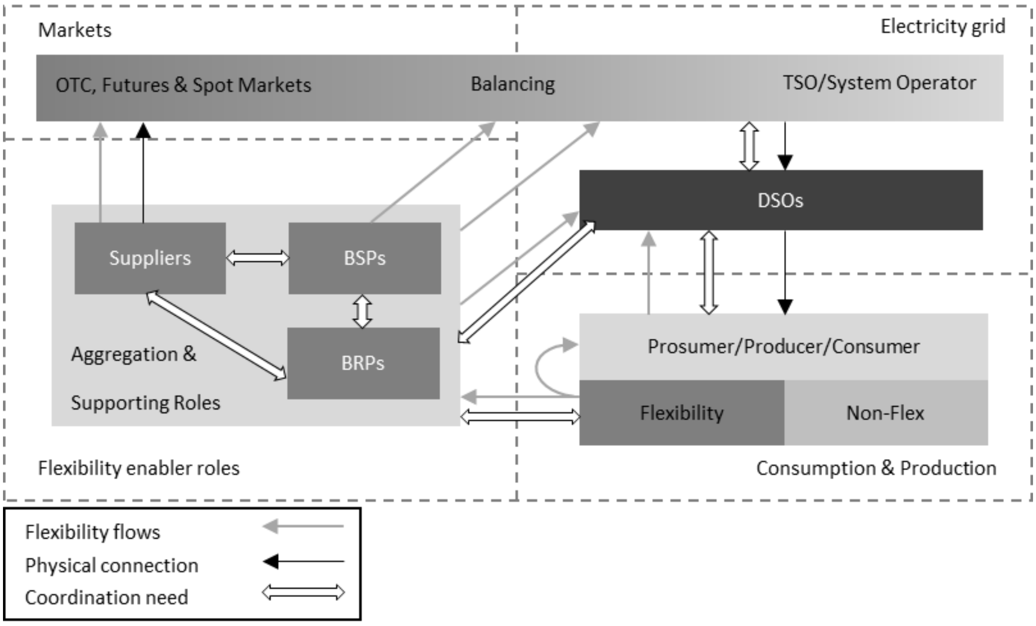


Figure 1.3. A stakeholder overview showing the flow of flexibility.

1.2.2.3 Technologies Layer

The technologies layer covers systems, technologies, and energy products and services that physically create a smart grid environment. In this section, the physical systems of smart grid will be analyzed from three perspectives; DER, demand side flexibility and resource side flexibility. These perspectives were to highlight smart grid flexibility, which is considered to be the key component for its integration into the electricity network (Verbong et al., 2013a).

1.2.2.3.1 Distributed energy resources

From the perspective of residential smart grids the following technologies can be distinguished: DER systems in the form of micro-generators and energy storage, smart appliances, smart meters, energy monitoring, and home automation (Table 2).

Table 1.3. Technologies layers and key elements (adapted from (Wijk et al., 2014),(Geelen, 2014))

Categories	Examples
Distributed Energy Resource systems: Micro-generators	Electricity: - Photovoltaic solar systems - Wind turbine Electricity and heat: - Micro cogeneration unit - Fuel cell - Hybrid and fuel cell electric vehicles - Solar heating and cooling
Distributed Energy Resource systems: Energy storage	Electricity: - Batteries (household or neighbourhood size) - Electrolysers Heat: - In home hot water storage - Storage heaters - Shared storage on buildings or neighbourhood - Ground, aquifers, phase-change materials, thermochemical materi-als…
Responsive appliances	- Electric vehicles (Battery) - Heat pumps

	- Air conditioners - Dish washers - Washing machines - Clothes dryers - Freezer/refrigerator - Battery operated home appliances robots (vacuum cleaner, kitchen) - 3D printers, robot arms - Close-in boilers
Smart/digital meters	- Electricity meters (frequency ranges from seconds to day intervals) - Gas meters - Meters that allow for breakdown to appliance level (usually part of a monitoring and control system)
Energy monitoring and control systems	- Sensors and energy monitoring systems, ranging from household aggregate to breakdown to appliance level - Gas measurement, often combined to a smart thermostat
Home automation for smart energy use	- Energy services gateway - Apps - Steering of deferrable load (smart appliances) - Home automation and control - Internet of things - Smart plugs and smart battery chargers (Lighting, usb grid's…)

With reference to the technologies layer, mainly capabilities regarding the flexibility of specific technologies or residential applications are of interest. In addition to the above, hydrogen as a storage medium has received much attention in the last few years because of the flexibility it can provide (Valverde et al., 2016), (Patel et al., 2011). Electrolyzers can provide wind/solar peak shaving by splitting water with renewable energy sources electricity and producing hydrogen. This bulk energy storage process is known as power-to-gas. At peak demand, fuel cells can use hydrogen to quickly respond to the load demand. Hydrogen energy technologies are complementary to batteries, which can supply day-to-day electricity, whilst hydrogen can be used for long-term energy storage, particularly seasonal storage (summer-to-winter).

1.2.2.3.2 Demand side flexibility

Technical flexibility stresses two main aspects: controllability (e.g., on/off modes, shiftability, modulation, and so on) and characteristics (e.g., minimum and maximum power, reaction time, etc.). Apart from these general characterizations of resources, metrics can be introduced to specify a certain resource with respect to its capability, or 'characteristics'. In (Lund et al., 2015), different approaches for defining flexibility in terms of characteristics are discussed, in which the three main aspects identified are ramp magnitude, ramp frequency, and response time. Figure 4 shows a classification of the residual load for the stakeholders group 'prosumer', in terms of controllability. The base load represents the consumption in the prosumer premises, without any degree of freedom for flexibility or controllability. Loads providing controllability can be distinguished along with their ability to curtail, shift or store energy. As a concrete example, we can mention smart washing machines or dishwashers, which can provide a controllability, albeit within limits (Staats et al., 2017), to the smart grid for it to activate before the latest run time defined by the user (Gercek and Reinders, 2018a). In the case where a user programs the schedule of the appliance for economic reasons, the smart grid will optimize this according to the three layers: stakeholder (objective), market layer (price), technology (demand shifting).

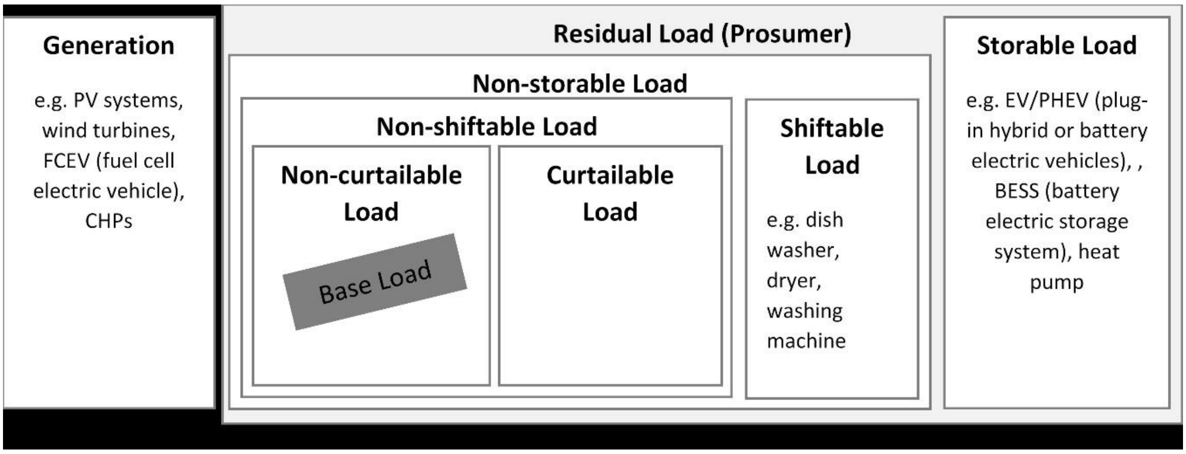


Figure 1.4. Prosumer - residual load in terms of controllability adapted from (adapted from (He et al., 2013))

1.2.2.3.3 Resource side flexibility

While generators and large resources can be described in terms of three main technical aspects, such as ramp magnitude, ramp frequency, and response time, smaller demand resources might need to be characterized using more details.
Based on individual technical parameters, the eligibility of the system types can be evaluated for smart energy product and service applications. The energy resources described in this section can be assigned following the categories of controllability, shown in Figure 4 at the beginning of this section. Regarding the characteristics of resources, Table 3 provides an overview of some these for individual systems.

The availability and activation duration of all the investigated systems is somehow limited either by technical parameters or by the needs or influence of customers. In terms of power supply or demand, most systems range within typical power connection values of households in Europe (~17 kW). Depending on system configurations, EVs or PV systems may exceed this value significantly, which may lead to increasing needs for grid investments (e.g., transformers, power lines, etc.). It was shown that the investigated systems at the residential level provide a different potential for flexibility applications. Whilst existing systems—such as PV systems, heat pumps, or appliances—provide limited controllability (except for downward regulation), the introduction of stationary battery energy storage systems in particular can enable full flexibility for local optimization or ancillary services.

Table 1.4. Characteristics of resources

Resource Type	Availability	Reaction time	Duration
PV System	Depend on weather and time of the day	seconds	Depend on weather and time of the day
Heat pumps	Fully available till temperature criterion of household is met	seconds	Fully available till temperature criterion of household is met
White goods and appliances	Customer dependent	seconds	Process dependent (non-interruptible)
Wet appliances	Customer dependent	seconds	Appliance dependent
Thermal storages	Fully available till temperature criterion is met	seconds	Limited by battery max. capacity
Battery Electric Vehicles (EV)	Customer dependent	seconds	Limited by battery max. capacity and customer
Fuel Cell Electric Vehicles (FCEV)	Customer dependent	seconds	Limited by tank capacity, contrary to EV, filling up the tank as fast as 4 min.

1.2.3 Discussions

Although smart grids are still in an early stage of development, in recent years, societal implementation has gained momentum through the deployment of smart meters and small and medium scale smart grid pilots (Verbong et al., 2013a), (Stephens et al., 2013), (Naus et al., 2014), (Wolsink, 2012). The transition to smart grids would create electricity systems that would enable consumers to make informed and empowered energy-related choices, promoting personal behavioral changes (Smale et al., 2017a), (De-Waters and Powers, 2011). In this regard, evaluative studies and reports, such as (ECME, 2010),(EU-Commission, 2010), (European Technology Platform, : SmartGrids, 2008), (International Energy Agency, 2011) have highlighted the relevance of end-users in smart grid deployment. Nowadays, statistically significant data concerning social factors in stakeholder issues are few compared to the number of papers on technologies and market layers analyses (Reinders et al., 2016). Social-acceptance, in regard to product adaptation, appears to be a slow process, nevertheless, it is one of the key factors in the fast deployment of smart grids into the actual grid (Smale et al., 2017a). The continuous interactions and co-evolution of the three layers will define the smart grid environment, and the more interaction there is, the more rapid the transition will be to a fully smart grid. Our study aimed to highlight this multi-layer interaction to enable a wider point of view and practical solutions.
The first crucial point for social implementation is the selection bias in monitoring surveys caused by the so-called Hawthorne effect (see (Schwartz et al., 2013)). For instance, one of the world's largest datasets of appliances, Pecan Street (Pecan Street, 2016), is sharing the circuit-level residential electricity data in the USA intended for research purposes. The data has shown that the monitored residences are consuming far less electricity (33–60%) compared than the means of that specific region's other network users, probably due to being a volunteer or being conscious that they are participating in a pilot experiment. Active participation of the individuals is crucial for efficient integration and energy resilience, therefore the design of smart products and services is crucial to maintaining their motivation to be energy efficient. In the stakeholders layer, detailed consumer profiles analyses are needed in order to point out such important facts, which will guide the technologies and market layers on structural issues in the electricity network. Treating raw data according to only the market and technologies layers, without considering end-users and stakeholders, is already inducing unneglectable simulation uncertainties on an hourly basis, and the high prediction errors may induce significant organizational and structural errors. The data purged of bias will help us to focus on specific smart energy products and services, their research and development (Glasgo et al., 2017a).
Pecan Street's recent data analyses from 12,083 monitored residences showed that 50% of the electricity used was related to air conditioning units, water heaters, and refrigerators (Glasgo et al., 2017b). Such applications could be shiftable loads if thermal isolation was feasible and sufficient, which again underlines the importance of load flexibility management. The main barrier would be the initial costs of these zero energy households, additionally equipping them with devices such as heat pumps, which in the EU are now supported by policy. Creating facilities and smart energy products, depending on end-users' surveys about these devices and comfort expectancies, would be a cost-effective solution. Moreover, users' knowledge with regard to smart grids (such as an abundance of feedback information) has been shown to both enhance acceptance and to create confusion, and in contexts, people prefer demand load control (the ability of energy suppliers to control user consumption) while they reject it in others.
For EU countries, the risk of residential peak demand is high and similar for countries such as Italy, Norway, and Germany, for average households, while on the other hand, Bulgaria and the UK differ completely (Torriti, 2017). Global warming also plays a role in the trend of peak demand. In 2014, France had the lowest peak demand on record since 2004 (Réseau de Transport d'Electricité, 2015). Other EU countries' consumption profiles and peak demand characteristics remain to be validated for the smart grids from ongoing EU pilot projects (Reinders et al., 2016). At the regional level, zone policies and network characteristics vary. For instance, for the Netherlands, the barriers to fast deployment of smart grids are mostly uncertainty of the benefits, with only about 11.1% of the network contains renewable energy generation in 2015 (Eurostat, 2015), while a target of 14% renewables by 2020 in the Netherlands has been stated (Ministry of Economic Affairs and Climate Policy, 2017). Meanwhile, Austria has a target of 34% renewable energy by 2020, and 100% self-sufficiency in energy by 2050 (Federal Ministry of Economy, Family and Youth, Energy Strategy Austria, 2017). The main reason for this is the use of hydroelectricity as a huge energy reservoir to flatten the demand curve, which improves the renewable energy cost effectiveness by erasing the need for residential batteries. Austria is actually marketing itself as the 'battery of Europe'. Transnational collaborations and knowledge sharing initiatives between these types of countries are in progress, in order to learn from favorable conditions and to consider weak

points, so as provide more solid initiatives (Reinders et al., 2016). For instance, in the Netherlands, there are some investment plans in operation until 2025, as the green hydrogen economy in north, which might be a solution for the electricity grid capacity and flexibility problems in a cost effective way, through combining with other renewable/sustainable energy sources (Northern Innovation Board, 2017). The renewable energy seasonal surplus could be converted and stored as hydrogen, transferred across the country by the existing gas network (after minor conversion), and could be stored in salt caverns to provide seasonal flexibility, and to balance regional pros and cons, salt caverns and the dramatic decrease in renewable energy production during winter.
Regarding energy efficiency and sustainable energy usage by EU citizens, the three-layer model usage will keep their motivations in pace, as feeling part of the energy transition. Smart products and services would give them the possibility to become greener or accomplish their economic objectives giving them a certain degree of freedom, meanwhile also providing the ability to the smart grid to optimize the shiftable load whenever available. Techno-economical approaches, or fully automated demand load control, or massive deployment of smart grids, would certainly bring resilience and efficiency from a technical and organizational perspective, which is of course a necessity (Marzband et al., 2018a), (Marzband et al., 2018b). However, in the residential sector, if not combined with the stakeholders layer, these approaches might fail to make citizens become more energy resilient or sustainable. Furthermore, because they might not feel part of the energy transition, the usage performance of new technology devices might drop. Or even worse, it paradoxically increase citizens' consumption, as they may tend to consume more due to disempowerment resulting from the automated processes. Automated demand load would certainly reduce the peak demand, by risking this to be perceived as a real constraint for the residential sector. Even used to a moderate extent, if end-user perspectives are not taken into account, they will greatly reduce the acceptance of smart grids. Our three-layer model aims to highlight such interactions and the possible consequences, where the solution should come from all layers, not only from a top-down approach. The main barrier to smart grid deployments is the lack of multidisciplinary considerations for the residential sector where uncertainties are vast and objectives, consumption and production patterns, geographic attributes, local authority aims and policies are not identical.

1.2.4 Conclusions

Our study aimed to present a three-layer model (stakeholders, markets, technologies) for the assessment of residential smart grids. In this way, knowledge about the actual performance of residential smart grids can be collected and evaluated within its framework. The use of the three-layer approach increases awareness of the multidisciplinary aspects of the problem, which most of the recent and extensive technical literature reviews point out (Nosratabadi et al., 2017).
We defined and discussed each layer in terms of recent issues from different perspectives. Uncertainties still exist with regard to market structures, task delegation, the necessity for new (data-handling) institutions, etc. Issues resulting from human factors and the stakeholders layers, comfort expectancies, the aims and requirements of smart grid users are still unknown parameters, however they are deemed to be crucial in order to fit the market and demand energy management systems in smart grids. If the goal of some consumers is to be more sustainable, and for others to relinquish any comforts, but only to sell some of their local energy production, then the conflict of interest has to be analyzed well considering the entire grid. Consuming only renewable energies and storing them may not be the greenest way, as batteries also have notable ecological impacts. Bottom-up end user and stakeholder capacities and demands must be analyzed in conjunction with statistical consumption graphs. Also, a portfolio of users identified for minimizing bias, should be considered in order to discern structural and pricing issues in smart grids. Modellers admit the necessity of including many parameters, especially stakeholder behavioral or characterization parameters (Patel et al., 2011). Social acceptance and practices also have to be considered closely and more data is needed to be more statistically significant, in order to define to what extent flexibility may play a role (Gangale et al., 2017).

2 INTERNATIONAL COMPARISON BETWEEN SMART GRID PILOTS IN THE NETHERLANDS AND AUSTRIA

2.1 SMART GRID PILOTS IN THE NETHERLANDS AND AUSTRIA [3]

2.1.1 Introduction

Already in 2011, the European Commission acknowledged the importance of promoting smart grids and smart metering throughout the EU in their communication “Smart Grids: from innovation to deployment” (European Commission, 2011). Several benefits were highlighted:

- Empower consumers to directly control and manage consumption patterns;
- Enable time-dependent electricity prices, providing more cost-efficient energy use;
- Enhancing security of the grid;
- Enable integration of renewable energy and electric vehicles;
- Boost future competitiveness and technological leadership;
- Provide a platform for the development of innovative energy services.

The translation of these theoretical benefits towards practical benefits has led to a proliferation of smart grid pilots within the EU, as is shown in Figure 2.1. According to the records of JRC, 527 Smart Grid pilots have been implemented in Europe, mostly categorized as Demonstration projects and R&D. Total budget for these projects is 360 milliard euro, with almost two third of the funds attributed for demonstration projects (JRC, 2019a). The geographical focus of the remainder of this report will be on Austria and the Netherlands. In this chapter, the studied pilots in these countries will be briefly introduced, before a more in-depth analyses of these pilots will be presented in Chapter 3 and Chapter 4.

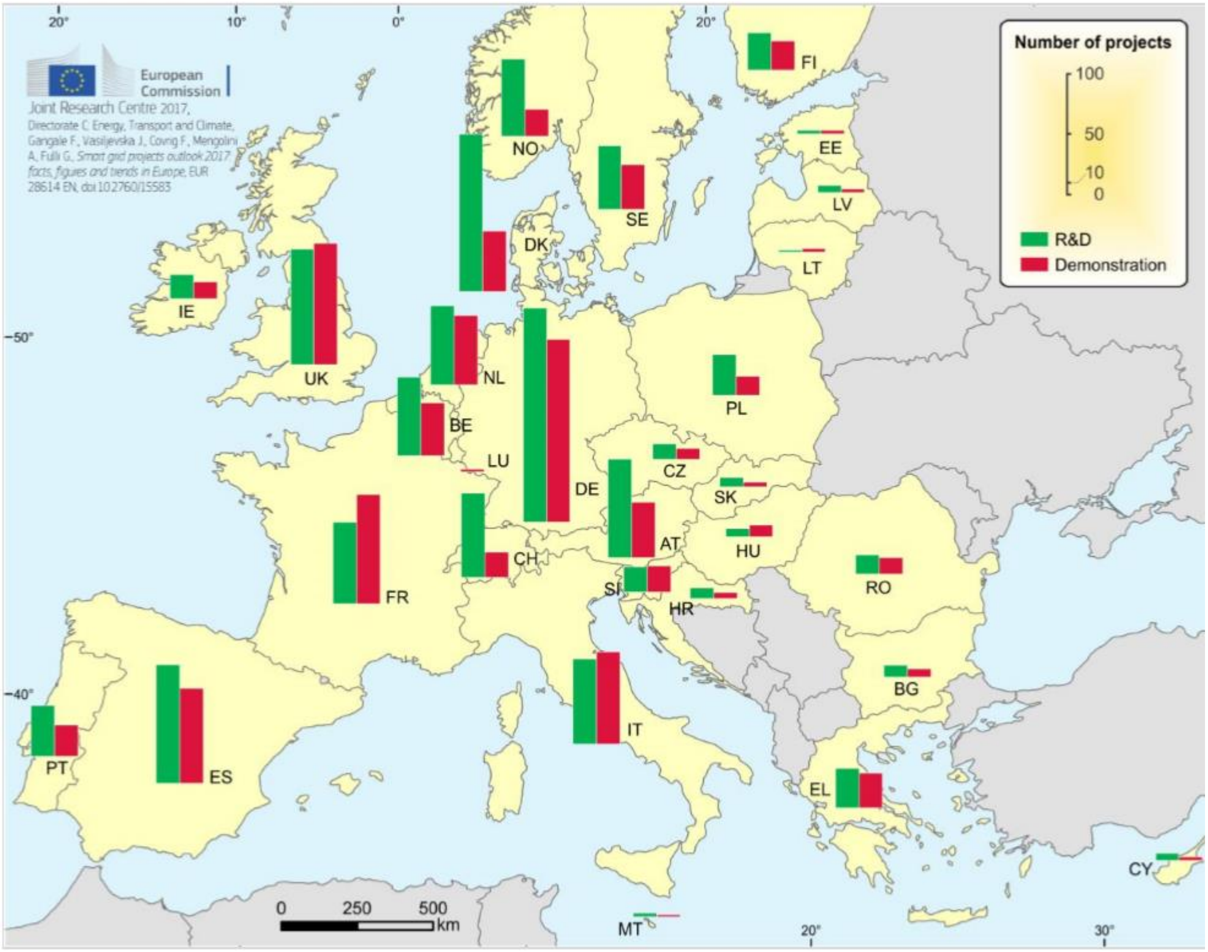


Figure 2.1. Smart grid pilots in the EU between 2004 and 2015 (Gangale et al. 2017)

[3] A significant part of this chapter has been written by Wouter Schram, Wilfried van Sark, Miguel Rey and Angèle Reinders

The Netherlands and Austria are two European countries with different socio-economic and environmental conditions. In this section these conditions will be shortly introduced and quantified where possible.

The number of inhabitants (CBS, 2019a) of the Netherlands at the beginning of 2019 was 17,29 mln this is about twice as much as the number of inhabitants of Austria in 2018 (Statistik Austria, 2018), namely 8,82 mln. With an area of resp. 41.528 km^2 (including interior waters) and 83.878 km^2, the population density of the Netherlands (416 person/km^2) is a factor 4 higher than that of Austria (105 person/km^2). The GDP (CBS Business Cycle Tracer, 2019) of the Netherlands in 2017 was 737,05 bn Euro, whereas the Austrian GDP was 369,69 bn Euro, resulting in a GDP per capita of resp. 43.000 and 42.020. As such one could conclude that the level of personal wealth is similar for both countries.

The number of persons per household also equals for the Netherlands (2,15) and Austria (2,3) as well as the life expectancy of men and women, resp. 80,1 and 83,3 for the Netherlands and 79,3 and 83,9 for Austria(CBS, 2019b),(Statistik Austria, 2018). In this context it can be concluded that both countries have relatively small households and long living healthy inhabitants.

In the Netherlands the so-called ‘Klimaatakkoord’ and the subsequent ‘Klimaattafels’ of the Dutch Ministry of Economic Affairs and Climate have set CO_2 emission reduction target for the whole country of 49% in 2030 with regards the emission levels in 1990. This has not resulted yet in a high share of renewable energy in the total energy mix, which was only 6,6% (2017) (CBS, 2018) mainly thanks to a high share of biomass conversions (4,02% in 2017), however the contribution of wind energy (1,07% of total energy mix in 2017) and solar energy (0,43% of total energy mix in 2017) is rapidly growing. For instance in the year 2017 (CBS, 2018) the energy produced by wind turbines increased with 15% compared to 2016, and energy generated by photovoltaic solar power systems increased with 31% compared to 2016. These are positive developments for a country with an annual global horizontal irradiation of 1100 kWh/m^2 (JRC, 2019b).

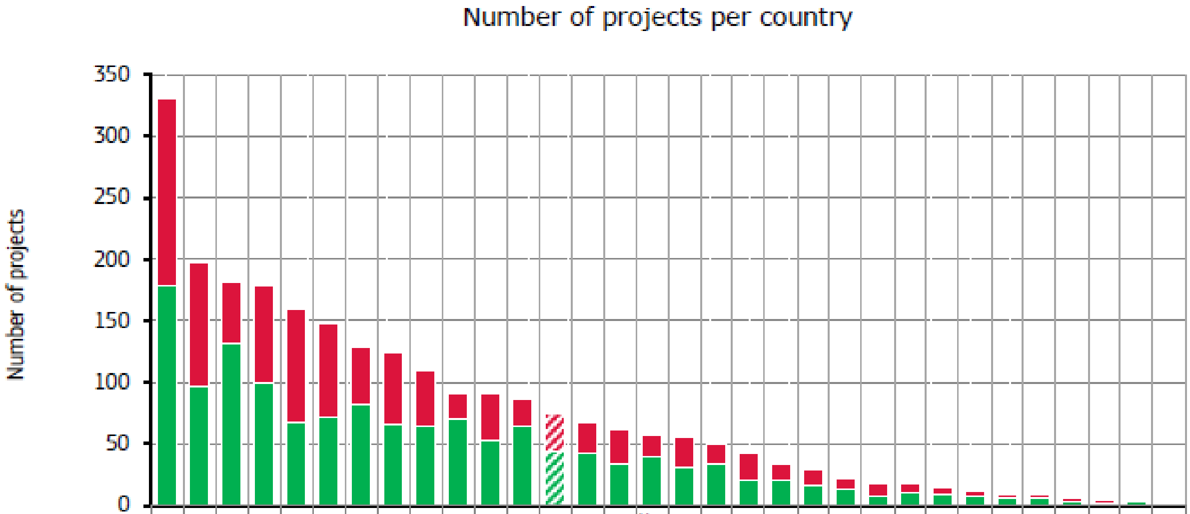
In Austria, the national strategy on energy (“Energiestrategie Österreich“) was adopted by the Federal Government in 2012 following EU’s 2008 resolutions on energy use and efficiency, and CO_2 emissions reduction. The strategy, aimed at increasing energy efficiency and stabilising energy consumption by 2020 at around 1.100 PJ (= 1,2 EJ = 1,2 x 10^{18} J), which corresponds to the energy used by the country in 2005, is built around three pillars (energy efficiency, securing energy supply, and expansion of renewable energy sources) and specifies 370 measures that address the most important areas where action is needed (buildings; production and services in industry, businesses and households; mobility, energy supply & demand). Besides the measures envisioned, the most important message from this policy is that the Austrian Government—and therefore, to some extent, the Austrian society—has become aware of the need of stop increasing energy consumption in the near future if we want to have any reasonable chance of tackling climate change.

The policy has been further refined in 2018 to set specific goals (Integral climate and energy strategy of the federation, 2018) that must be achieved by 2030: a reduction of CO_2 emissions of 36 % with respect to 2005 values; for example, emissions from transportation must come down from current 22,9 million of tons of CO_2 equivalent (t CO2eq) to 15,7 million t CO2eq, and emissions from buildings must reach 5 million t CO2eq (current: 8 million t CO2eq). Further measures include reduction of energy import by expansion of renewable sources (e.g. biomass, heat pumps and solar thermal), and the substitution of natural gas by bio- and synthetic methane. A complete decarbonisation of the country is planned for 2050; before that goal can be reached, the share of renewables in the total energy consumption must grow from the current 33,5 to 45-50 % by 2030 (Austrian Federal Ministry for Sustainability and Tourism, 2017) . Also by 2030, all of the electricity production must come from inland renewable sources (this already happens in the small federal state of Burgenland; country-wide the current share is around 70 %, see note 12).

The high proportion of renewable energy in Austria is possible by the large hydroelectric capacity and extensive use of biomass; both sources produce around a third of all renewable sources, with smaller contributions from district heating (10 %), brines (7,3 %), biofuels (5,7 %), and wind energy, solar thermal, biogas, heat pumps, geothermal and photovoltaic (together 11 %).

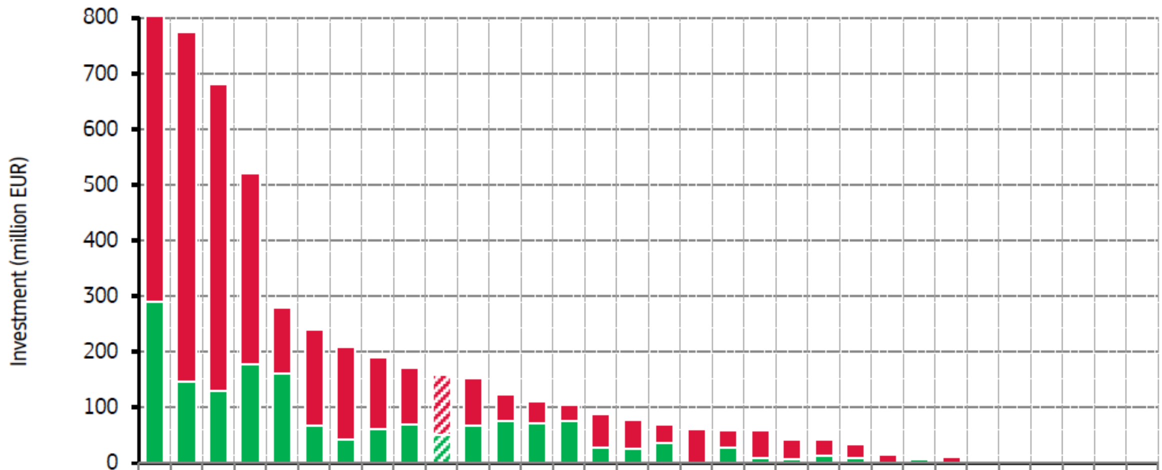
2.2 Comparison of the Smart grid landscape in Austria and the Netherlands

Some general conclusions about Austria and the Netherlands can be drawn from the Joint Research Centre report *Smart grid projects outlook 2017* (Gangale et al., 2017). Both in the number of smart grid projects and the amount of investment Austria and the Netherlands the countries perform above the European average. Austria has slightly more projects than the Netherlands, with 128 versus 124 projects, but the investment per project is larger in the Netherlands: 1.7 M€ per project in the Netherlands versus 1.2 M€ in Austria (see Figure 2.3). Netherlands performs well in the category of private investments; Austria has a relatively high share of national funding (above 20%). Most of the pilots studied in the CESEPS project took place around 2013/2014, which is in line with the general trend in the EU (Figure 2.4). Another important parameter is the density of the investments, namely the Netherlands is cited as a high density spot in many reports .



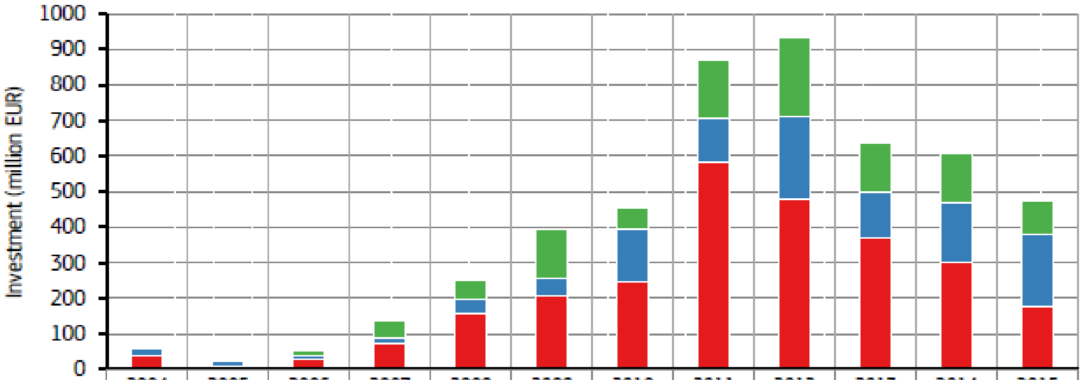
	DE	UK	DK	ES	FR	IT	AT	NL	BE	CH	SE	NO	Avg	PT	EL	Non-EU	FI	PL	SI	IE	RO	CZ	HU	BG	HR	SK	LV	CY	EE	LT	MT	LU
Demonstration	152	101	50	79	91	77	46	58	44	21	37	22	32	26	29	18	24	16	22	14	14	9	10	7	5	4	3	3	3	3	2	2
R&D	178	96	131	99	68	71	82	66	65	70	53	64	43	42	33	39	31	34	21	20	16	13	7	10	9	8	6	6	3	2	3	0

Figure 2.2. Number of smart grid projects in the EU (Gangale et al., 2017) .



	DE	UK	FR	ES	DK	IT	NL	BE	SE	Avg	AT	CH	NO	FI	PT	EL	PL	LU	Non-EU	RO	CZ	SI	IE	HU	SK	LT	BG	LV	HR	CY	EE	MT
Demonstration	520	628	550	344	117	172	166	128	102	108	84	47	41	29	62	53	32	61	30	49	36	28	25	14	3.7	8.9	5.1	3.5	2.4	1	2.3	1.2
R&D	289	146	130	177	161	67	43	62	69	52	68	76	71	77	27	25	36	0	28	9.1	7.1	13	8.8	1.8	8.2	1.2	2.9	4.2	3.8	3.7	1	1

Figure 2.3. Amount of investments to smart grid projects in the EU (Gangale et al., 2017)



	2004	2005	2006	2007	2008	2009	2010	2011	2012	2013	2014	2015
National	4.64	1.14	11.96	53.23	53.54	137.13	63.01	163.25	224.74	137.54	139.68	94.16
EC	23.90	10.62	13.47	14.23	42.14	53.48	147.94	121.79	232.63	129.34	166.06	200.20
Private	36.51	11.43	26.90	72.31	157.11	204.50	245.96	583.26	479.09	367.61	302.39	177.68

Figure 2.4. EU wide investment in smart grid pilots (Gangale et al., 2017)

From Table 2.1 and Table 2.2 we can also notice that in both Austria and the Netherlands, many pilots studies are undertaken in order to learn more about the energy behavior of residents. Almost all pilot have smart meters installed. Most pilots expand this by also implementing smart appliances and trying to control these in a smart manner.

When comparing Austria and the Netherlands, we observe many similarities. Next to the smart meters, in many pilots PV systems have been installed. Additionally, energy storage plays an important role in both countries, however the specific storage technology deployed differs. In general, pumped-hydro storage and heat storage is more commonly used in Austria, whereas battery storage (either in EVs or in home batteries) is deployed more frequently in the Netherlands. As such there exist a stronger focus on heat in Austria. Furthermore, in Austria more emphasis is put on power quality related metrics, such as voltage control.

2.2.1 Smart grid pilots in the Netherlands

The Dutch government has put a large emphasis on the importance of smart grid pilots (Ministry of Economic Affairs, 2015). This was even supported by law, making it possible to give certain areas a special status for permitting allowing to experiment with new energy solutions that go beyond current standard regulation (Rijksoverheid, 2015).

Figure 2.5 shows an overview of all smart grid pilots that were found in a first exploration for this project. From this short list, a considerable number of pilots has been studied more in-depth. A technical analysis was performed on PowerMatching City, Jouw Energie Moment, Rendement voor Iedereen, Liander, EnergieKoplopers, Smart grid Lochem and the campus pilots in solar e-bikes at UTwente and Car as a Power Plant at TUDelft. Main reason for selecting these pilots was data availability.

Table 2.1 2.1 provides more details on these pilots. We see that a part from the campus pilots, all projects had a smart meter and solar panels. Other installed technologies differed considerably per pilot. For the stakeholder analysis, PowerMatching City, Smart Grid Lochem, Rendement voor Iedereen and Couperus Smart Grid were selected for reasons further explained in section Table 2.1. The orange points in Fig.2.5 are the pilots that we do not have the access of data, they are detailed in Appendice A.

Figure 2.5. Overview smart grid pilots in the Netherlands with blue numbers the pilots that are studied in more detail from a technical angle (Chapter 4) and in violet the pilots that were subject to the stakeholder analysis (Chapter 3).

Table 2.1. Summary of the main technologies used in selected smart grid pilots in The Netherlands.

Pilot	Start-End Date	Nr. of Cases	Technologies													
		(house-holds or Vehicles)	Smart Meter	Energy Management System	Energy App	Battery EV	Fuel Cell EV	Smart Appliances	rooftop PV systems	Virtual Power Plant	Micro Combined Heat	Demand-Response	Heat Pumps	Home Battery	Electric Boiler	Stationary Fuel Cell
Power Matching City Groningen	2007-2010	25 houses	x	x		x		x	x	x	x		x			
	2012-2015	40 houses	x	x		x		x	x	x	x	x	x			
Jouw Energie Moment Breda	2012-2015	382 houses	x	x	x			x	x			x	x			
	2017-present	93 houses	x	x					x			x	x	x		
Rendement voor Iedereen Amersfoort	2012-2014	100 houses	x		x	x			x							
Hoog Dalem Gorinchem	2014-2017	42 houses	x	x					x				x	x		
EnergieKoplopers Heerhugowaard	2015-2016	203 houses	x	x					x				x		X	x
	2017-present	100 houses	x						x				x	x		
Smart grid Lochem	2012-2015	250 houses	x		x	x			x				x			
Solar e-bike: Smart Living Lab UTwente Enschede					x	x				x						
Car as Power Plant: The Green Village TUDelft	2016-present	1 hydrogen car 1 hydrogen scooter					x									
Total	2007-present	1144	9/11	6/11	4/11	4/11	2/11	3/11	9/11	3/11	2/11	3/11	7/11	3/11	1/11	1/11

All of the residential smart grid demonstration projects mentioned in Table 2.1 use core technologies such as smart meters, energy management systems and/or energy apps, as well as rooftop PV systems. Most residential smart grid homes have heat pumps as an alternative for gas heating. Aso batteries of

EVs are being investigated in these pilots assuming that they fit well in future regulations of utilities. Both heat pumps and EVs are expected to result in widespread use in the next five years. Only one of the pilots investigated contains stationary fuel cells, Also just one pilot has electric boilers.

2.2.2 Smart grid pilots in Austria

In contrast with the Dutch situation, a high penetration of PV occurs already in the Austrian power system. Therefore Austrian residential smart grid pilots hardly have rooftop PV systems. The main aim seems to create flexibility and resilience of the network as a whole by matching residential demand with the supply of electricity generated by large PV systems in the vicinity of residential areas. Table 2.2 summarizes the demonstration projects and the main technologies employed in Austria. The locations of these pilots are shown in Fig. 2.6.

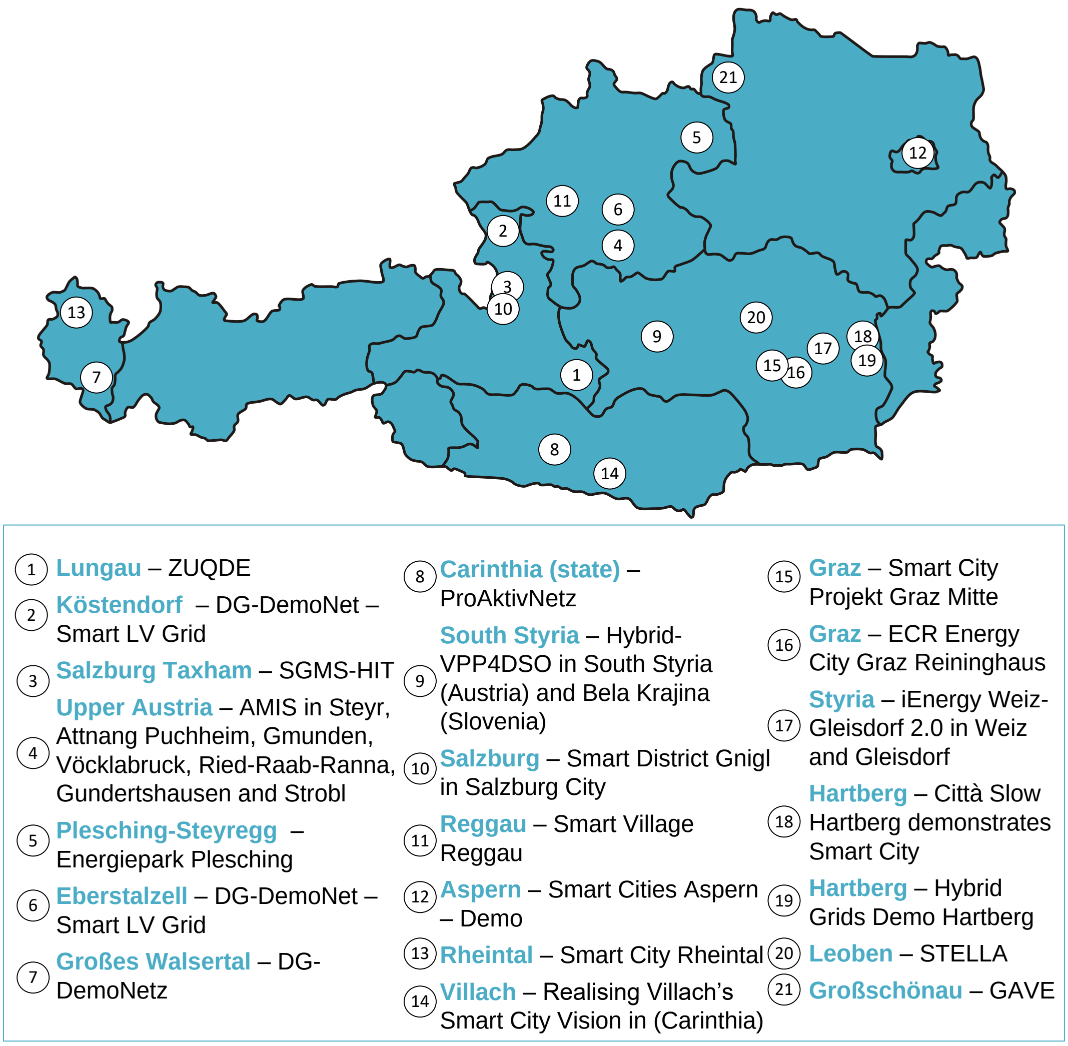


Figure 2.6. Overview of smart grid pilots in Austria.

Table 2.2. Summary of the main technologies used in smart grid pilots in Austria

Pilot	Start-end Date	Nr. of Cases (households or other)	Technologies: Smart Meter	Energy Management System	Energy App	Battery EV	Fuel Cell EV	Smart Appliances	Rooftop Solar Panels	Virtual Power Plant	Micro Combined Heat	Demand-Response	Heat Pumps	Energy Storage	Electric Boiler	Stationary Fuel Cell
DG-DemoNet-Smart LV Grid Köstendorf	2011	90 houses	x	x		x			x					x		
SGMS-HiT Salzburg Taxham	2011-2015	130 houses	x	x	x	x		x	x		x			x		
Energiepark Plesching Plesching-Steyregg	n.a.	121 houses	x	x	x			x								
Smart Regau Regau	2014-2017	170 residents						x								
Smart Cities Demo Aspern Vienna	2014-2030	111 houses	x		x			x				x				
Vision Step I Villach Villach		1300 houses	x						x							
Smart Future Graz Graz	2012-2017	169 appart-ments							x							
Energy City Graz – Reininghaus Graz	2013-2015	162 apart-ments, offices, shops											x	x		
iENERGY 2.0 Weiz-Gleisdorf			x			x										
Total	2011-2017	2253	6/9	3/9	3/9	3/9		4/9	4/9		1/9		1/9	3/9		

As mentioned, because the focus in Austria is different from the Netherlands, so are the technologies employed, namely, various energy storages are demonstrated in situ, mostly for life time investigations and increasing the reaction time of the local grid for a greater resilience. Few projects have energy management systems or energy apps, although, more projects have smart appliances compared to the Dutch sample. This is due to the need of creating flexibility as mentioned previously by an excess of PV energy which occurs mostly during day time. Demand shifting could in that case avoid curtailment of the PV systems. Paradoxically, only one project investigated heat pumps, because the Austrian wood fired boilers benefit from subsidies. The Austrian concern seems to be creating and improving resilience of the grid in larger scales as they succeeded to integrate large scale PV. In contrast, because of the lack of land and unavailability of hydropower, Dutch pilots tend to focus on integration of new and sustainable technologies which could be locally applied.

3 STAKEHOLDERS

3.1 Introduction [4]

Smart energy systems are realised in residential projects across the globe with the aim to experiment with smart energy products and services (SEPS), the amount of the load which the grid can handle, users' responses to financial incentives, and more. Such pilot projects, with a diversity of SEPS and different networks, provide experiences with the use of smart grids in practice to a range of stakeholders, and in some cases also to the residents, who are the "users" of the local energy systems. Learning in and from these projects is essential for a conducive smart grid development in the context of a sustainable energy transition. Recently, there has been an increase of studies paying attention to the social actors in smart grid development, especially regarding the motives and responses of users (Hansen & Borup, 2018; Naus & van der Horst, 2017; Obinna U. , 2017; Skjølsvold, Jørgensen, & Ryghaug, 2017; Smale, van Vliet, & Spaargaren, 2017; Bulkeley, Powells, & Bell, 2016; Kessels, et al., 2016; Kobus, Klaassen, Mugge, & Schoormans, 2015; Nyborg & Røpke, 2013). They lack however in-depth empirical research on the level of engagement of users' in their relationship to other stakeholders as well as the learning process of all stakeholders including users.

The existing smart grid pilot projects in residential areas are a rich source of information regarding the responses and experiences of users and other stakeholders as well as their relationships. In the Netherlands, user aspects have received special attention since the IPIN (Innovation Programme Intelligent Networks) policy programme, which expects them to be actively involved in the projects in a variety of ways. The Netherlands, hence, provide an interesting context for studying the level of users' engagement and the learning among all actors involved in these pilot projects, especially with regard to user aspects. This chapter provides an oversight of the empirical findings regarding the following research questions:

1. Which stakeholders are involved in Dutch pilot projects and in what way, and what are their roles vis-a-vis users?
2. What are the main learning experiences in a diversity of these pilot projects, especially regarding user aspects and what does this mean for the development of the smart grid niche?

The research started with two preparatory literature reviews (Gultekin & van Mierlo, 2018; van Mierlo, 2018) (van Mierlo, 2018). The JRC report indicates 58 demonstration of smart grid projects (figure 2.4), neither all of them are focusing on residential sector nor occurred during our project (Gangale et al., 2017). To get a good overview of stakeholders and their roles involved in Dutch pilot projects in housing, we analysed the project documentation of 31 Dutch pilot projects with more than 15 households (Brouwers & van Mierlo, 2018a). These are all the Dutch projects with valid information available on internet, supplemented with findings from a similar exploration by Naus (2016).
For an in-depth insight in the stakeholders' expectations and motivations as well as their learning, we selected 4 Dutch projects that highly differ regarding smart energy system features and social relations. This diversity provided rich insight. The selected projects are PowerMatching City - phase 2; Smart Grid Lochem; Profit for all – Amersfoort; and Couperus; see Table 3.1.

On November 29 2018 a workshop with 17 participants (12 male, 5 female) was conducted at a local energy cooperative (Lochem Energy), in order to develop a learning history of the project Smart Grid Lochem. The participant group consisted of 14 active members of Lochem Energy, 2 project managers of the project Smart Grid Lochem and 1 representative from the DSO. This workshop formed the basis for a learning history of the project Smart Grid Lochem (Brouwers & van Mierlo, 2018b).

Interviews were conducted with several stakeholders of each projects about their experiences (see Table 3.2). A more extensive elaboration on the findings can be found in Brouwers, van Mierlo & Gültekin (2018).

[4] This chapter is written by Hilde Brouwers, Barbara van Mierlo and Esin Gültekin. The division of tasks was as follows: Hilde Brouwers: interviews, coding, analysis, workshop and writing; Barbara van Mierlo: proposal, literature review, analysis, workshop, writing, interviews and coordination; Esin Gültekin: proposal; literature review; majority of interviews and transcripts.

Table 3.1. Number of interviews conducted with representatives of each stakeholder group.

Name project	*Location*	*Start date*	*End date*	*# house-holds*	*Subsi-dized by*	*Features smart energy system*
Smart Grid	Lochem	Jan. 2012	Sept. 2015	170	Agentschap NL (IPIN)	Domestic solar panels and invested in a collective solar park. No smart appliances, use of smart meters and feedback on energy levels via an app.
PowerMatching City – phase 2	Hoogkerk	Jan. 2012	Jan. 2015	40	Agentschap NL (IPIN)	Domestic solar panels, batteries, electric scooters, smart heat pumps, smart washing machines, a PowerMatcher (software system that regulates energy supply and demand). Smart meters and feedback via tablet.
Couperus Smart Grid	Den Haag	Jan. 2012	Jun. 2015	288	Agentschap NL (IPIN)	Wind energy via an energy company. Makes use of automated smart heat pumps.
Profit for all - Amersfoort	Amers-foort	2011	2015	200	Utrecht Economic Board	Domestic solar panels, with households being able to choose 4 smart appliances. Smart meters were provided and demand was shifted by flexible tariffs.

Table 3.2. Interviews per stakeholder group.

Stakeholder group	*Number of interviews*
Users	3
User representatives	2
Users – energy cooperative founders	2
DSO	2-3*
Technical researcher or consultant	2
Social researcher or consultant	2
Economic researcher or consultant	1

** 1 person was interviewed as a social researcher at the time of the projects and representative of an involved DSO to which she moved later*

To investigate the learning among users further, we organised a workshop about the project with the most active user engagement: Smart Grid Lochem. The workshop for developing a learning history of the project took place at the local energy cooperative (LochemEnergy) on 29 November 2018 with 17 participants (12 male, 5 female). The participant group consisted of 14 active members of LochemEnergy (users), 2 project managers of the project Smart Grid Lochem and 1 former employee of the DSO (Brouwers & van Mierlo, 2018b).

3.2 Stakeholders' involvement in Dutch smart grid projects

Grid operators, energy companies, policy institutions and local energy cooperatives initiate smart grid projects to experiment with a wide range of issues.

In the first part of this section, we explore the key stakeholders in the projects and their interrelations. It provides an overview of the number and type of stakeholders involved in the 31 investigated Dutch projects. Whether and how users are engaged with the smart energy systems can be expected to be dependent on how they are related to the corporate actors participating in the projects. If citizens take the initiative for a smart grid projects as members of a local energy cooperative, their engagement is presumably much larger than if a grid operator initiates a project involving automated control of smart appliances.

In the second part of this section, the user engagement in these projects is elaborated. One of the literature reviews showed that confusion exists about what an active involvement of users is or could be, as it tends to be discussed in very general formulations (van Mierlo, 2018). Therefore, different types of engagement are discerned in this study:

- demand shifting
- energy saving
- co-creation
- co-provision

Most of the existing, insightful studies concern users' involvement in demand shifting, with their results providing some rules of the thumb for triggering active responses. The results are however somewhat scattered about, due to the high diversity in energy systems in smart grid projects. A major implication of these studies for smart grid products and services is that they should take into account people's practices and relationships within the households and with their neighbours. Powells *et al.* (2014) suggest to not only invent ways to let people be more flexible in the timing of their practices, but to reconfigure their practices in novel ways, especially those restricted by time constraints or social conventions. Slow cookers for instance would enable people to continue to eat together at conventional dinner times while still shaving peak demand. Another proposed practice-aligned intervention is a launderette that uses stored, solar-heated hot water for washing laundry, which could provide services both to communities and to those managing the distribution network.

Other users' roles, those of energy saver, co-designer/-creator and co-provider, are neglected in current studies (van Mierlo, 2018). They are therefore presented as detailed as possible, in the second part of this section.

3.2.1 Corporate actors

In the Netherlands, until 2018, 31 smart grid projects were realized or in a late stage of preparation. For an overview of their characteristics, see appendix A. In 90% of these projects a DSO participates in the project (see table 3.3). Grid operators are most often project manager (12 times). When not leading the projects, they often still have a significant role in these pilots. The various DSOs that operate in the Netherlands, which are Enexis, Stedin and Alliander, are all three equally involved.
Energy cooperatives are involved in 7 cases (23%). In 6 projects they are the project manager, and in 3 of these they are in charge of the project with another stakeholder.

Energy companies, such as Eneco, Essent or Greenchoice, are seldom mentioned as project partners in the project documentation. They figure in 10 cases, but strikingly never as project manager. Whereas they used to have a leading role in the introduction of energy saving policy and distributed renewable energy, they seem to be playing the second violin in the smart grids development.

Researchers and consultants are involved in many projects. They figure in 55% of the projects. In the case of Profit for all there are up to 8 different (groups of) researchers or consultants. Overall, the distribution between economic/social researchers or consultants and technical researchers or consultants is more or less equal. Technical research institutions do not always merely conduct research but take up

Table 3.3. Stakeholders involved in the projects.

Type of stakeholder	*Times involved*	*Times involved as project manager*
DSO	28	12
Energy cooperatives	7	6
Energy companies	10	0
Researchers / consultants	17	5
SEPS supplier or developer	19	2
Housing corporations	9	0
Regulatory bodies	9	2
Aggregator	1	0

different roles, like supporting the development of business models or providing software. The technical consultant and research firm, DNV GL, played a dominant role in 4 projects.

SEPS suppliers or developers, such as the research organization TNO or the software company IBM, are involved in 61% of the 19 projects. They initiated 2 projects in which they experiment with their own energy management systems. In other cases, their role can be compared to research or consultancy as the systems in the pilot project are under development or continuous improvement. The pilot projects are used as testing environment for their SEPS.
Housing corporations are involved in almost 1/3 of the pilot projects, for instance as one of the location providers or as a way to reach residents. They do not take up the role as project manager.
Regulatory bodies, such as municipalities or province government officials, are involved in 8 projects, as far as their roles are acknowledged in the project information. Some of these projects aim for a city or city district to become carbon neutral. In two cases, they are co-initiators of the project, together with other stakeholders.
In only one case, in Rijsenhout, the aim was to involve a specialized aggregator in 2018 in order to trade energy from and to a shared battery. It is unclear whether this was realised.

3.2.2 Users' engagement

Users are self-evidently part of all these projects in residential areas, even if they are not aware of it. The number of households participating in the projects varies considerable, from 17 households up to 300. Table 3.4 gives an overview of the project goals that are communicated to users in the formal communication of Dutch projects (Naus, A quick scan of smart grid projects in the Netherlands, 2016).

Table 3.4. Various project goals communicated to users in the IPIN programme *(Naus, A quick scan of smart grid projects in the Netherlands, 2016).*

Category	*Number of projects (out of 31 in total)**	*Percentage of total*
Sustainability	27	87%
Autonomy / control	10	32%
Community	13	42%
Cost savings	24	77%
Technological innovation	15	48%
Comfort	11	35%

In the Netherlands, about half of the smart grid projects in housing actively engage users. But even if actively engaged, this engagement is usually partial (Naus, A quick scan of smart grid projects in the Netherlands, 2016). To get more grips on the issue of users' engagement, we explored the specific project features that could be expected to instigate engagement in one way or another. Table 3.5 provides an overview of various forms of engagement related to several characteristics of the projects.

Table 3.5 User engagement features in the projects. N is number of projects with information on the issue.

	Much	*Moderate*	*None*
Information / feedback (N=25)	72%	20%	8%
Financial incentives (N=26)	31%	11%	58%
Involvement in project design (including taking initiative) (N=24)	33%	25%	42%
Involvement in management (N=19)	32%	42%	26%
Ownership (N=24)	54%	38%	8%
User control (N=14)	0%	43%	57%
Shared facilities (N=25)	8%	40%	52%

In most cases, users' involvement is stimulated with feedback, often via an app or tablet, about energy consumption, local production and/or the balance between the two. This is meant to stimulate demand shifting or energy saving. In 8% of the 25 projects with information on this issue such feedback is lacking altogether. Financial incentives are present in almost a third of the projects. Such incentives are mostly provided for demand management reasons, and in a few projects to stimulate energy saving as well. In the projects with moderate feedback, information is provided without a defined purpose (for instance, stimulating demand shifting or reducing energy use).

Engaging users for co-creation takes place in a direct form if users are substantially involved in the decision making of the design of a project or specific SEPS. This is the case in one third of the projects, largely because of energy cooperatives taking initiative or becoming involved in a project in an early phase. In 25% of the projects users' needs are explored in advance (moderate involvement) and in 42% of the projects not any potential user is involved in any way in the design phase. Users can also provide feedback to developers in a later phase of the projects. This is the case in 74% of the projects to a larger (32%) or lesser degree (42%).

Co-creation can be regarded to occur more indirectly as well, if users own (parts) of the systems and control these themselves. Ownership is defined high if users had to decide to buy specific features of the local system (such as solar panels); it is moderate if facilities were provided to the users or there is a mixture of privately and externally owned components; and low if all components are owned by corporate project managers. In more than half of the projects, the residents own (most) of the smart energy system components, particularly the solar panels. They are however, dependent on other stakeholders owning system components in almost half of the projects.

User control indicates the extent to which the users control their own electricity consumption and production by the use of the smart features; i.e. the smart appliances, renewable energy and storage technologies. The more control they have, the more their engagement is needed for a successful project. As Table 4.5 shows, not even half of the projects provide only partial control by users, mainly achieved by using semi-automatic washing machines. In the majority of the projects, users have no control over the local energy system because of automation, among others in the case of the batteries.

(Co-)provision is regarded as an active role of users because their conduct "influences the grid and community, by reducing risks of load and voltage problems enabling more households to use PV" (Kendel, Lazaric, & Maréchal, 2017, p. 17). Such perceptions of co-provision are merely technical; just the possession of renewable energy make residents a provider. They are pre-occupied with the flexibility dimension of smart grids and hence do not go beyond demand shifting and co-creation. A more radical perception of co-provision is that of active, responsible citizens organised in energy cooperatives active in the renewable transition process whereby the relationships between the energy sector and users drastically change. This occurs if users indeed take and get the responsibilities and power of being an energy provider. While this is not the case for any investigated project, we looked at shared facilities to get an idea of increasing interdependencies between residents in an area or region. Shared facilities indicate to what extent the users are dependent on community members, which again increases their engagement with the project if successful. Of the projects, 8% involved full sharing, via among others a collective battery for 35 households or collective cars. In 40% the sharing is moderate, for instance domestic heat pumps which are centrally steered or a combination of individual technologies with a virtual power plant.

These findings confirm the conclusion of the literature study. If users are actively engaged with smart grid development, this is predominantly via project features that stimulate demand shifting, and energy saving to a lesser extent. Also in the Netherlands, co-creation and co-provision get less attention. Co-creation occurs mainly when local energy cooperatives are initiating or otherwise becoming involved in a smart grid projects. Co-provision is hardly existing. Sharing facilities may provide a relevant entry point to strengthen this roles of users.
Another finding is that demand shifting and energy saving are still mainly addressed with individualistic, consumer behaviour models as far as could be detected from the project information. We did not find any sign of a social practice-based orientation, as proposed in key social-scientific studies.

3.3 Learning in the smart grid niche

In the Netherlands, an innovation niche of smart grids as a socio-technological novelty is developing. In total, 31 residential smart grid projects with 15 households or more have been implemented in the Netherlands. In 2012, 8 projects started, which were all IPIN projects. After 2012, few new pilot projects started (just 2 projects in 2013 and none in 2014). In recent years, this number rose again, with 5 in 2016 and 7 in 2017 (Brouwers & van Mierlo, 2018a).

So far it is unclear how the residential smart grid niche develops, what knowledge is developed through the experimentation, what new rules and relations are developing and whether and how the development of this niche contributes to changes in the energy system. To understand how the specific niche(s) develop(s) in relation to the current energy system and sustainable system transitions, it is useful to investigate learning in the experiments and the cumulative learning in the niche(s) (made up by the collection of the experiments). In our study, learning processes are understood as the development and specification of new ideas inside a niche, in and through interaction between stakeholders within experiments and their experiences in practice (van Mierlo, 2012).

Expectations of key stakeholders about a future situation of smart grids instigate them to realize experimental projects. The learning in the practice of these projects feeds back upon the expectations and social relations. Over time, the learning in and through the local experiments may lead to aggregated knowledge about social and technical aspects of smart grids, the development of new generic rules, improved trust and changed relationships between consumers and producers. Figure 3.1 depicts how learning in local experiments may lead to an emerging proto-regime that provides an alternative to the current dominant system, in the context of this research the fossil fuel based, centralized energy system (Raven, 2012).

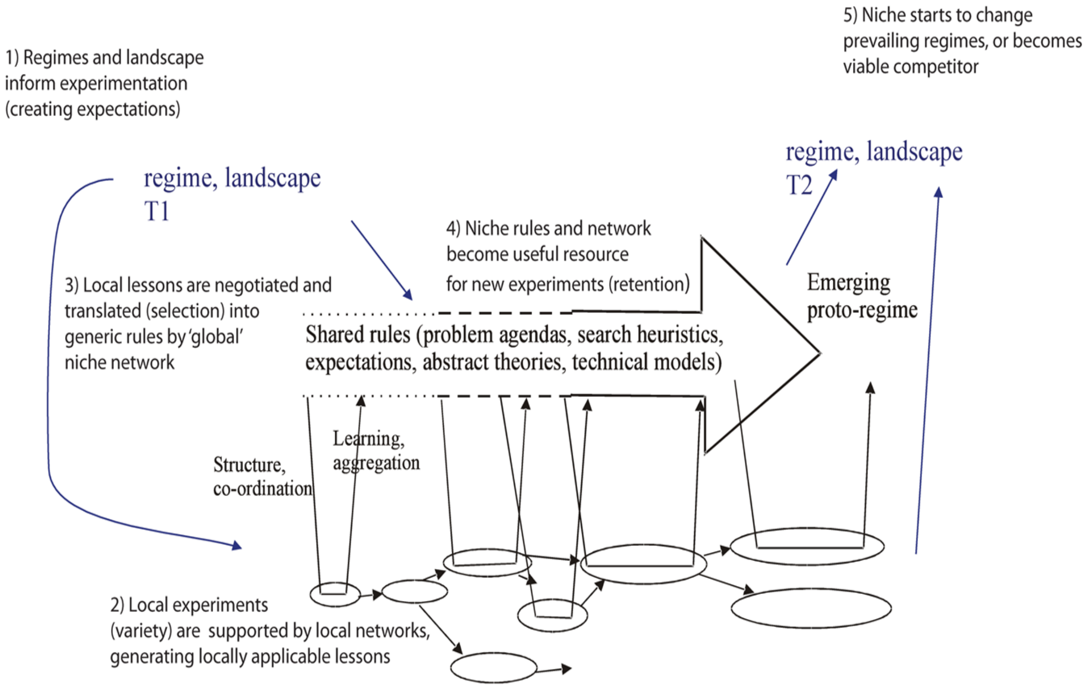


Figure 3.1: Learning in experiments and the aggregation of knowledge into generic, shared rules (Raven, 2012).

To investigate the learning in the smart grid niche, the empirical study of the 4 selected residential smart grid projects aimed to answer the following questions:

1. Which stakeholders are involved in the projects, in what way and for what reasons?
2. What learning took place in the projects regarding user engagement?
3. What knowledge flows in and out the projects and how is knowledge aggregated?

3.3.1 Involvement and expectations stakeholders

Figures 4.2 to 4.5 map the involved stakeholders in all four projects and how the relations between corporate actors and users were shaped. They show in the blue circle the project partners (often called 'consortium') and in the green circle the users.

As can be seen, DSOs, SEPS-suppliers, researchers and users figure in all cases. In two projects, the DSOs were project manager and in 2 others they became involved in a later stage, to test SEPS. Interestingly, in all projects socio-economic researchers were involved to investigate users' needs or responses; in 1 case they entered the project only at a later stage, when it had become clear that more attention would have to be paid to users (PowerMatching City).

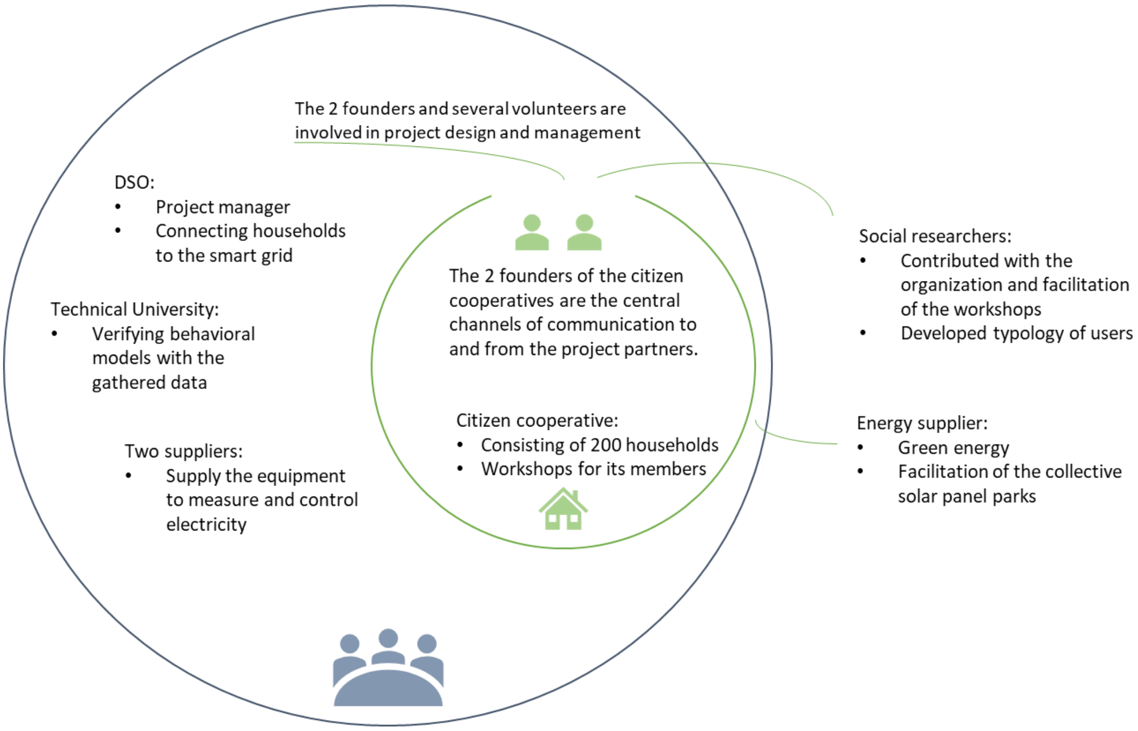


Figure 3.2: Map of the social network in Smart Grid Lochem.

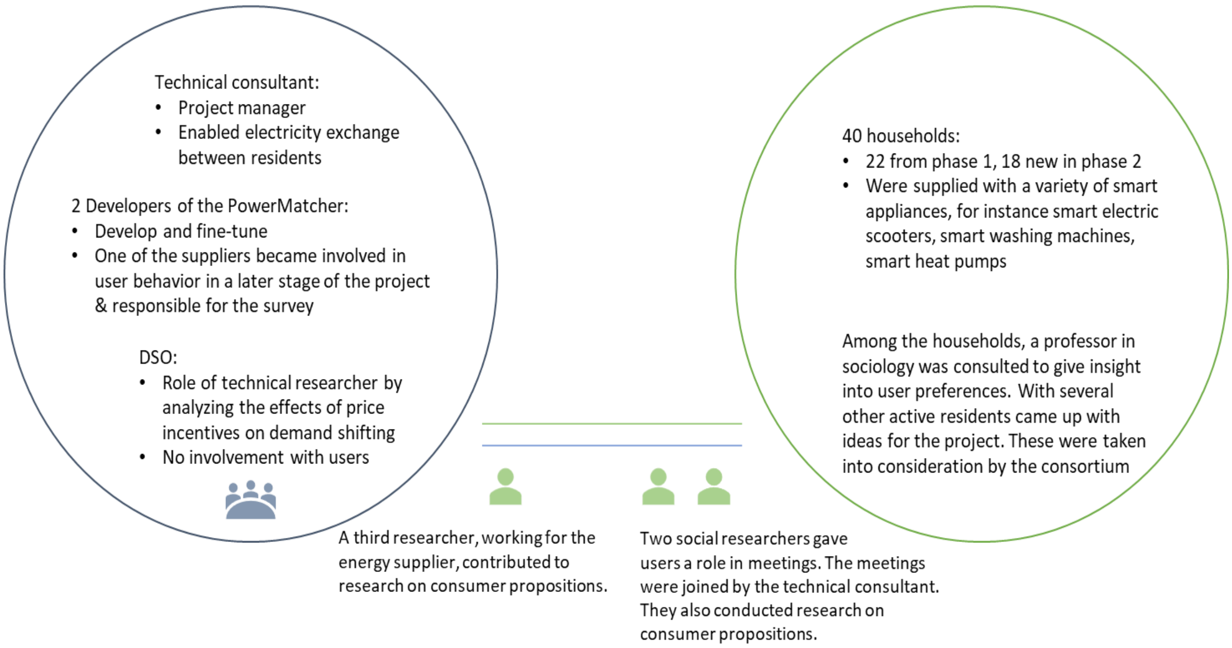


Figure 3.3. Map of the social network in PowerMatching City - phase 2.

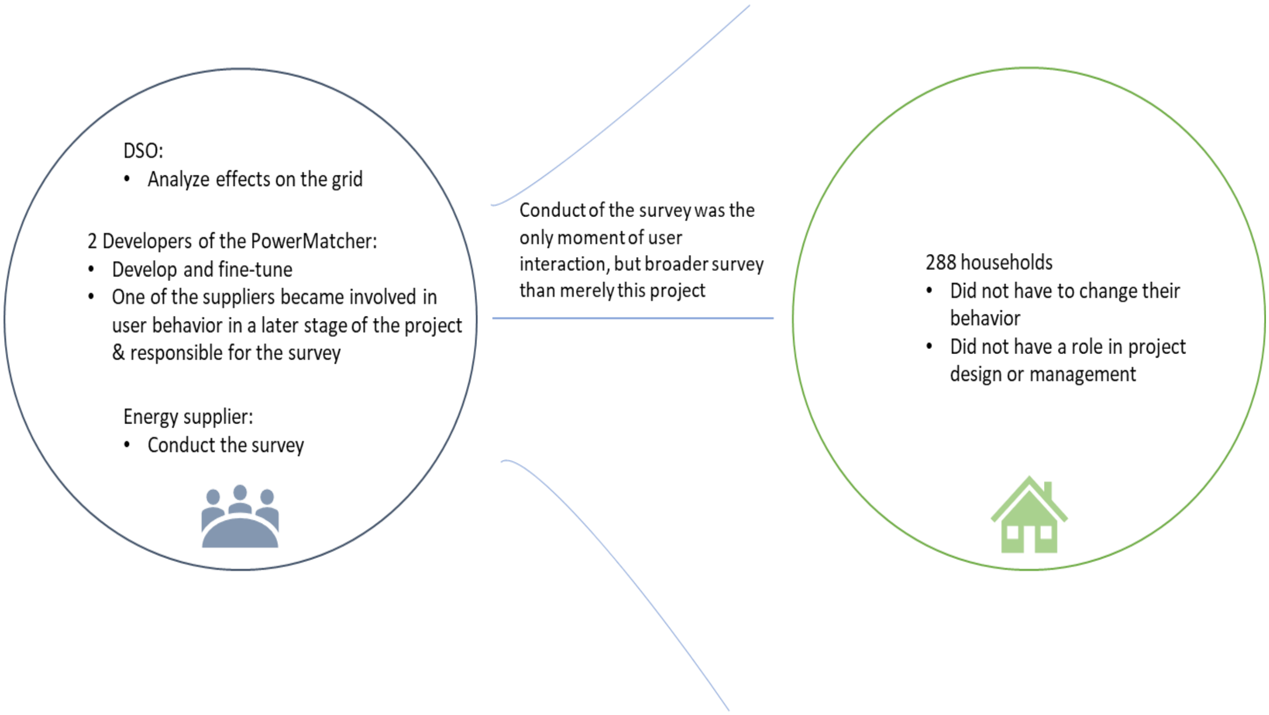


Figure 3.4. Map of the social network in Couperus

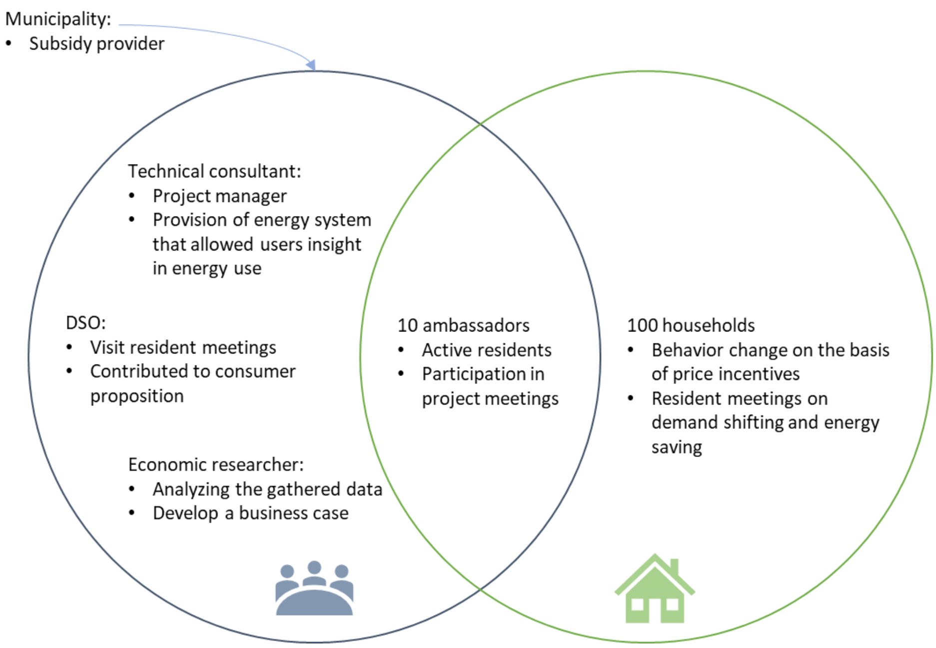


Figure 3.5: Map of the social network in Profit for all - Amersfoort

The relations between corporate stakeholders and users are highly diverse. In 2 projects the users were intensively involved, in the 2 others more extensively. Smart Grid Lochem and Profit for all some specific users had a very active role in project management. As such, respectively the project leaders and board members of LochemEnergy and the “ambassadors” in Profit for all performed the role of intermediary between the households and the corporate stakeholders. They did so in different ways. The 10 ambassadors willingly checked the participation contract and smart energy system before implementation in the other households, to ensure that the users’ interests were fairly represented in the contracts and for a smooth implementation of the energy system. The project leaders of LochemEnergy had their own goal in organising the users; they aimed to build an active community to strengthen the energy cooperative.
In the other two projects, the users were much less involved, with the least involvement in Couperus. In this project, a survey among the energy supplier’s clients was conducted to get an idea of what would stimulate behaviour change. Also, the residents moving in the newly built apartment complex had to accept being a participant in the experiment. In Power Matching City, phase 2, the residents were represented by social researchers conducting research on their desires and a social researcher from the area who spoke on behalf of his neighbours (and was therefore in this project a social consultant). The residents themselves had to choose between a sustainable and cost-effective proposition of the Power Matcher.

The 3 grid operators saw smart grids as an extra possibility to deal with the enhanced production of renewable energy. Smart grids would be helpful to increase the flexibility in energy consumption and hence balance supply and demand, but the extent of benefits was considered to be unclear. Therefore they were convinced that enhancing the grid capacity is necessary anyway. They were involved in the projects with the aim to analyse the effects of (smart) technologies on the grid. For some technologies, such as the PowerMatcher, the DSO expected to be able to upscale the technologies after the project ended. This turned out to be disappointing (see 4.3.2). They also expected that there is potential for a market in demand shifting and flexibility. This expectation was also not met (see 4.3.2). One DSO initially had little interest in smart grid experiments, because of the perceived lack of room for innovation in Dutch energy law and regulation. The DSOs were also searching for a relationship with users, which they did not have before with their traditional role of managing the electricity grid. Hence, two DSOs were also interested in the interaction itself with users and in analysing the project’s effects on energy consumption behaviour.

The technical consultants and suppliers were primarily interested in product development. The main technical consultant (DNV GL) saw a bright future for smart grids and expected users to become an important stakeholder in the market. Hence, there would be ample room to develop and supply good products. Smart energy systems could provide added value compared to smart meters, as it would help to connect technologies with one another as well as connect technologies to users. It is interesting to note that the technical consultant had high expectations of the PowerMatcher (which was used in 2 of the case projects) and saw this as the basis for future smart grids.

The social consultants and researchers were personally interested in investigating how to motivate users to shift energy demand, which they assumed to be quite difficult. Some social researchers perceived it of utmost importance to not only investigate people’s wishes, but also to provide them room to influence decisions taken in the project. The economic researcher in the Profit for all project expected that organising flexibility could provide his organisation an interesting business case, because flexibility would have to be created anyway. To this end, he aimed for supporting energy cooperatives who according to him would not be able to operate in an economically viable way on their own.

The main motivations of the interviewed users participating in the projects are related to an interest in sustainability and/or an interest in energy. Users state: *“I have an interest in sustainability and climate issues since I was young”* and *“I really want to change the world a little bit. Especially in the field of a municipality being energy neutral.”* Other factors, such as cost reduction and becoming more self-sufficient were considered an extra benefit by some of them.

Community formation is found important by both user representatives and the energy cooperative. User representatives were primarily interested in bringing people together and using this community to achieve a (local) change, for a sustainable energy system in PowerMatching City or for users themselves (cost-saving) in Profit for all. In PowerMatching City the energy cooperative that was present was not directly involved. In Smart Grid Lochem the project leaders speak mainly about community formation in order to strengthen their energy cooperative: *"We used this project to make our cooperative large and strong."*

3.3.2 Learning in the projects

3.3.2.1 Smart grid Lochem

With a workshop with active users and several interviews with users and other stakeholders, the learning in Smart Grid Lochem was investigated in-depth. Figure 3.6 depicts the most important experiences during the project (negative, neutral as well as positive) and their consequences according to the participants. Interestingly, the experiences in this frontrunner project were mostly negative for events in the early stages of the project and positive in the later stages. The continued efforts of the project leaders of the energy cooperative seem to have played a major role in the ultimate success of the project.

Figure 3.6 : Crucial moments in Smart Grid Lochem according to active members

The first crucial experiences according to the workshop participants, were related to the bankruptcy of the first participating energy company; a small green energy supplier. This was a very negative experience: *"Well, that bankruptcy was of course most tiresome."* Several users lost money due to the bankruptcy, because the excess money paid via their energy bills was not returned at the end of the year. At the end of December 2012, all participants were informed via e-mail that the involved energy supplier had gone bankrupt. They received an offer from other energy suppliers to whom the participants were automatically and randomly transferred by Dutch authorities. This event created a lot of unrest. Even though the participants were informed with e-mails and newsletters the project managers received a lot of phone calls from users in search for information. In March 2013, participants were informed via e-mail and the newsletter that Eneco would become the new energy partner of Lochem Energy. Participants could switch to Eneco and get 50 – 75 Euros cooperative discount.[5]

The second and third experiences are related. The delivery and installation of both the smart meters and the intelligent home system (which consisted of a box generating data from the smart grids and sending them to an app presenting graphs to the users) caused several problems. Firstly, the delivery of the smart meters was delayed and secondly the feedback system was not fully developed yet and did not work during the first tries. At some point however, most of the user-participants had a working system with real time information. Even though households have shown to be ambivalent to information on energy use, and information does not necessarily lead to new and more sustainable practices (Naus, Spaargaren, van Vliet, & van der Horst, 2014) the information was found to be useful in the working group on energy saving. These were organized by the project leaders to which all users were invited.

[5] In 2016, LochemEnergy partnered with Greenchoice as energy supplier.

The meetings helped the users to gain insight in their energy consumption and bring it down. A user in this project stated: *"We had so much fun in the workshops on energy savings and on electric vehicles. And to try different things with that. So people did save energy."* The founders of the cooperative concluded that the project had attracted new members to the cooperative and the workshops especially contributed to building a community among the members: *"So if you have joined in such a project, even though it is a combination of research and practical experiences, it works to attach people to your cooperative for a longer period of time."*

However, a few months after the project Smart Grid Lochem, the DSO discontinued its daughter company MPare that provided the feedback system. As they were no longer updated, the databox and the app of MPare stopped working. This caused again some frustration, except for the users who had chosen for other software in the meantime.

The first positive experiences were related to the PV-systems, albeit these were not very prominent in the memory of the workshop participants. When deciding to participate in Smart Grid Lochem, in their words ""the IPIN-project", users had to choose between individual solar panels or joining a solar park, by renting or purchasing 5 or 10 solar panels. Several parks were realized over time. Both individual and collective PV-systems filled the users with pride. Lastly, one of the participants explicitly stated that he found it awesome to be a precursor of the Dutch postal code regulation for energy cooperatives. This regulation is currently in place to stimulate collective solar systems, as it ensures that the profit of solar parks may be distributed among residents with the same postal codes without having to pay tax. Smart Grid Lochem is regarded by Naber *et al.* (2017) as a project that transforms regime dimensions, as users became more aware of the energy system and the DSO learned about the grid. However, they do not include that the collective solar panel parks in this project were a precursor of this Dutch regulation, another way in which LochemEnergie contributed to the change of a regime element.

Also positively experienced were the two black-out, or pressure-tests initiated by leaders of the cooperative. Residents of a street were asked to charge electric vehicles (which were provided for the test by family, friends and neighbours), turn on all their devices at 8pm and to bake provided pizzas in their ovens at the same time. The second test indeed led to a black-out of the grid. This happened to the surprise of the DSO who tried to charge the electric vehicles smartly. Although the tests were presented as a bit of fun to the users by delivering the pizzas, the managers of the cooperative concluded that its responsibility in the renewable energy transition was much larger than they had anticipated. The DSO tried to stop the test at first, because it felt that ensuring steady electricity supply was its right-to-existence. After the test it became more open-minded towards such tests.

After these experiences both active residents of the cooperative and the leaders show concern on how to address the rest of the citizens of Lochem. In their view, a large part of the inhabitants is not interested in energy or sustainability issues (see also Naber, Raven, Kouw & Dassen, 2017).

3.3.2.2 PowerMatching City

In PowerMatching City the main integrative learning concerned the device to balance supply and demanc; the PowerMatcher developed by the research organisation TNO. The technical consultant saw this system as the basis for future smart grids, but he discovered various problems during the project. In the first phase of the project, the flexibility was organised by automatic control of washing machines, heat pumps, dish washers and even smart charged electric scooters. This was not always appreciated by the users, as in their view the system's needs were prioritised over their own needs. In addition, they indicated that they wanted to gain more insight in the workings of the system. The next phase therefore, was improved by co-creation sessions with users. In addition, and as a result of research into users' motivations, the users could make a choice between a sustainability proposition or a cost-effective one. This led also to a new problem with the PowerMatcher, as the system needed to be adjusted. Integrating even more propositions in the future was perceived a potential problem by the technical consultant. Among other developments in wider society, this led to the rise of the Universal Smart Energy Framework (USEF). This is a standardized framework for different flexibility propositions.

In the second phase of the project users started washing when it was sunny after 14 days, because they had a better understanding of the energy system. This understanding was facilitated by the involvement in design and the previous participation in phase 1. As a result, one of the partners concluded that there had been too much of a technology-push in the first phase, which should not to be repeated in any other project. He adds: *"With a little bit of effort we could have learned much more and it would have been more fun for people to participate."* It can thus be concluded that much less was learned than would have been possible.

The second phase was useful for gaining insight in users' needs. As opposed to the technical consultant's expectations, users proved to be able to articulate their needs quite well. Users were very disappointed when the project ended and components of the system were discontinued.

Lastly, social researchers, the technical consultant and the users' representative showed concern about how to involve the wider public, in essence citizens who are not interested in energy issues and in smart grid development.

3.3.2.3 Couperus

The Couperus project saw very little integrative learning. A survey was conducted among the customers of the energy company, exploring what financial advantages would motivate people to change their energy consumption patterns. It was concluded that the requested advantages were too high to be realistic. Enhancing the grid would be cheaper. As a result, the main conclusion was that user involvement is hard to achieve. The DSO is therefore still waiting until a market on flexibility arises: *"We do not shape the market. That is not the position we have. At the end the clients has to want so."*

Because of the little user involvement, little was learned about this issue, in this project.

3.3.2.4 Profit for all - Amersfoort

The goal of Profit for all was to develop a project based on users' wishes. This caused friction between users and some stakeholders, as they had different goals in the project. Users wanted to investigate the topic of energy saving, which was not seen as a lucrative topic by all other stakeholders. Users were disappointed in the response of stakeholders. They state: *"We were working on a much broader scope (…), they only thought of that as complicated."* Moreover, bad collaboration within the consortium, which was acknowledged by all stakeholder groups, was also noticed by the users: "*We were a loose vehicle, we just went forward. There was so much discussion going on about who does what, whereas we were fully working on the project."*

Nonetheless, the users' enthusiasm led various stakeholders, such as the DSO, technical consultant and social researchers, to conclude that users' involvement is possible. The DSO already experimented with user involvement in other projects, in the same way as in this project.

In this project, users indicated that they found the resident meetings technically complicated, making it hard to understand everything: "*Well, all the terminology that was used during such a meeting. Yes, that was a bit too far for me. I am not a technician myself."* Even though this is an important aspect for future user involvement, it is interesting to note that this experience was not mentioned by other stakeholders.

Regarding the feedback system, users indicated that a decrease of use was related to an increase in insight in their energy behaviour and that the tools had thus served their purpose. This contrasts the general concerns about "response fatigue" (Kessels *et al*., 2016). The consortium found that users were more likely to reduce energy use when they got stimulating messages that focused on cost-saving, compared to messages that focused on sustainability motivations.

Stakeholders (excluding users) concluded, on the basis of the economic research, that at this moment no business case can be developed out of the flexibility of refrigerators in the households.

3.3.2.5 Learning and changed expectations

The learning in the projects influenced the ideas about smart grids. Some expectations about future energy systems and the role of users of various stakeholders were confirmed or became specified, others were altered.

Overall, demand shifting has been achieved in the projects, leading some of the DSO's expectations on demand shifting to be affirmed. The same accounts for expectations regarding energy saving in Profit for all and smart Grid Lochem.

Despite the insecurity about the potential of demand shifting, DSOs expected to enter a market for flexibility. However, their expectations regarding a soon to be flexibility market were not met in either Couperus or Profit for all. Also, the economic researcher expected to gain from the flexibility market. Nevertheless, these stakeholders still see potential in a future for smart grids in which energy demand

grows and electric vehicles gain a more dominant position, although as an extra option rather than an alternative to enhancing the grid.
On the role of users, the main learning of stakeholders is that the potential for user involvement is higher than expected. Technical consultants, DSOs and social researchers are positively surprised by users' enthusiasm and are already experimenting with user involvement in other projects. The technical consultant's perception of users also moved from a client-centered perspective to regarding a user as someone who is able to define his/her needs and respond to requests for demand shifting.
The users themselves were disappointed after the projects finished, which also indicates their engagement was larger than anticipated by the corporate actors. This however, is not the result of learning, but project management.
In 3 of the 4 projects, the users formed ideas about useful forms of feedback regarding their energy use. They were most inspired by real time information. Through such feedback (and in the case of Smart Grid Lochem the working group meetings) the users gained insight in the energy system and/or their energy use. Some of them reached a phase of "saturation", when they assumed to have gained sufficient insight.

3.3.3 Aggregating knowledge flows

Figures 4.2 to 4.5 map how knowledge was flowing in and out of all four projects. On the basis of these knowledge flows, it can be discerned what knowledge has been aggregated and what the learning in the single projects meant for ongoing smart grid developments.

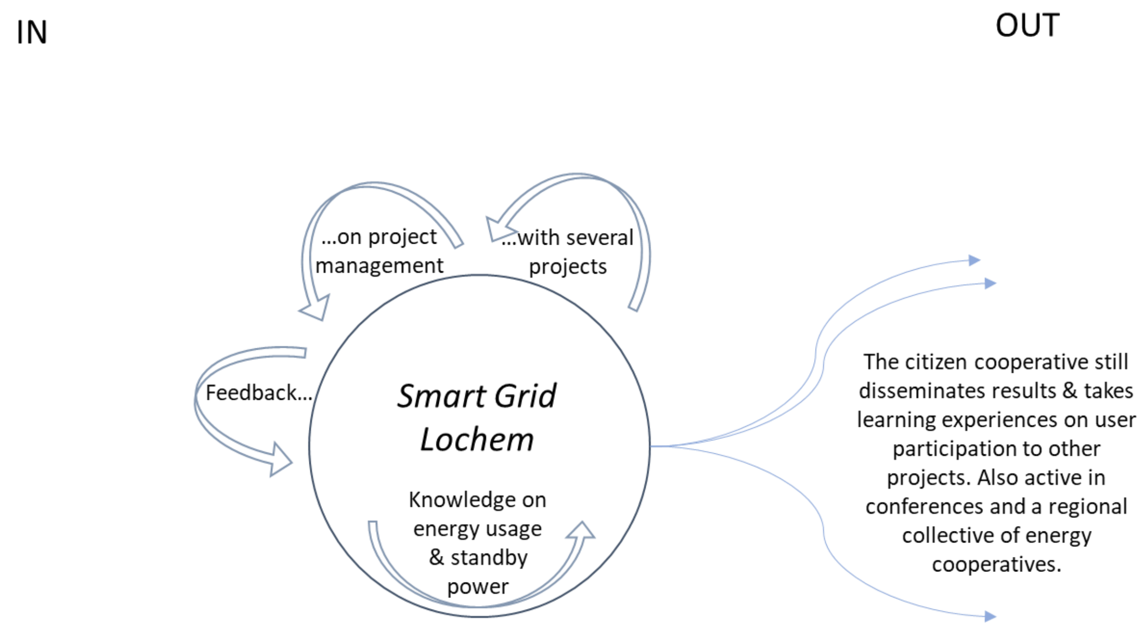


Figure 3.7: Knowledge flows Smart Grid Lochem.

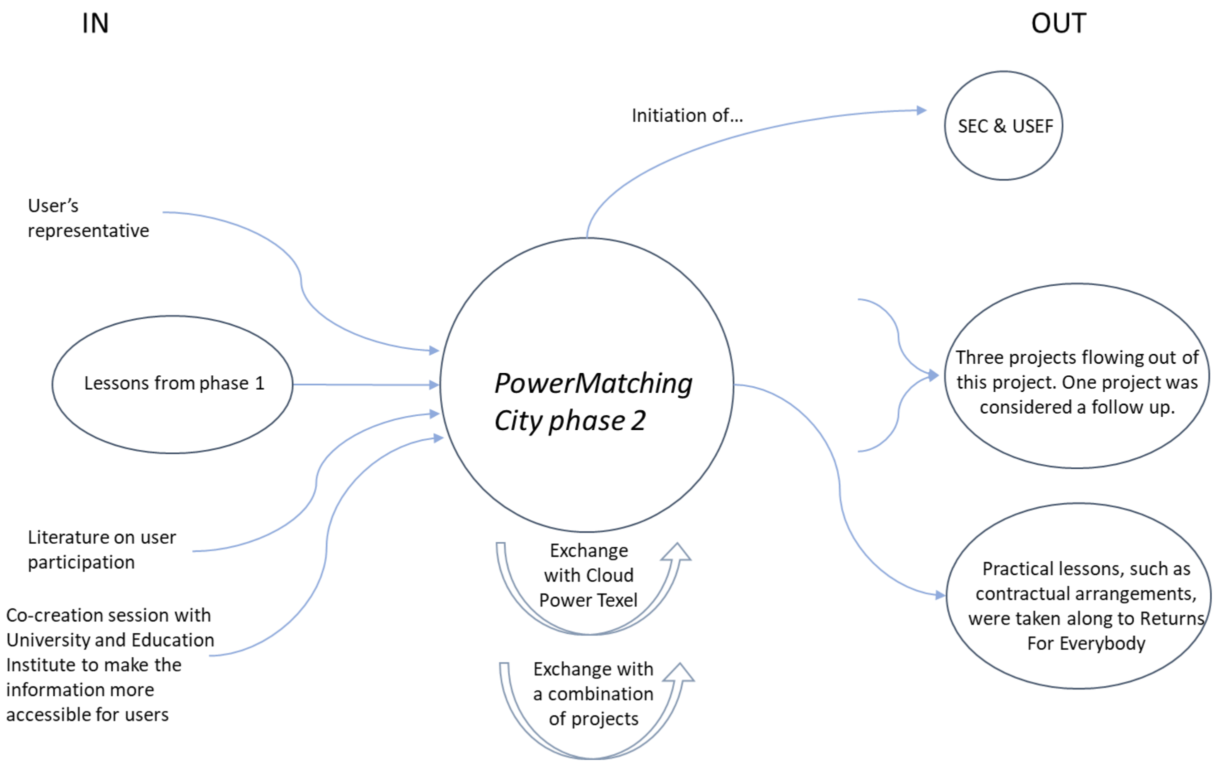


Figure 3.8:Knowledge flows PowerMatching City

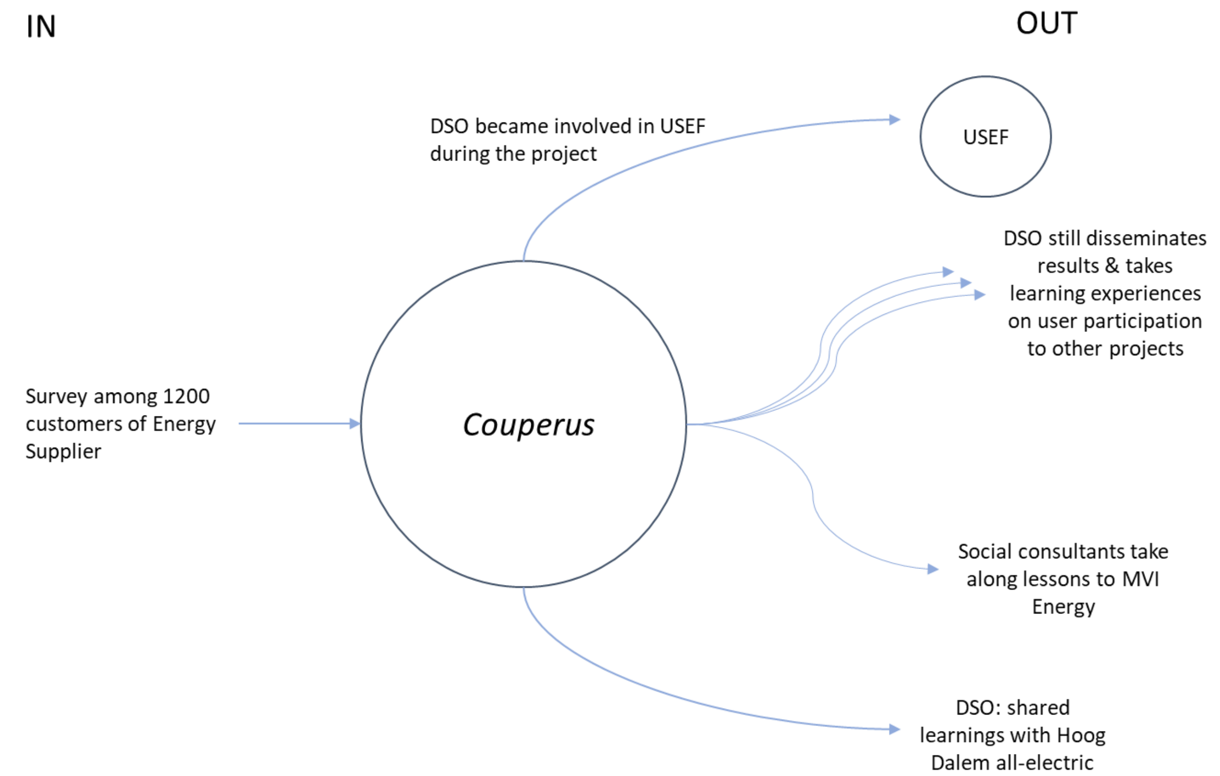


Figure 3.9: Knowledge flows Couperus

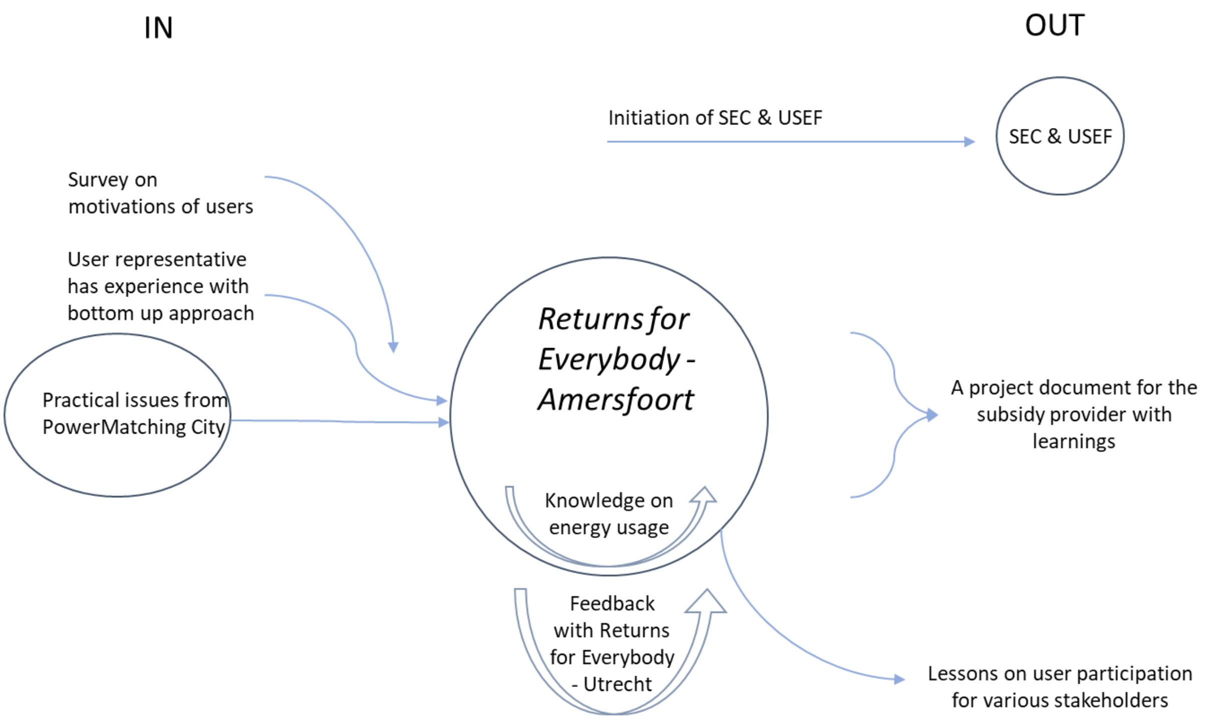


Figure 3.10: Knowledge flows Profit for all

All investigated projects made use of one or more knowledge sources. Couperus used the least and PowerMatching City the most diverse sources. Knowledge flows entering the projects were more about social than technical aspects. This is quite self-evident since technical knowledge was already available in the consortia of especially Couperus and PowerMatching City because these experiments were technical studies. Four sources of knowledge were used:

- Information from and exchange with partners of earlier, predecessor or parallel projects (e.g. Profit for all and PowerMatching City). This information concerns among others the importance of involving users, project management (in the case of Smart Grid Lochem) and practical issues, such as contractual arrangements.
- Expertise of consultants and commissioned research in the (re-)design of the projects. Some people hence are attracted as a partner or subcontractors because of their expected knowledge, among others on user participation and the provision of feedback. Related knowledge input builds on additional research and project experimentation, such as the consumer survey in Couperus and the stress tests in Lochem.
- User representatives providing knowledge about user desires and motives (PowerMatching City) and participatory projects (Profit for all). The board members and project leaders of Smart Grid Lochem had also such a role, being a resident of Lochem.
- Existing literature about participatory processes.

In addition, important knowledge was drawn from the novel collaborations and direct project experiences that were picked up in the very same project by the stakeholders. The partial success of PowerMatching City – phase 2 for instance is attributed to the accumulation of knowledge of multiple partners bringing in their experiences from other projects (Naber, Raven, Kouw & Dassen, 2017). An example of learning from direct experiences is the knowledge on energy use and energy saving measures that was shared between residents during meetings. This was visible in smart grid Lochem and Profit for all.

All investigated projects actively disseminate knowledge stemming from the experiences in the project. This is done in the following ways:

- Lessons are personally taken along to either direct follow-up projects or new projects. This is the case for all four investigated projects and the main source of knowledge flowing out of the projects. Such knowledge flowing out of the projects concern both social and technical aspects, such as how the DSO experiments further with user involvement after the project Profit for all and the workings of the PowerMatcher or the results the DSO has acquired by the tests on the grid respectively.
- Lessons are personally shared with participants of other projects.
- Lessons regarding techniques and the market are aggregated by contributing to standardization frameworks in the context of the Universal Smart Energy Framework (USEF). USEF aims to provide an international common standard for smart energy to unify markets and decrease the costs of projects and technologies and develops a market model for the trading and commoditization of energy flexibility, and the architecture, tools and rules to make it work effectively.
- Learning experiences are shared in generic forms such as IPIN documents or conferences contributions, in one case to account for the project results with the subsidy giver and in other cases to inform a wider public. In the documentation of the IPIN projects lessons are shared between projects on user involvement. Documented lessons are that user involvement is a matter of culture change and should therefore be embedded in project organization. They focus on users' needs, because the authors see smart grids as a means to achieve a sustainable energy transition, not an end. Still, they regard users as 'clients' and share lessons on communication for influencing (RVO, 2015). One of the interviewees however, stated that little was learned from other IPIN-projects, because there were few meetings and they lacked interaction between the projects.

Aggregated knowledge concern 1) the conclusion that there is not yet a flexibility market; 2) the emerging rule to not use a technology-push approach; and 3) that users do play an important role in smart grid development. The ideas about how and why to involve users have not yet become further specified however.

Knowledge streams both in and out of the projects predominantly via persons or organisations and much less via aggregating research, documents or meetings. Especially persons and organisations involved in a plurality of projects (the grid operators and DNV GL) bring their knowledge along from project to project, and thus for instance connect the learning experiences in Profit for all with PowerMatching City. This is however not possible for stakeholders involved in single projects, such as the users and some social researchers. Their experiences such as disappointments due to discontinuation or in Profit for all the friction between participants regarding the importance of energy saving, can thus easily be lost for other stakeholders.

Because most knowledge flows via persons or organizations and they participate in more projects, follow-up projects are thus a good way to aggregate knowledge. However, aggregating the knowledge of users on the basis of their own experiences rather than other stakeholders' experiences need special attention. Also in the case of standardizing lessons learnt in generic frameworks, contributions from the users' perspective need to be guaranteed.

3.4 Conclusions and recommendations

Dozens residential smart grid pilot projects have been realized in the Netherlands. While their main aim often is to experiment with flexibility, user aspects have received quite some attention since the IPIN-programme. This chapter reports on the findings of research about what stakeholders in what way are involved in Dutch pilot projects and their main learning experiences, especially regarding user aspects. The goal was to explore what this means for the development of the smart grid niche.

The research was conducted with a combination of methods. A broad overview was provided by investigating all publicly available project information of all Dutch residential projects with more than 15 residents. While many projects did not report on some other relevant issues, like the involvement of secondary actors and user control of the smart energy system, this exploration provided ample evidence of among others the organization of the project consortia. To gain in-depth insight on the expectations and motivations of the actors involved in the projects, we conducted semi-structured interviews with stakeholders of 4 diverse projects and a workshop at one of these projects. This is the preferable method in case of rather undefined expectations related to new technologies and social innovations.
A drawback of the selected projects is that they finished some years ago, being part of a development phase with the first larger residential projects. We call them "early projects" in the conclusions below. It means that the experiences in these projects are not necessarily representative of experiences in later projects. It also hindered at times a clear recollection of events and experiences by the interviewees. At the same time, these recent interviews enabled to investigate the actual expectations of the stakeholders about the future of smart grids. Moreover, the findings were backed up by our literature reviews.

In more details the main conclusions are:

- The public organizations, grid operators, play a more dominant role than energy companies, that used to be important for introducing renewable energy to households.
- The grid operators had to develop ideas about their own relationship with users which hitherto were non-existent. In a few of the in-depth investigated projects, the DSOs started seeing potential for user involvement. In contrast, in the project without user involvement the grid operator remained pessimistic about the possibilities; the project provided no triggers to rethink this expectation.
- Many researchers, both technical and social, were and are involved in the projects. In 2 early projects, the technical consultants were positively surprised that users were able to clearly articulate their wishes and showed enthusiasm about the smart grid project. The roles of social researchers concerned the information needs of users; their expectations did not change much due to their experiences in the early projects.
- Expectations of DSOs and consultants about a flexibility market have so far remained unfulfilled.
- The Dutch residential smart grid projects are managed by two types of consortia; without or with sincere involvement of users in design and management. User involvement seems to have become more important over time. In two early projects, the consortia made a move from a technology push approach to user involvement.
- The levels and forms of user engagement vary largely in the Dutch projects as a result of the huge variance in project features that supposedly stimulate user engagement whether or not

intentionally: feedback provision; financial incentives; involvement in project design and management; ownership of energy system components; user control; and shared facilities. While feedback and ownership are quite prevalent, and user involvement in management is moderate, the other features are more rare.

- User involvement in design and management usually takes place via intermediaries: project leaders of local energy cooperative, a group of "ambassadors" or otherwise some selective users representing others who can be regarded as intermediaries if they consult the wider group of users.
- Project leaders and board members of energy cooperatives operate on behalf of the members of the cooperatives. These cooperatives have wider goals than just the smart grid projects that seem to be instigated for reasons of community building.
- In general, demand shifting is key to the goal and set-up of projects, also in the case of mediated participation. The majority of the residents participating in the projects still are addressed as consumers, albeit energy aware.
- Overall, demand shifting has been achieved in the early projects, leading some of the DSOs' expectations on demand shifting to be affirmed. The same accounts for expectations regarding energy saving in the 2 projects in which this was a more important goal than demand shifting.
- Users seem more interested in energy saving than corporate actors (see also Hansen & Borup, 2017 and Smale, van Vliet & Spaargaren.)
- In the 3 early projects with user involvement, the users gained insight in the energy system and/or their energy use and learned about useful forms of feedback (real time information). Working group meetings seem to be additional way of stimulating energy awareness.
- Some of the active users reached a phase of "saturation", when they were convinced to have gained sufficient insight, others continued to find ways to save energy or shift energy demand. This nuances conclusions about "response fatigue" (Kessels *et al.,* 2016).
- Little has been learned about co-creation and co-provision as forms of user engagement. These could be instigated by involving users in project design and management, ownership, user control and shared facilities. Such project features are hardly implemented however, and even if they are, seldom evaluated or reflected upon in the projects.
- The current projects provide little information about how to engage the majority of Dutch inhabitants, who on average may be less interested in energy than the users in current projects. They provide either insight regarding a selective group of energy-aware users or no insight if users are not involved at all.
- Some learning experiences have become aggregated over time: 1) the conclusion that there is not yet a flexibility market; 2) the emerging rule to not use a technology-push approach; and 3) that users do play an important role in smart grid development. The ideas about how and why to involve users have not become further specified however.
- Knowledge streams both in and out of the projects predominantly via persons or organizations and much less via aggregating research, documents or meetings. Especially persons and organizations involved in a plurality of projects bring their knowledge along from project to project. Experiences of stakeholders involved in single projects, such as the users and some social researchers tend to get lost for other stakeholders: e.g. the users 'disappointments due to discontinuation or friction between participants regarding the key goals of the project.

Recommendations following from these detailed conclusions are to:

- Actively involve residents in pilot projects to enable both corporate actors and users to learn about user involvement, positively as well as negatively.
- Set-up projects with different levels of user engagement in order to include the users who are less interested in energy and evaluate these projects with all the users.
- Instigate user engagement more and in other forms than with the well-known and more or less taken-for-granted methods of feedback and financial incentives. Ownership by users, users' control and influence in decision making at the level of the project would be interesting forms to experiment with. This again, would provide all participating actors the opportunity to learn about such project features if such lessons are systematically extracted.
- Anticipate and organize a continued involvement of users after the ending of a project as the discontinuation caused major disappointment in two projects.

- Address users not just as energy consumers, but also as managers of local energy system, meaning they would gain decision making power, to learn about their role as empowered co-providers (see also Geelen, Reinders & Keyson, 2013).
- Undertake aggregating activities with users on the basis of their own experiences rather than other stakeholders' experiences. Also in the case of standardizing lessons learnt in generic frameworks, contributions from the users' perspective need to be guaranteed.

4 EXPERIENCES WITH SMART GRID TECHNOLOGIES

4.1 Introduction[6]

This chapter focuses on the smart grid systems, energy technologies and smart energy products at the end-user level in smart grids studied in The Netherlands. It thus presents the main results obtained from Work Package 4: on “Technologies and Methods”. In this chapter, we present the results of the analysis of three smart grid pilots in The Netherlands and the two pilot projects on universities campuses. One of the main challenges of the project was to obtain the measured energy data from the smart grid pilots due to privacy issues. Only from three of them data was available, namely Power Matching City (Bliek et al., 2010), Jouw Energie Moment (Jouw Energie Moment, 2019) and Rendement voor Iedereen . Smart meter open data from Liander on electricity consumption and production of an anonymous Dutch neighbourhood was used as reference for comparison (Liander, 2018). In Chapter 2, in

Table 2.1 2.1, an overview of the technologies applied in the smart grid pilots and pilots on campus that were studied in the CESEPs project is presented. In this chapter we go deeper into the technologies and analyse the performance of the pilots and their potential to offer flexibility via demand side management techniques. While in conventional households, energy resources at a customer level are mainly uncontrollable, new smart grid technologies enable different possibilities to which energy resources can be controlled, and thus provide flexibility to the grid operator. The term flexibility is defined by EDSO: *“On an individual level, flexibility is the modification of generation injection and/or consumption patterns in reaction to an external signal (price signal or activation) in order to provide a service within the energy system.”* (EDSO, 2014).

The structure of the chapter is as follows. First results on the energy performance analysis of the three smart grid pilots in The Netherlands are presented (section 4.2) (Schram et al., 2018b), (Gercek and Reinders, 2019) . In Section 4.3, results of studied demand side management techniques will be presented (Gercek and Reinders, 2018b),(Gercek and Reinders, 2018b), (Lampropoulos et al., 2018), (Lampropoulos et al., 2019). Sections 4.4 and 4.5 present the results of the demonstrations projects on university campus which are a solar charging station for e-bikes (Zhang et al., 2019),(Apostolou et al., 2018a) and use of hydrogen mobility for combined transport and power generation for the built environment (Robledo et al., 2018a),(Robledo et al., 2019a),(Oldenbroek et al., 2018), respectively of University of Twente and Delft University of Technology . Section 4.6 presents the conclusions of this Chapter.

4.2 Analysis of smart grid pilots

[6] A significant part of this chapter has been written by Carla Robledo, Wouter Schram and Cihan Gercek

A brief description of these three smart grid pilots and the energy technologies that were employed are is given:

Power Matching City (PMC): Phase 1 (2007-2011) of this pilot consisted of 25 households in Groningen equipped with decentralized generators, in the form of micro combined heat and power (µ-CHP) and PV panels, as well as steerable loads, such as: hybrid heat pumps(HP), electric vehicles (EV), home management systems and smart appliances such as dishwasher and washingmachines.. Specific software to match demand and production was developed: the "PowerMatcher". In the second phase (2012-2015), more houses were incorporated, summing up to a total 40, and a variable tariff scheme for electricity was implemented.

Jouw Energie Moment (JEM): This smart grid pilot project consisted of two phases. The first phase, 'JEM 1.0', was carried out from 2012-2015. It included 382 residential households in new constructed buildings in Breda (Easy Street/Meulenspie) and Zwolle (MuziekWijk). All the participants received a smart meter connected to an energy management system (EMS, display in home), where they could see instantly when energy supplied from renewable sources and/or cheaper. Also the houses had smart wash machines, rooftop solar panels and flexible energy tariffs. In JEM 2.0 the smart washing machine was not implemented. Instead the use of a home battery behind the meter to store locally produced renewable energy was analysed in combination with flexible energy tariffs. The group of houses in Meulenspie-Breda (39 Households) presented a heat pump connected to the EMS and an app was developed that was connected to the smart meter. The main goal was to analyse scalable and profitable business models to stimulate end-users to change their energy consumption behavior and alleviate the grid during high peak demand. A second neighborhood in Breda of which electricity consumption was monitored, was Easy Street. This entails apartments inhabited by students and these households neither have PV panels nor heat pumps. We do not possess the data of Zwolle, therefore the households numbers is limited to 170 households in Breda. Despite this, JEM is the largest dataset studied in this report in terms of participating households.

Rendement voor Iedereen (R4I): The Smart grid: Rendement voor Iedereen (Profit for all) project ran from 2012 to 2014 in two central cities in the Netherlands: Utrecht and Amersfoort. The goal was to develop business cases focused on future smart grids and accompanying energy services. In both cities, smart meters were installed in 100 households that were equipped with solar panels. These meters measured grid power interaction at an unusual high time resolution of 10 seconds. For the CESEPS project, data was collected and analysed from the Amersfoort pilot.

In order to compare the pilots, the year 2013 has been chosen since it is the one that we could access data from the pilots. Nonetheless for PMC we could only access 2012 data and which were used to compare with the other pilots. Moreover, data from all households was not available for all pilots. From a data diagnosis, it followed that the monitoring fraction was higher than 90%. The analyse here presented in this report is based on 21 households for PMC, 117 households for JEM (26 for Meulenspie and 91 for Easy Street), and 79 households for R4I. Several parameters have been chosen to be able to characterize and compare the pilots, such as, total (yearly and monthly) electricity load, peak imported electricity and PV feed-in, and Self-Consumption and Self-Sufficiency ratios. For grid operators, the peak imported electricity and PV feed-in are important parameters, as these define the capacity that is needed for household connections, cables and/or transformer substations among others. The Self-Consumption ratio (SCR) is defined as the directly on-site consumed renewable generated electricity over the total renewable generated electricity, and the Self-Sufficiency ratio (SSR) is defined as the directly on-site consumed renewable generated electricity over the total electricity consumption. They are calculated as shown in Equation 4.1 and Equation 4.2, respectively:

$$SCR = \frac{E_{C\_RE}}{E_{RE\_tot}} \times 100\% \tag{4.1}$$

$$SSR = \frac{E_{C\_RE}}{E_{C\_tot}} \times 100\% \tag{4.2}$$

where E_{C_RE} is the on site renewable energy consumption and E_{RE_tot} is the total energy generated by renewable sources and E_{C_tot} is the total energy consumption. These are also important parameters to understand the impact of on-site renewable energy generation in the pilots. This also applies to load duration curves, which are used to compare the consumption/production of electricity among the pilots. Table 4.1 resumes the main features of the data and the properties of the data.

Table 4.1 Summary of main features of the pilots and their data

Residential Smart Grid demonstration projects	Location	No. HH*	Time step interval of data	HEMS	Energy App.	Heat Pumps	Smart Appliances
Jouw energy moment	Breda Easy street	117	15 min.	x	x		
	Breda Meulenspie	26	15 min.	x	x	x	
Powermatching City	Groningen	21	5 min.**	x		x	x
Rendement voor iedereen (Profit for all)	Amersfoort	79	10 sec.**		x		

*Only households >90% of monitoring fraction have been included to the analysis (at 15 min.).
**Time step interval has been reduced to 15 min. by using mean values, to enable the comparison

4.2.1 Electricity consumption and production

For the ease of understanding of our readers, the seasonal effects can be seen in the monthly electricity consumption and production profiles, as shown in Figure 4.1.

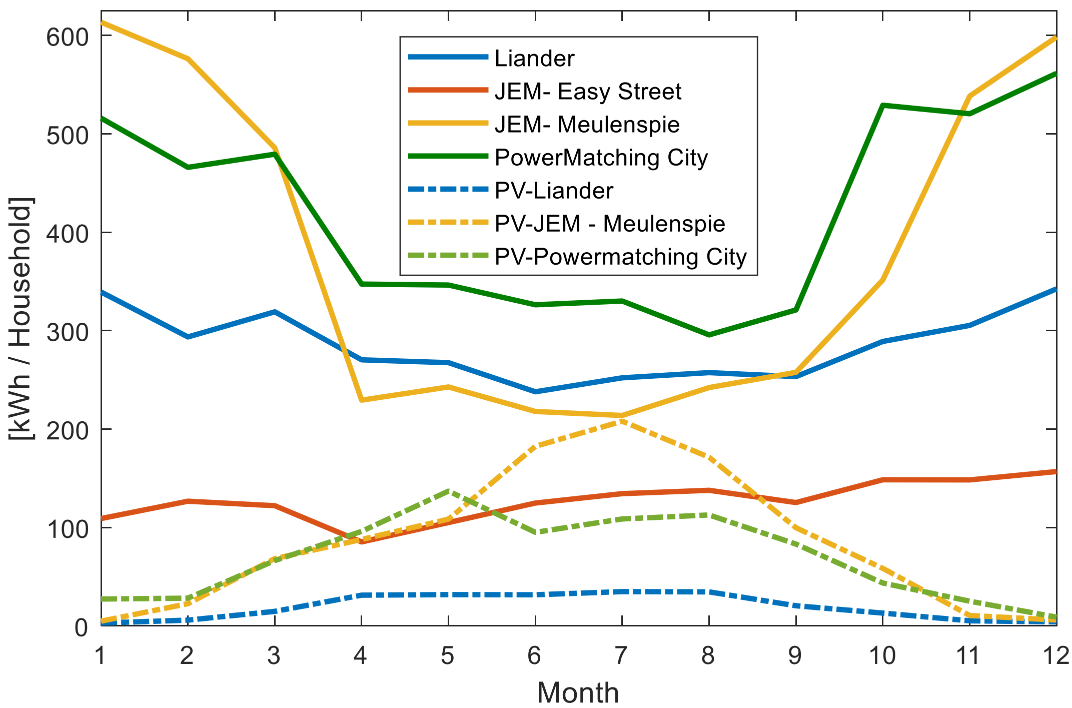


Figure 4.1. Monthly electricity consumption and production profile over the year.

In the summer months solar power generation increases in all pilots. For the months of July, the solar generation even meets the total consumption in the JEM – Meulenspie pilot. Next to the PV system size, the location and the year play a significant role in the electricity produced by PV systems. PMC PV output indicates that the month of May 2012 was relatively sunny. JEM –Meulenspie PV output shows that for 2013, the highest solar energy production occurred in July. The consumption patterns are relatively constant for the Liander as well as JEM-Easy Street, but seasonal variations are observed in both JEM-Meulenspie and PMC. In those two pilots, large electricity consumption differences are observed between winter and summer due to the heat pumps, which demanded higher amounts of imported electricity during the cold period.

Further, to analyse the impact of the different energy technologies and the different configurations of pilots, the concept of *residual load* is introduced. This is the total load (hourly demand) minus the generation from renewable power generation on-site, and it is calculated as shown in Equation 4.3:

$$P_{residual} = P_C - P_{RE} \tag{4.3}$$

where $P_{residual}$ is the residual load, P_c is the momentary electricity consumption in power and P_{RE} is the total renewable energy production in power at that time. In other words, in this case it shows the remaining demand that needs to be supplied by the grid to the pilots. The *residual load* concept allows quantifying the amount of flexibility required for a given pilot, at the times of surplus (negative values) either by demand side response techniques, delivery of power to the grid or electricity storage. Pilots that contain heat pumps are treated separately from those that didn't because of their distinct results in power. Figure 4.2 shows the residual load curves of the two smart grid pilots without heat pumps, such as Rendement voor Iedereen and JEM-Easy Street, and the Liander Zonnedael open data set that is used as reference, which shows the average net power consumption per household of the pilots over an entire year. Figure 4.3 presents the residual load curves that corresponded to the pilots including heat pumps (PMC and JEM-Breda-Meulenspie). The area under the curve is thus the electric energy (electricity) used per household. The negative values represent electricity fed in to the grid from the solar production. In this way we can see that R4I, PMC and JEM-Breda-Meulenspie offer the greatest potential for flexibility of all the pilots analyzed (see Figure 4.2 and Figure 4.3). Only JEM-Easy Street had a lower electricity consumption at all times compared to Zonnedaal. From this data it seems that this pilot effectively achieved its goals of having a slight slope of load duration (except the first 1%) as users were asked to steer on prices. Nevertheless, households size is by far the most an important parameter to consider: Easy Street in Breda contains of apartments inhabited by students, who evidently have a lower energy consumption in general. R4I had a slightly higher consumption 20 % of the time, but for the remainder it showed a lower consumption than Zonnedael. Also the peak demand was kept the same.

PMC showed the highest consumption of all smart grid pilots and also the highest peak demand, up to 5 kW (see Figure 4.3). This is due to the fact that the pilot had a large number of residents per household, large household surfaces (150-199 m2), and included heat pumps for space heating With respect to PV production, R4I had the highest feed in values of all the pilots, due to the fact that it had the highest shares of households with PV system installed (61 out of the 79 households). This notion is further confirmed by Figure 4.4, where the boxplots of the yearly household energy demand from the grid and PV power fed in the grid are plotted for all the four data sets.

Most households in R4I have a slightly lower imported electricity than Liander Zonnedael. The average in R4I is 3.01 MWh and in Zonnedael 3.2 MWh. Given that R4I has many PV systems installed, and PV-generated electricity that is directly consumed on-side (i.e. self-consumption) is excluded from the residual load, we can conclude that electricity demand in R4I is probably somewhat above the Dutch average (~ 3.3 MWh), and that of Zonnedael is in line with the average. Both in imported electricity and PV fed in the grid, we see large differences between the households; the upper quartiles show a spread of around 2 MWh. Since most households in the Zonnedael data set are not equipped with PV systems, all households that do have these are considered outliers. Both in imported electricity and PV fed in the grid, we see large differences between the households, indicated by the maximum and minimum whiskers in the boxplot. Since most households in the Zonnedael were not equipped with PV systems, all households that do have these are considered outliers (red crosses). For the households of the two pilots including heat pumps, JEM (see right side of Figure 4.4), the consumption is one to two MWh above the Dutch average, with a considerable increase of electricity consumption during winter.

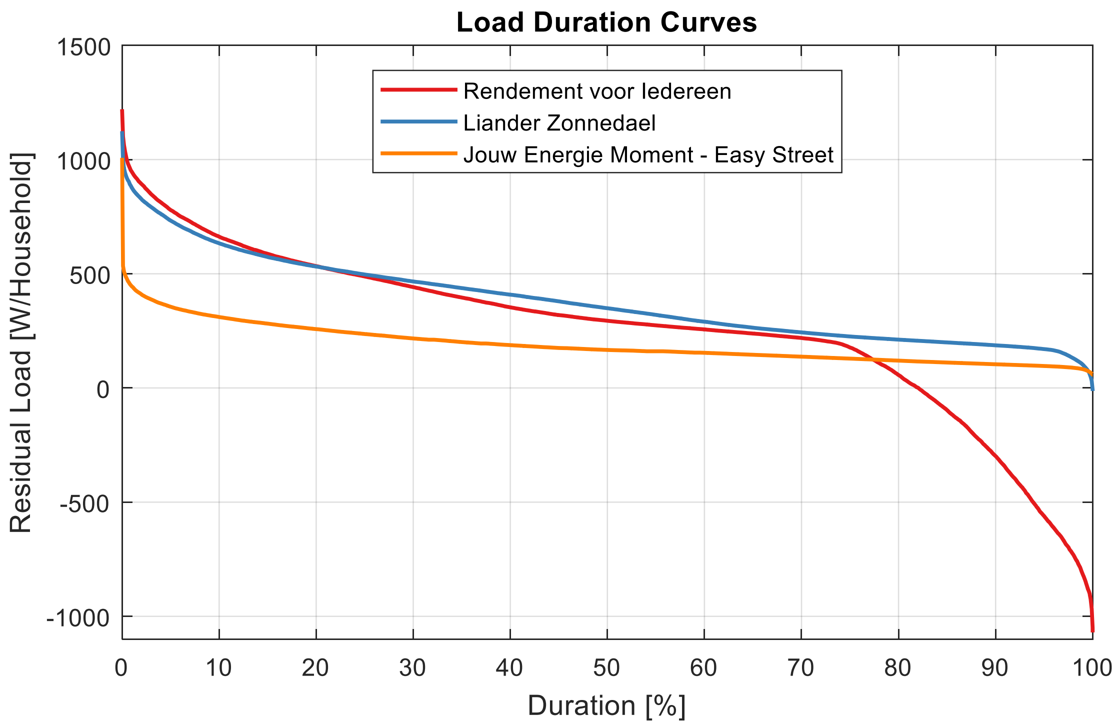


Figure 4.2. Load duration curves of the "Smartgrid: Rendement voor Iedereen" project, the Liander Zonnedael open data set, and “Jouw Energie Moment” project exclusively Breda-Easy Street.

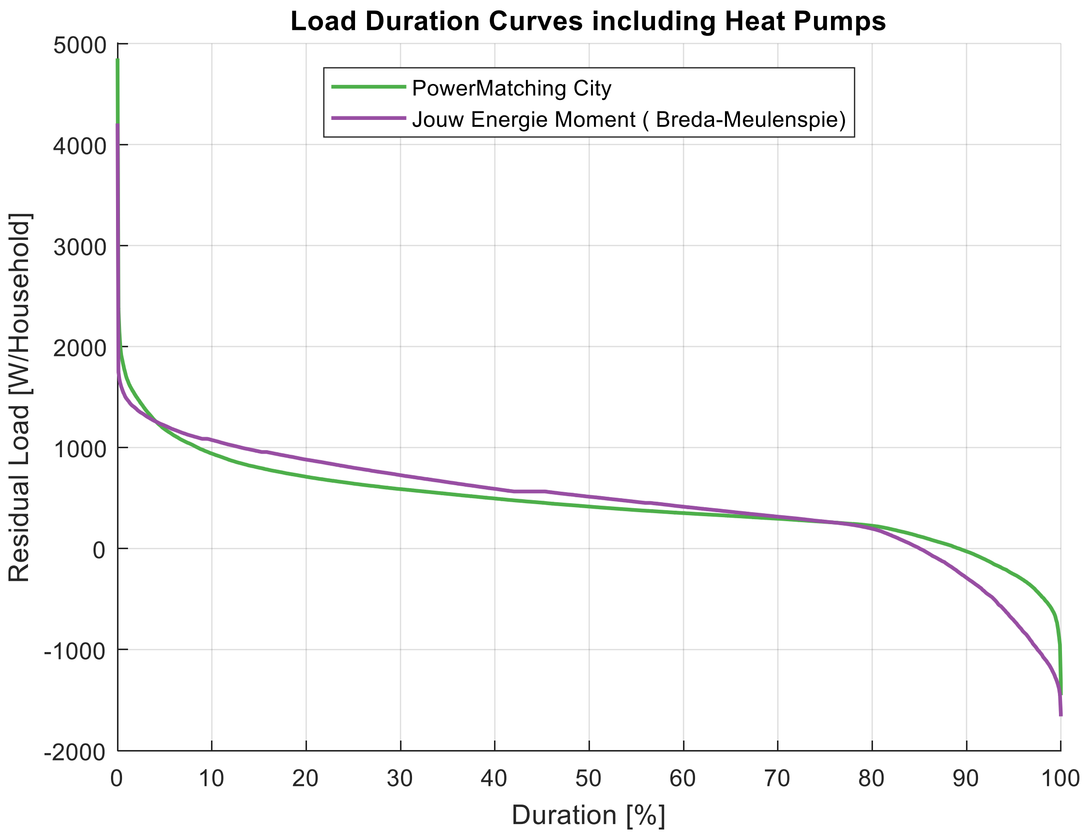


Figure 4.3 Load duration curves of the ‘’ PowerMatching City’’ project and “Jouw Energie Moment” project, Meulen-spei group (all households are equipped with heat pumps).

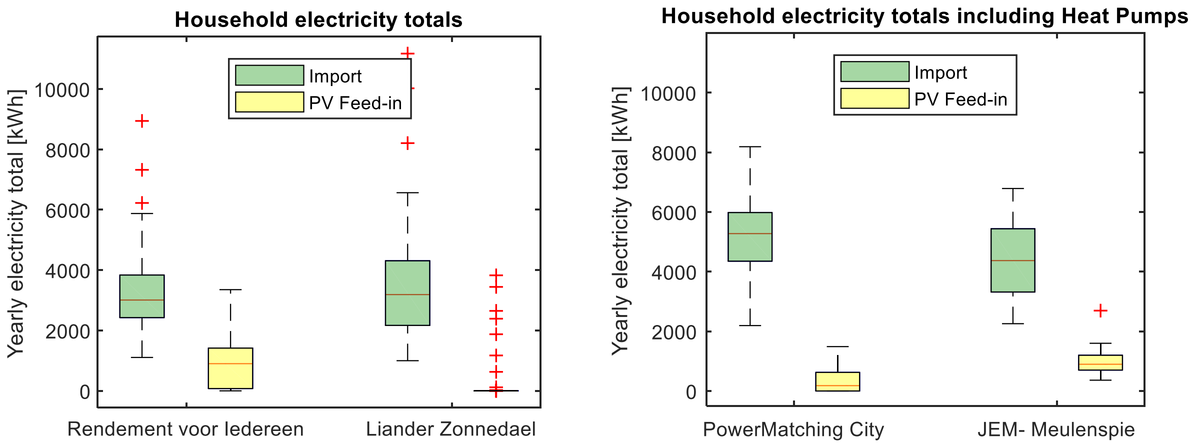


Figure 4.4. Boxplots of annually imported electricity from the grid and Surplus PV (feed-in) to the grid. *
** On each box, the red line indicates the median, and the bottom and top edges of the box indicate the 25th and 75th percentiles, respectively. The whiskers extend to the most extreme data points not considering the outliers, and the outliers are plotted individually in red.*

4.2.2 Peak load

Peak load refers to a relatively short period of time when electricity demand is reaching its highest value of the day. Usually it occurs when families come back to their homes form work/school and turn on their lights, TVs, appliances,and heating/cooling systems... With increasing electrification of products (heat pumps, electric vehicles, for example), the grid is subjected to higher amounts of electricity. And if this occurs all at the same time, the risk exists of overloading and thus grid failures. That is why it is important to look at peak load values in smart grid pilots in the Netherlands. Figure 4.5 shows the distribution of the power peaks measured for individual households at a time scale of 15 min., as well as the normalized peak for the whole community. The latter is the aggregated peak divided by the number of households. JEM-Easy street was not plotted as few peaks were appearing and unfortunately PV data was absent. Between the pilots analysed, peak imported electricity ranged between ~ 2 kW and ~ 9 kW for all pilots, with 4 outliers present above 9 kW. We summarized the different residential connections in the Netherlands in Table 4.2, regarding their power limits, availability for new connections and their application.

Table 4.2. Connection of households and their power limits and their application (Liander, 2019)

Connection	Household limit(kW)	Appliance limit (kW)*	Availability	Application
1x25 A	5.75	3.68	No longer applied	
1x35 A	8.05	7.36	No longer applied	
1x40 A	9.2	7.36	Only for small houses	Standard household appliances
3x25 A	17.25	11	Standard house connection for new connections	+ solar panels and EV
3x35 A	24	11	Large connection	+solar panels, EV, heat pump

*Considering security plugs of 16 A, which is the standard for the Netherlands (IEC TR 60083, 2015).

The limit values significantly vary on the household connection. Exceeding the concerned limit value, could have consequences, such as melting of cables or transformers. The connections can always be upgraded for the old and small households if there would be PV or appliances added. From the actual available connections, only one who presents a possible risks is 1x40 A connection, for only 4 household out of 243 according to our data analysis. We would like to draw your attention that this connection is applied only for small houses and that for the standard house connection, there is no data who exceed the limits. Moreover, when the households are aggregated, the average peak per household in the 15 minutes when the community imported electricity peaks, is only around 1kW for pilots without heat pumps and 4 kW for pilots with heat pumps. This shows that it is rare that all imported electricity peaks occur simultaneously. Overall R4I presented similar behavior to Liander Zonnedal dataset, but extreme points appeared. However, the households with heat pumps, the community imported electricity peaks raise to 4kW. Heat pump electricity demand has a higher degree of simultaneity than other electricity demand, as it is strongly correlated with outside temperate. PMC had the highest peak import values, which correspond to the use of the high consuming heat pumps and larger household size.

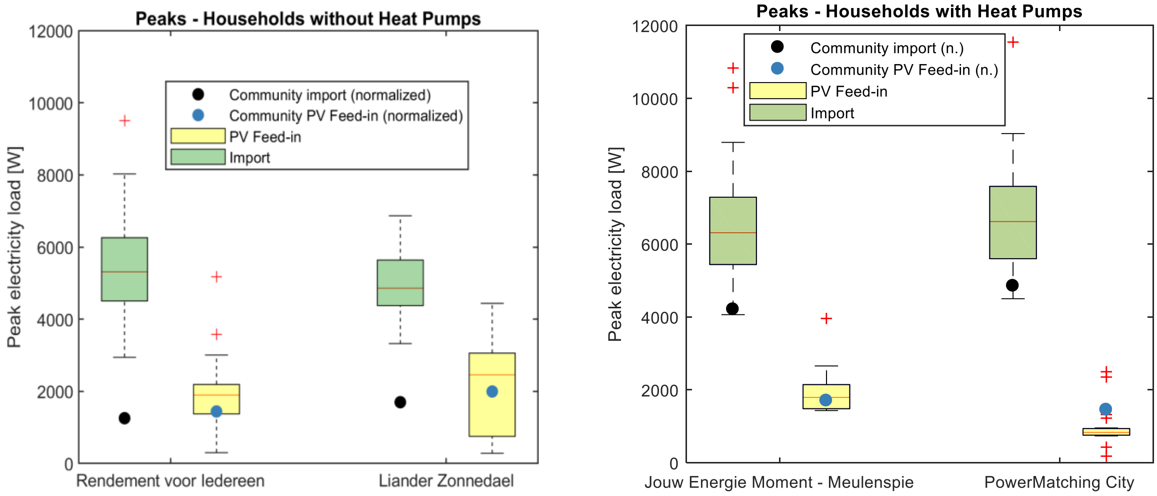


Figure 4.5 Boxplots of the peak value of imported electricity and PV power fed in the grid for 2013 (2012 for PMC pilot) for individual households.

** On each box, the red line indicates the median, and the bottom and top edges of the box indicate the 25th and 75th percentiles, respectively. The whiskers extend to the most extreme data points not considering the outliers, and the outliers are plotted individually in red. he black dots represent the normalized import peak for the whole community and the blue dot, the normalized PV feed-in peak.*

An increased delivery of electricity to the grid, because of a surplus of renewable energy that is generated on-site, can also have similar consequences for power grid failures. With respect to the solar PV fed in to the grid, R4I showed the largest values. The second largest delivery of renewable power in the grid was realized by JEM-Meulenspie. PMC had a virtual PV system for 18 households, with power delivered controlled and distributed by an energy algorithm, which made the distribution narrower, and the physical PV rooftop installations as the outliers. That's probably why the community aggregated normalized point is more than the average at that particular moment. In Liander Zonnedael there are really few households with solar power and are considered outliers. For the households without heat pumps, even the highest outliers are safe in the sense that they do not pose a danger of outages given their relatively low values. 3 households with heat pumps has peak over 10 kW, but they would be most like to have a large connection which allows their safe operation even in the extreme scenarios.

4.2.3 Self-consumption and self-sufficiency ratio

With the limited data that we had we could only calculate these indicators for R4I and PMC for 2012, which is shown in Figure 4.6 for all households.

Again we observe a large distribution of the households, but with a median SCR of around 40% for R4I pilot and 70 % for PMC, the general pictures shows relatively high SCRs. This can be explained by the relatively low PV system sizes in these pilot; with fewer PV electricity generated, larger parts of the generated electricity can be directly consumed.

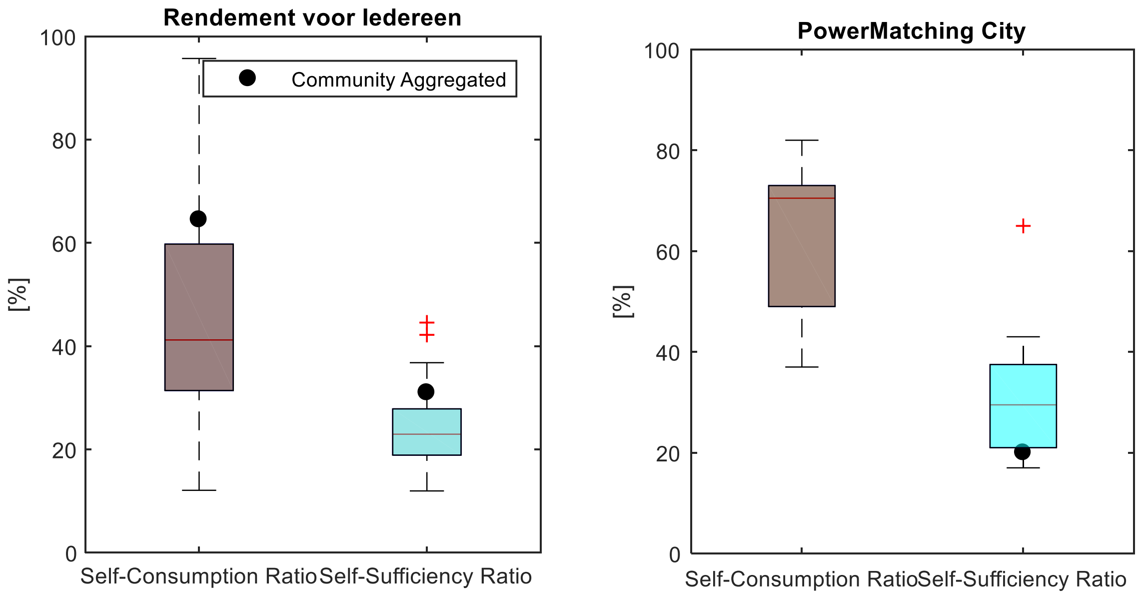


Figure 4.6. Boxplots of annual Self-Consumption Ratios and Self-Suffic*iency Ratios of all household for two smart grid pilots. **

*On each box, the red line indicates the median, and the bottom and top edges of the box indicate the 25th and 75th percentiles, respectively. The whiskers extend to the most extreme data points not considering the outliers, and the outliers are plotted individually in red.

4.3 Demand side management

Demand Side Management (DSM) refers to tools and techniques that encourage end-users to optimize their energy use. The most common DSM techniques are classified as:

- **Energy Conservation and Efficiency Programs:** The main objective is to save energy. This is mainly achieved by technologies such as, thermal isolation of houses, efficient lightning, and solar hot water systems. These technologies help to reduce demand, to lower high peak prices, and reduce greenhouse gas emissions due to less stress on gas or coal power plants.
- **Demand/Load Response Programs:** The main objective is to shift and reschedule energy consumption process. It refers to the switching off or rescheduling of loads by the end-users in response to the request of the grid operators. This can lead to save the system from exceeding the peak rating and avoiding a system failure.

The use of these techniques can lead to an optimized energy use, bringing benefits to both end-users and grid operators; End-users can reduce their electricity bills by adjusting the timing and amount of electricity/gas used, and grid operators can benefit from shifting of energy consumption from peak to non-peak hours, to avoid congestion issues.

DSM techniques implemented in smart grid pilots in The Netherlands mainly focus on Demand/Load Response Programs. In this section, the use of three technologies implemented for such purpose are discussed. Namely:

- **Smart Appliances:** These are appliances that are connected to the home energy management system and can respond to signals of the grid operator to shift or reduce their consumption. Commonly used smart appliances are, washing machines, dryers, dishwashers, and hot water buffer.

- **Photovoltaic Systems:** As PV systems can also be controlled in a sense of varying their output of active and reactive power, they can be incorporated as a distributed renewable energy resource with an effect on demand side management.

- **Battery Energy Storage Systems (BESS):** They can be considered as flexible or storable load. Depending on the operational strategy of the storage system can fulfil various DR services. Because the energy is not consumed but stored, flexibility of storage systems is very high with respect to their operational limits (e.g. maximum charging/discharging power, capacity).

4.3.1 Flexibility with smart washing machine and dishwasher

From the point of view of power consumption, white goods like washing machines and dishwashers have to be considered, since their potential for automated distributed resource is substantial, especially on a short timescale during the water heating cycle. The availability of white goods and appliances for the demand side management depends largely on the use case. As long as automated schemes are used, the availability is very high, since white goods are used in almost every household or larger living community, i.e. shared facilities. However, the flexibility can only be used when the white goods are actually ran by users, i.e. when they are switched on. This poses some challenges in taking advantage of the flexibility of these sources.

Driven by requirements on proper operation of the washing program and optimal use of detergents manufacturers do not allow interruptions. Only the whole washing program can be shifted (Cheng et al., 2014). Figure 4.7 gives an example of the typical power consumption of a washing process. We can assume 2 to 2.5 kW during 30 minutes is the major demand side management power potential. From an energy perspective, studies showed that potential exists particular in combination with interaction or changes in consumer behavior, by shifting the start of the operation (e.g. washing machine or dishwasher) in times of low energy prices or avoiding curtailment of PV ("Washing with the sun").

In Jouw Energie Moment 1.0, a clear change of user behavior appeared from the beginning until the end of the project. The main conclusion was that end-users used more efficiently energy since they had more insight in their energy use. Households started to use less energy in the evening peak hours and more during the hours that the sun was shining. 66% of all the smart appliances were used in "self-consumption" mode [4]. But the smarter use of their appliances was manually done by real people, and not automatically set by the HEMS. This resulted in JEM 2.0 version to not implement automated smart appliances.

At Power Matching City, on average per household, 408 hours of dishwasher activity and 297 hours of washing machine activity were recorded during the year of 2012. Table 4.3 presents the annual energy consumption per appliance and how much less it is compared to Dutch and European average.

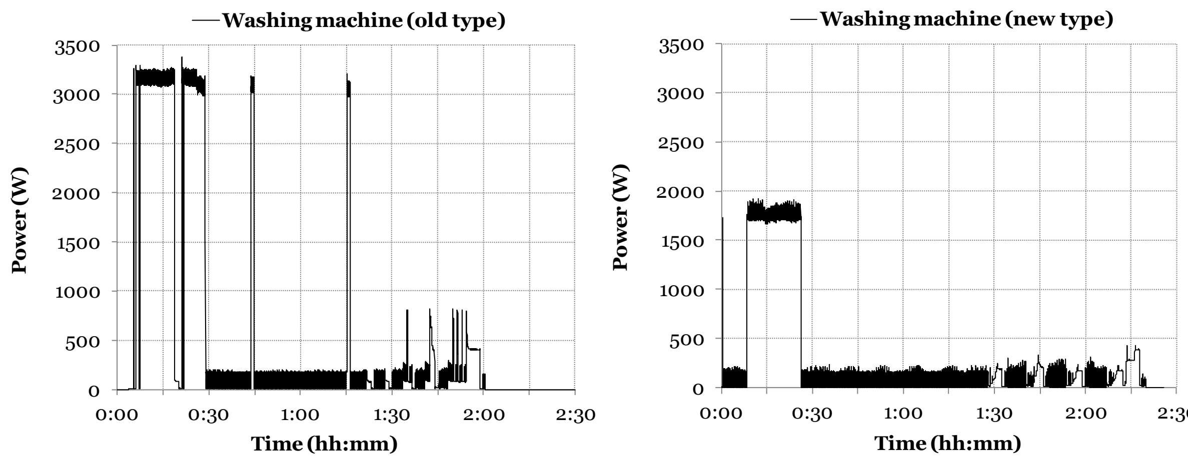


Figure 4.7 Two types of a washing machine, one of an old type and one of newer technology, where the energy efficiency improvements and consumption behavior changes are visible *(Lampropoulos, 2014)*

Table 4.3 Smart appliance electrical consumption at Power Matching City in 2012, compared to Dutch and European average consumption.

	Power Matching City	Comparing to	
Smart Appliance Type	**Annual Energy Consumption**	**Dutch Average**	**EU-15 Average**
Dishwasher	215.7 kWh	N.A.	-8%
Washing Machine	130.8 kWh	-10%	-25%

The total consumption of the dishwasher for 2012 was 215.7 kWh per household. This value was 8% less than the European average value (Stamminger et al., 2008). For the washing machine, an average of 130.8 kWh were used per household. This was 10% lower than the average Dutch laundry electricity consumption and 25% less than the European value (Pakula and Stamminger, 2010), which shows the efficient use of the smart washing machine comparing to the classical machines. In total, these smart appliances brought 346.5 kWh of load flexibility to the grid per household, which corresponds to 10.5% of an average Dutch household electricity consumption over 2012, and 6.8% of the average household electricity consumption in PMC.

Figure 4.8 shows the algorithm which was used by the PowerMatching City's EMS to relate the use of time of the smart appliances with a price scheme. The peak hours were considered between 17-23 h on weekdays.

Based on the algorithm four different modes of operations where available: "Low price", this was at off peak hours and when no solar was available; "Self-consumption", when there was solar PV input available, "Balancing", times of high rate tariff but not peak hours; and "Comfort", times of high rate tariff and peak hours. The distribution of the use of the smart appliances per mode of operation is shown in the pie-graph in Figure 4.9.

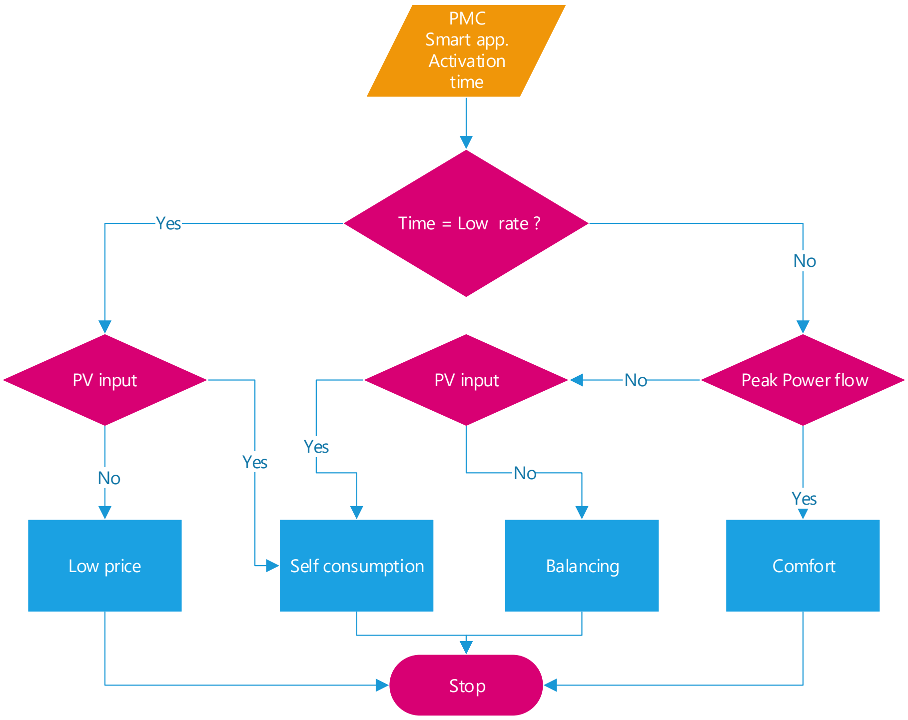


Figure 4.8. Algorithm used by Power Matching City's Energy Management system to determine the mode of operation.

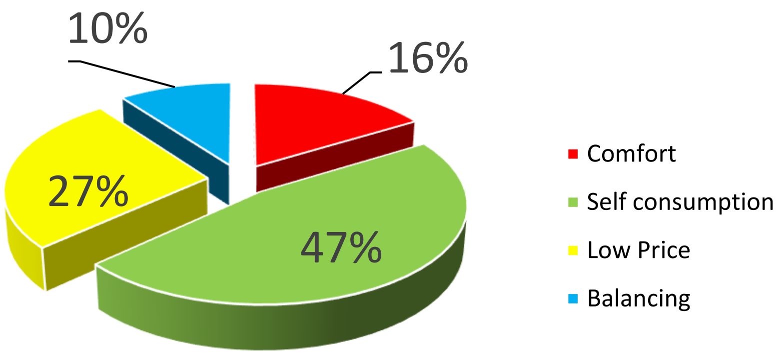


Figure 4.9 Distribution of smart appliances energy use according to the four modes of operation.

As a result of the end-users having insight in their energy behavior, the appliances where used most of the time (47%) when solar power was available. Only 16% of the time, the appliances where use din peak hours. By using more favorable tariff schemes, this 16% usage can become a flexibility asset to the gird operators.

In Jouw Energie Moment 1.0 there was a clear change in the behavior from the beginning until the end of the project. The main conclusion was that the end-users used more efficiently energy since they had more insight in their energy use. Households started to use less energy in the evening peak hours and more during the hours that the sun was shining, to use renewable energy. 66% of all the smart appliances were used in “self-consumption” mode (Enexis, 2016). This resulted in a higher value than in Power Matching City. But the smarter use of their appliances was manually done, and not automatically set by the EMS. This resulted in JEM 2.0 version to not implement automated smart appliances.

4.3.2 Photovoltaic Systems

As Photovoltaic Systems (PV) can also be controlled in a sense of varying their output of active and reactive power, they can be incorporated as a distributed renewable energy resource on the demand side.

Control capabilities include:

- the possibility to reduce the active power output;
- the possibility to increase active power output to the maximum available from the primary energy source (solar irradiation) if the system has been curtailed before;
- the variation of the output of reactive power (e.g., ancillary services like reactive power provisioning or voltage control). Typically grid codes give the range of operation, where the operation point may or may not impact the active power output.

In combination with a home EMS, generated power could be charged into battery, used for shiftable load (e.g. heating) or in-feed into the system, and thus change the total net power used from the electricity network. Within the CESEPS project this was analysed, by combining optimal sizing of batteries for households self-consumption with peak shaving at district level. This was done with the data provided from the pilot Rendement voor Iedereen, for 79 households in 295 evenly distributed days, with a resolution of 10 s. By performing simulation of batteries and Net Present Value (NPV) analysis, the average optimal storage size for self-consumption was determined to be 3.4 kWh (in case of abolishment of net metering). Figure 4.10 shows a histogram of the optimal storage size of all investigated households.

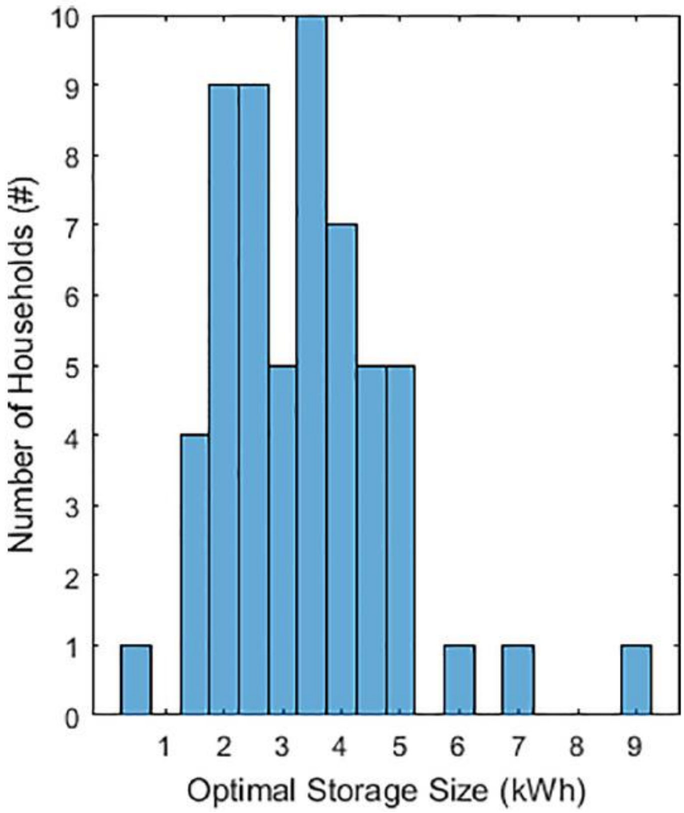


Figure 4.10 Histogram of frequency of optimal storage size *(Schram et al., 2018c)*.

A positive NPV was found for 58 out of the 79 households. Depending on the PV system size, total net metered consumption and specific characteristics of the load profiles, differences in the range of 0.5-9 kWh optimal storage size were obtained, with an average of 3.36 kWh (SD=1.49) and mode and median both of 3.5 kWh. The NPV values ranged from 72.0 € to 1.74 k€, with an average of 697€ (SD=296). The peak shaving potential could be amplified to a decrease of 22 % or 51 % when the batteries are controlled by using heuristics or by assuming perfect foresight together with power minimization algorithms, respectively.

4.3.3 Battery Energy Storage System

Battery Energy Storage Systems (BESS) can be considered as a flexible or storable load. Depending on the operational strategy of the storage system can fulfil various DR services. Because the energy is not consumed but stored, flexibility of storage systems is very high with respect to their operational limits (e.g. maximum charging/discharging power, capacity).

Typical home energy storage systems operate 'locally' to store on-site or self-generated electricity from PV or other sources, either at the household level or community level. A typical strategy is to store surplus generation and use it later to supply the local demand, to increase the self-coverage or direct-use of the PV system. One can distinguish between consumer owned storage and district or community storage (CES). CES is emerging as an attractive solution to increase the utilisation of RES in households. Within CESEPS a stochastic smart charging framework for CES in residential microgrids has been developed. Figure 4.11 shows a scheme of the microgrid considered in this framework.

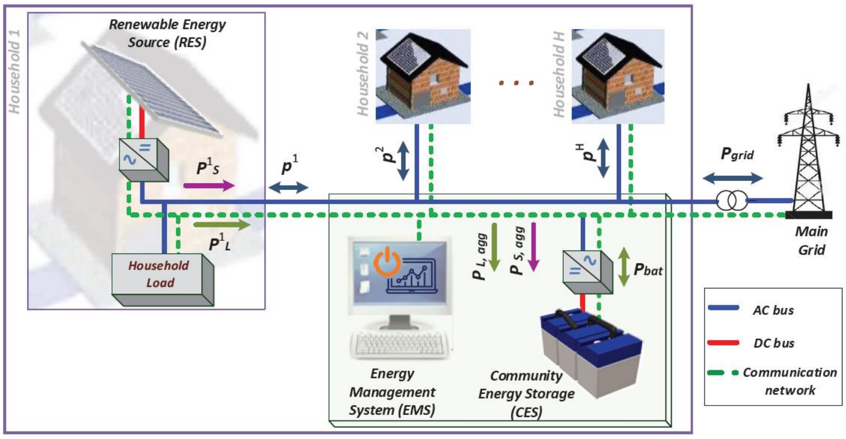


Figure 4.11 Scheme of the microgrid with community energy storage considered *(Al Skaif et al., 2018)*.

The framework used linear optimization for scheduling the charging process to times when electricity prices were low, as to minimize costs, while accommodating the aggregated surplus renewable energy of households. As well, it made use of Markov chain-based forecasting approach (AlSkaif et al., 2017) for generating synthetic aggregated surplus PV power and residual load profiles day-ahead, using real load and PV history profiles form 10 households of the R4I smart grid pilot. Results showed that based on a time-varying electricity tariff and depending on the annual period, the CES with smart charging can bring a cost saving up to 68% in comparison with the traditional scenario without CES.

Typically, BESS are well available for providing flexibility. However, it must be considered for which purpose the batteries have been installed at the first place. If the BESS have been installed in order to increase self-consumption, the availability for other flexibility purposes like control reserves is limited to some extent. Intelligent algorithms can harvest the flexibility left besides the main use case of self-consumption. Aggregators have already taken advantage of it in several European countries like Germany or Switzerland. Furthermore, different requirements arise when trying to use BESS for self-consumption and network services, such as resolving congestions. In such cases, the availability of BESS appears to be almost not existent unless an emergency option is implemented so that the network operator can take advantage of the BESS at all times.

From all the analysed smart grid pilots in The Netherlands, three of them have implemented batteries. A SmartStorage unit pilot close to a transformer station has been setup by Enexis to gain experience in using district storage to support DSO activities (Kling et al., 2015). In Hoogdalem, Stedin has rolled out a test with 24 homes that had combined PV system and home battery, and 8 homes that only had a battery. Conclusion was that the installed capacity of the batteries was too small to have actual impact on the maximum load on the grid. It did though increase the self-consumption of solar power in a range of 20-50 %. Version 2.0 of Jouw Energie Moment implemented 35 Tesla Powerwalls as battery storage system, in combination with heat pumps, solar PV panels, and an innovative energy-computer, that managed the heat pump and battery given certain criteria. The prosumers were able to choose, based on electricity prices, when to set their load-shifting appliances. Business case for such concept is still unclear. Technically it was possible to realize, but challenges lied in bringing all stakeholders together and having them agree on ways to operate the batteries.

4.4 Solar powered electric bikes

In recent years, e-bikes have been becoming a very popular transportation means in The Netherlands, especially among the elderly and commuters. More specifically, the share of e-bikes in bike sales has rapidly grown from 12% in 2009 to over 28% in 2015 (RAI Vereniging, 2019). At the moment, there are around 2 million e-bikes in The Netherlands, compared to around 23 million regular bikes (Beslist.nl; DutchWordPress; Harms and Kansen, 2018), (RAI Vereniging, 2019). The introduction of the e-bike could be effective in the sense to reduce usage of cars and if charged with renewable electricity then they have great potential to reduce CO_2 and particulate emissions in transportation. With the term ‘solar powered e-bikes’ we refer to two types of e-bikes: electric bikes with integrated PV solar cells on their wheels or other parts of the e-bikes’ skeleton, which can charge their batteries when parked and during trips, and solar charged e-bikes that are connected to solar-powered charging stations to charge their batteries when parked. Therefore in the CESEPS project, two energy products related to solar powered e-bikes were developed and tested at the university campus (Zhang et al., 2019). As well, a survey was conducted with employees of two Dutch university, aiming to investigate the target group and users’ notion about tis sustainable transportation mode (Apostolou et al., 2018b).

4.4.1 Product Development

One of the products developed was a solar e-bike charging station located in the bicycle parking lot of a building at the University of Twente campus (shown in Figure 4.12 a).

(a) (b)

Figure 4.12. Pictures of (a) solar charging station at UT campus and (b) home solar e-bike charging kit.

It enables students and employees (publicly available for every citizen) to charge their bikes with solar energy for free. It consist of six solar panels, a PV inverter that converts DC current into AC current and feeds it into the public grid, and 12 solar e-bikes, which also have PV solar panels in the front wheels. The charging stations is connected to the building's low-voltage grid, so the charging may be effectuated from the grid when there is no solar input. In this way, users are assured to get their battery charged at all times. Figure 4.12 b shows the home solar charging kits that were developed. It is composed of a solar panel, a battery, MPPPT charge controller, a display, and a sine wave inverter. These home charging kits were installed in user homes in order to enable them to charge their e-bikes with 100% renewable energies, as the system is isolated from the grid.

4.4.2 Power quality[7]

To analyse the impact of a charging station of E-bike in the campus, while there is sun and the PV input is delivering to the grid. Together with TU GRAZ and UT, electrical measurements were conducted and a set of provocative tests at UT campus, where weather and the number of e-bikes charged varied. The tests were meant to reveal the total harmonic distortions(THD) that charging station could inject to the gird which will cause two main affects (Zhang et al., 2019):

- Copper loss and stray loss of the local transformer, heating up, reducing its lifetime
- Malfunction or refusal of relay equipment.

In order to understand the controller behavior, a model was constituted and the system was analyzed analytically in time domain as well as in frequency domain by simulation, . The model results are conform with the experimental results (Zhang et al., 2019). Figure 4.13 shows the experimental results and

[7] The section is based on the published article : Zhang, Z., Gercek, C., Reinders, A., and Fickert, L. (2019). Resonance Instability of Photovoltaic E bike Charging Station: Control Parameters Analysis, Modelling and Experiment. Applied Sciences.

a resonance component of grid admittance with about 10 dB amplitude rising from 1650 Hz to 1730 Hz. It passed through 1730 Hz from below at around 1000 seconds, therefore the effects are not expected to have major impact on the e-bikes. The simulations results confirmed the found resonance frequency. The influencing factors we obtained by provocative tests and electrical measurements shows: the bandwidth of the phased locked loop (PLL) and the bandwidth of the current controller are the main factors affecting the stability of the inverter, and these factors can be optimized by changing the control parameters of the controller. For example, the bandwidth of the PLL and the current controller can be reduced to expand the inverter stability range. We would like to emphasize that these instability phenomena is rare, and provoked by plugging in e-bikes simultaneously, which is unlikely to happen in everyday life. Else the charging station passed all the other tests and performed as expected, successfully charging the e-bikes and delivering surplus electricity to the buildings at UT.

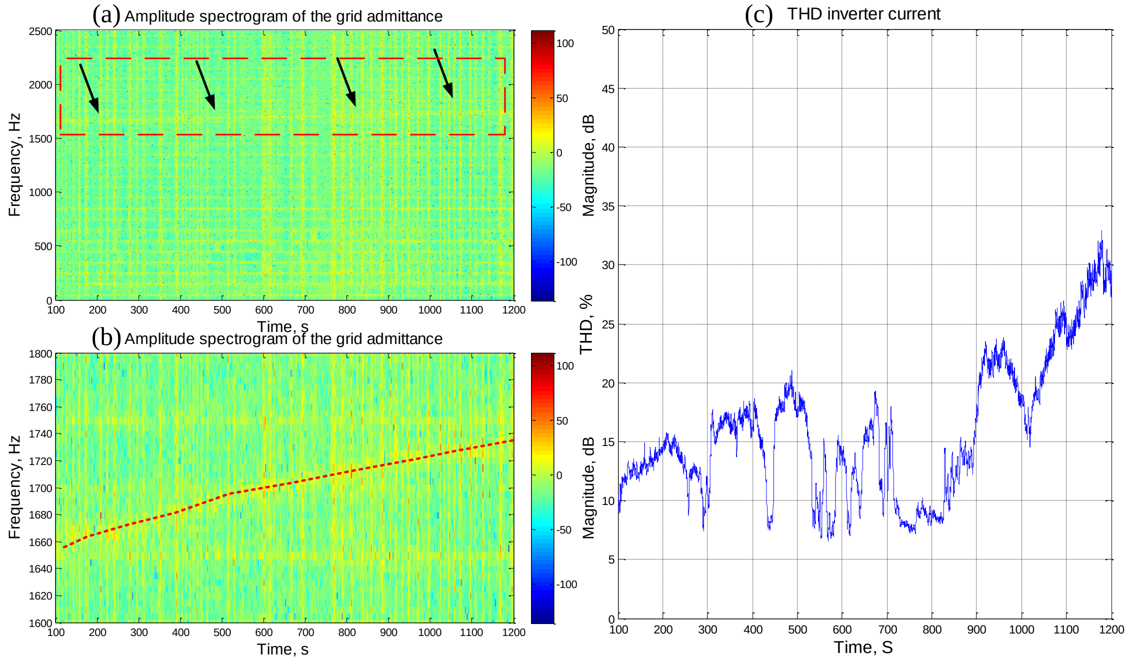


Figure 4.13 Measurement data for Photovoltaic Charging Station: (a) grid admittance amplitude spectrogram; (b) partial enlargement of (a); (c) THD of inverter output current (Zhang et al., 2019).

4.4.3 Users' experience[8]

The purpose of the solar e-bike field experiment was to investigate the solar e-bike's target group and users' notions about this new sustainable transportation mode, by observing and analyzing users' behavior when using the solar e-bike for their daily trips. A survey was conducted in The Netherlands with 79 participants using the solar powered e-bikes; 37 of them were working at the University of Twente and 42 at Eindhoven University of Technology (Apostolou et al., 2018c; van den Berg, P. E. W., Vinken, S., Geurs, K., Arentze, 2017). All participants filled out pre- and post-test surveys, before and after they used the solar e-bike. The solar e-bike that was used in this study was a Sparta M7S LTD with a 400 Wh battery, containing a small photovoltaic (PV) panel in the front wheel consisting of 6 modules of 18 CIGS cells each (36 V and 11–12 W per module-per bike; 6 × 11 = 66 Wp or 6 × 12 = 72 Wp) (Apostolou et al., 2018a).

Since the tested user sample was limited with regard to the amount of participants and their background, results were not representative for a broader group of people; however, they present interesting user experiences, offering a good starting point for further research on subjects related to user interaction with solar e-bikes, and the problems, frustrations and difficulties that users faced with them, as well as users' positive comments for this new transportation mode and ways to improve them. The general experience of solar e-bikes was quite positive. Table 4.2 presents a summary of the results from the survey.

[8] The section is based on our published article : Apostolou, G., Reinders, A., and Geurs, K. (2018). An overview of existing experiences with solar-powered e-bikes. Energies 11.

Table 4.4 Solar e-bike commuters survey results and OViN (e-bike commuters) data comparison among Dutch users.

Variable	Survey Data (n=79)
Age (years)	44 ± 11
Gender (1= male, 2= female)	1.4 ± 0.5
Commuting distance (km)	10 ± 10
Average gross income (€/month)	2750 ± 1

The commuting distance of the participants was between 1 and 56 km, with a mean of 10 km (see Figure 4.14).

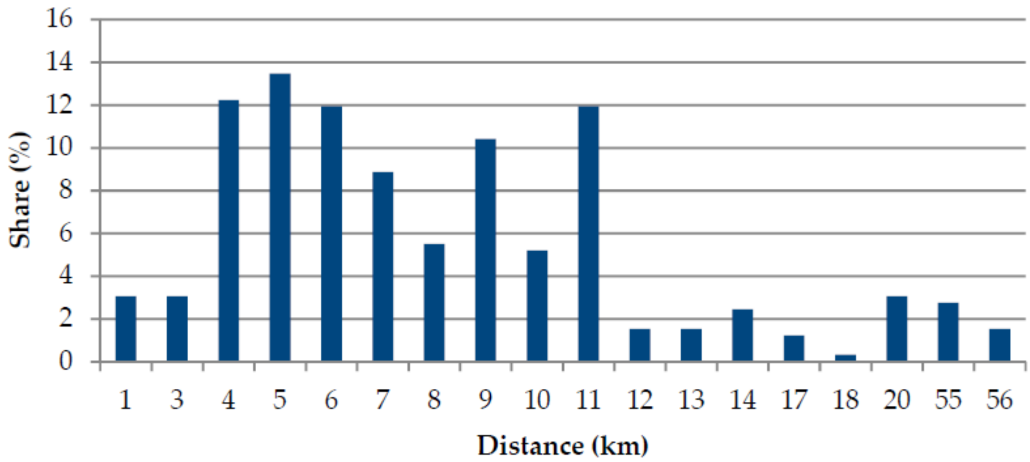


Figure 4.14 Commuting distances (in km) with the solar e-bike, (n= 327 trips). Results presented in this histogram are based on the survey conducted at UT and TU/e.

The age of the participants ranged between 20 and 72 years old, with a mean of 44. The proportion of males and females was 61% and 39%, respectively. The percentages of male and female users were not related to the gender percentages of the students and/or the staff of the technical universities, but were completely random. The users were selected voluntarily based on their own willingness and availability to participate in this survey. Data showed that the main target group of solar e-bikes are commuters in the age group between 40 and 60 years old, commuting distances longer than 6 km, with a gross income higher than €2500 (Table 4.4). Solar-powered e-bikes, either at the wheel or via a charging station, are concluded to have potential as a sustainable way of transportation in urban areas and cities, potentially replacing the conventional means of transport. Survey results showed as well that crosswind hindrance was one of the biggest issues that solar e-bike users faced during the tests. The PV panel on the front wheel made the solar e-bike highly unstable, and riders had difficulty cycling against the wind. PV cells on the e-bikes' wheels during cloudy weather might give around 1 to 10 W, depending on the time that the e-bike is parked under diffuse irradiance. Unfortunately, less than 10 W over 8 h is not such a significant contribution, and it might only be efficient for a partial charge of the e-bike's batteries. Therefore, solar charging stations seem to be a better option compared to solar e-bikes with integrated solar cells in their wheels.

4.5 Hydrogen powered mobility in the built environment

4.5.1 Introduction

Hydrogen (H_2) is a high-quality energy carrier that can provide the flexibility needed by the power sector. The use of hydrogen as fuel in transportation has been considered the main disruptive field of application in the hydrogen economy, but it has also great potential to provide energy to all sectors, including residential and industrial areas. For example, it can be used to store renewable energy at utility scale, in stationary fuel cell systems for buildings, back-up power, or distributed generation or even blending it into existing natural gas pipelines to increase the output of renewable energy systems for example by avoiding curtailment of renewable energy and using surplus energy to produce hydrogen. By employing fuel cell technologies, hydrogen can be used with high efficiency and zero or near-zero emissions at the point of use (Gupta, 2009). They combine hydrogen and oxygen from the air to produce DC power, water and heat (EG&G Services Parsons, 2000). With this in mind, it can be stated that hydrogen technologies have the potential to link different energy systems, such as power and heat supply, energy storage and transportation.

Within the CESEPS project was implemented at the demonstration site of The Green Village[9], the living campus of the TU Delft. The “Car as Power Plant” (CaPP) experiment. It was focused on using hydrogen fuel cell cars for electricity besides providing the typical use of mobility (van Wijk and Verhoef, 2014). Cars are being used only 5 % of the time for transportation. So, when parked, the fuel cell in the car can be used to produce electricity from hydrogen in a cleaner and more efficient way than the current electricity system – with useful ‘waste’ products, like heat and water. The produced electricity can be fed into the grid or be used directly in houses or offices.

The pilot project at The Green Village in TU Delft consisted of connecting a Hyundai ix35 FCEV to the Dutch grid to deliver up to 10 kW DC power. Experiments were carried out to evaluate the operation of such vehicle-to-grid connection, as well as the dynamic response to evaluate what possible frequency reserve services such connection could provide to the grid. Further, the “mini-CaPP” project was launched in 2017, where a hydrogen scooter was tested to provide power to appliances, in vehicle-to-load (V2L) mode and to the grid in V2G. The methods used to analyse the performance of these vehicles delivering power and the results obtained are presented below.

4.5.2 Fuel Cell Electric Vehicle-to-Grid (FCEV2G)[10]

The experimental set-up consisted of three main components:

- By the manufacturer, a modified commercially available Hyundai ix35 FCEV [14, 32] with a special V2G DC (Direct Current) outlet plug;
- a Vehicle-to-Grid DC-AC discharge unit (V2G-DCAC) which converts DC power in the range of 300–400V received from the FCEV into three-phase AC power at 380V. The power discharge setting can be manually defined in the V2G-DCAC. DC switching safety and grounding was incorporated in the V2G-DCAC unit;
- a three-phase 380 V AC grid connection including fuses and kWh meter.

All three components can be seen in Figure 4.15, at the demonstration and test location at The Green Village. The two orange circles indicate where these components can be found. On the right is the

[9] The Green Village is the living campus of the TU Delft, where new and innovative ideas are testes to create a sustainable, lively and entrepreneurial environment where to discover, learn and show how to solve society’s urgent challenges (2018).

[10] The section is based on our published articles : Oldenbroek V, Hamoen V, Alva S, Robledo C., Verhoef LA, van Wijk AJM. Fuel Cell Electric Vehicle-to-Grid: Experimental Feasibility and Operational Performance as Balancing Power Plant. Fuel Cells 2018 and Robledo CB, Oldenbroek V, Abbruzzese F, van Wijk AJM. Integrating a hydrogen fuel cell electric vehicle with vehicle-to-grid technology, photovoltaic power and a residential building. Appl Energy 2018;215:615–29.

vehicle and on the left, in the enclosed unit, is located the discharge unit and the connection to the AC grid.

The Green Village is the living campus of the TU Delft, where new and innovative ideas are testes to create a sustainable, lively and entrepreneurial environment to discover, learn and show how to solve society's urgent challenges (2018).

Figure 4.15. Experimental Fuel Cell electric Vehicle-to-Grid (FCEV2G) set-up at The Green Village, Delft University of Technology in the Netherlands.

Figure 4.15Figure 4.16 illustrates the simplified electrical architecture of the V2G-DCAC and its main components.

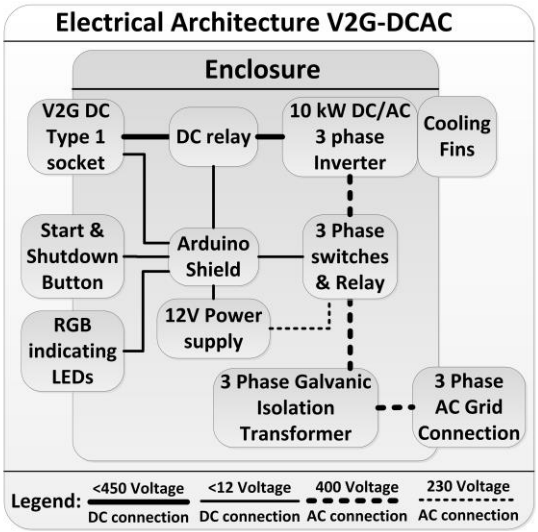


Figure 4.16 Scheme of the electrical architecture of the V2G-DCAC discharge unit, allowing the delivery of electricity from the FCEV to the AC grid (Oldenbroek et al., 2018).

To evaluate the performance of the FCEV2G set-up, field tests measurements were conducted at four different power outputs; 1, 3, 5 and 10 kW DC constant values. Each test was repeated five times for statistical purposes. During the tests, different variables were measured, such as average fuel cell DC power produced, average AC power delivered to the grid, hydrogen mass consumed, and duration of tests. The system performance was analysed based on the experimental hydrogen consumption rate ($H_{2_{rate}}$) and tank-to-grid (TTG) efficiency (η_{TTG}). The $H_{2_{rate}}$ was obtained for each test according to:

$$H_{2_{rate}}\left[{}^{kg}/_{h}\right] = \frac{m_{H_2}}{\Delta t_{test}} \quad (4.4)$$

where m_{H2} was obtained by measuring the difference in mass in the hydrogen tanks before and after the test and Δt_{test} was the duration of the test in hours. TTG efficiency expresses the conversion of H_2 chemical energy into AC electric energy delivered to the grid. It accounts for all the losses associated with the entire power generation and delivery system. TTG efficiency ($\eta_{\ TTG\ (H_2 \rightarrow AC\ grid)}$) was calculated according to:

$$\eta_{\ TTG\ (H_2 \rightarrow AC\ grid)}[\%_{HHV}] = \frac{\bar{P}_{AC}}{\frac{m_{H_2}}{\Delta t_{test}} \cdot \frac{HHV_{H_2}}{M_{H_2}}} \times 100\% \tag{4.5}$$

where m_{H2} is the hydrogen mass expressed in grams consumed in the test, Δt_{test} is the test duration in seconds, HHV_{H_2} is the higher heating value of hydrogen equivalent to 285.84 kJ/mol, and M_{H_2} is the molar mass of molecular hydrogen of 2.016 g/mol. Figure 4.17 shows the results obtained for TTG and hydrogen consumption rate for these carried out tests.

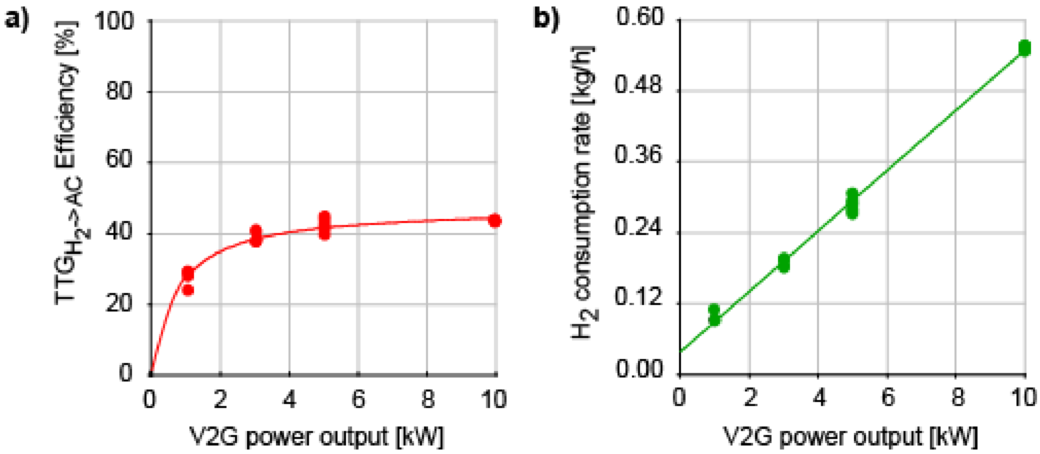


Figure 4.17. a) TTG efficiency in converting hydrogen to AC electricity based on HHV of the FCEV2G set-up and b) hydrogen consumption rate in V2G mode at different power outputs.

Overall, the system performance below 3 kW becomes significantly less efficient than at higher power outputs, as there are too many losses associated with the balance of plant and DC/AC conversion in comparison to the electricity being produced at higher power outputs. Above 3 kW, the efficiency of the system practically remains unvaried. A measured Tank-To-AC-Grid efficiency of 44% was obtained when the car was operating in vehicle-to-grid (V2G) mode at 10 DC (9.5 AC) power output (Oldenbroek et al., 2017b; Robledo et al., 2018b). It is important to determine the rate at which hydrogen is consumed in the V2G experiments, since there is a fixed amount of approximately 5 kg of hydrogen available for V2G operation in the Hyundai ix35 FCEV. Figure 4.17 b shows that the hydrogen consumption rate increased linearly with the power output, and follows the relationship shown in:

$$H_{2_{rate}}[kg/h] = 0.04 + 0.05 \times P_{V2G} \tag{4.6}$$

Based on the average hydrogen consumption rate obtained at the different power outputs, it can be concluded that 5 kg of hydrogen can deliver approximately 52 straight hours of V2G at 1 kW power output and 9 hours at 10 kW power output.

Besides, the dynamic response of the FCEV connected to the grid delivering different power outputs, below 10 kW DC, was also measured (Robledo et al., 2019b). The experiments showed that both power sources of the fuel cell electric vehicle, which are the fuel cell stack and the battery, are suitable to offer fast frequency reserves. For the vehicle tested, the ramp up reaction times were in the range of 0.13 - 0.20 s and for ramping down 0.17 - 0.23 s. The potential economic value that aggregated FCEVs could generate by providing frequency reserves with their fuel cells onboard, was also analyzed via modelling of a car park offering frequency reserves. The results from the model show that when the fuel cell stack is used as power source in V2G, the most financial interesting option is to offer only aFRR (asymmetric Frequency Restoration Reserves) upwards. Providing this service can yield monetary benefits if the car park has a high and constant occupation.

4.5.3 Mini-CaPP: The Hydrogen Fuel Cell Scooter with plug-out features for power generation

Adding to the car as a power plant experiment, the use of a hydrogen fuel cell electric scooter (FCES) in combined driving, V2G and vehicle to line (V2L) mode was analysed. The scooter used for this study was a FCES model 4.8 from APFCT, as shown in Figure 4.18.

Figure 4.18 Hydrogen fuel cell electric scooter model 4.8 from Asian Pacific Fuel Cell Technology company.

The scooter's power system is essentially composed of a Proton Exchange Membrane (PEM) fuel cell stack (FC), an air blower, a water pump, a Lithium Nickel Manganese Cobalt Oxide (Li-NMC) battery, a DC-DC converter and hydrogen storage canisters (HSC). The fuel cell is the main power supplier, while the battery accounts for peaking power demand. The fuel cell stack and the battery are placed in parallel, which means all combinations are possible to power the loads: only FC, only battery or both FC and battery. The battery is only charged via the FC, there is no plug for external electric charging.

The use of the scooter in three different modes (drive, V2G and V2L) was tested by simulating three patterns in a Kikusui PLZ4-1000W DC electronic programmable load. The load was connected to the DC bus of the scooter and when the load was turned on, the scooter began to supply the demanded power. The scooter was submitted to 30 repetitions per mode, making 90 in total. In order to collect data under scooter operation, sensors were installed to measure the current and voltage of fuel cell, battery and the output delivered to the load, hydrogen content in the storage system and temperature of the fuel cell, while the runs were performed. With this data the system efficiency was calculated.

The total system efficiency (η_{system}) was calculated using Eq. 4.7:

$$\eta_{system} = \frac{E_{out} - \Delta E_{battery}}{E_{H_2}} \tag{4.7}$$

where E_{out} is the electrical energy deliver to the load (either in drive, V2G or V2L mode), $\Delta E_{battery}$ is the difference in battery energy and $E_{H_2}$is the hydrogen energy consumption. $\Delta E_{battery}$ was calculated as the difference of energy discharged by the battery ($E_{battery,dis}$) and energy supplied from the fuel cell to charge it ($E_{battery,ch}$) during a full run, as shown in Eq. 4.8.

$$\Delta E_{battery} = E_{battery,dis} - E_{battery,ch} \tag{4.8}$$

The hydrogen energy consumption, E_{H_2}, was calculated as shown in Eq. 4.9,

$$E_{H_2} = \Delta m_{H_2} \times HHV \tag{4.9}$$

where $\Delta m_{H_2}$is the difference of hydrogen mass at the start and end of the run, multiplied by the higher heating value of hydrogen. Thus the efficiency values informed in this study are based on HHV of hydrogen.

Using Eq. 4.7 yields the efficiencies depicted in Table 4.3. The overall system efficiency values shown here are average values obtained per mode.

Table 4.5 Average values for energy delivered, amount of hydrogen consumed and system total efficiency per mode.

	V2L	Drive	V2G
H_2 consumption (g)	16.8	13.8	7.6
Efficiency (%)	29	32	39

As is shown in Table 3, V2G resulted in the most efficient mode, followed by driving and V2L was the least efficient mode. Operating the system at almost maximum power, like in V2G, is thus beneficial for using hydrogen efficiently: there is a relatively high amount of energy delivered by the scooter system in comparison with drive and V2L mode, relative to the amount of hydrogen energy fed in.

4.6 Conclusions

This chapter presented the experiences obtained with several technologies employed in smart grid pilots in The Netherlands, with special focus on solar power generation, smart appliances, heat pumps and home energy storage systems. The assessment was realized by comparing three smart grid pilots in 2013, of which data was available to the project's consortia. From the analysis, It can be concluded that It is practically impossible to compare pilots next to each other, since synchronization is hardly possible with different types of homes, number of inhabitants and different energy system configurations. Much of the data was available for small amount of households, leading to low statistics, therefore it is difficult to draw generic conclusions. Nonetheless, it is clear that households with heat pumps will face an increased electricity consumption compared to the Dutch average. This is quite relevant for the Netherlands, as all newly built buildings are not allowed to be connected to the gas network anymore due to Climate Agreement (klimaatakkord). Most of them are looking for heat pumps as a solution for heating, but in that case network operators will face increase costs for reinforcing the grid. As well, quite low self-sufficiency ratios have been obtained in the pilots, since their solar PV installations where quite small. This is expected that self-sufficiency will increase with the current trend of installing larger solar installations on roof tops. In these cases, special interest arises in home or community energy storage, by batteries or hydrogen, to be able to cope with the seasonal differences (high solar power production in summer, while the consumption is higher in winter).

In order to quantify to which extent flexibility could be provided by smart energy technologies, a detailed assessment was carried out. Smart appliances, such as dishwashers and washing machines are found out suitable for end-users in combination with direct use of solar generated energy, providing more sustainable cleaning practice: “washing with the sun” . Those smart products increased the self-consumption ratio, in that sense, could decrease potential peak load. As the PV generation capacity was modest, the curtailment was not needed, therefore we could not study the impacts of smart appliances on real curtailment situation, however it would potentially play a major role to avoid curtailment losses. Regarding the end users financial benefits, there was little interest in providing flexibility to the grid, by washing at times of low electricity prices, since resulting in modest income/earnings. An even higher potential of flexibility lies in solar PV combined with home/community battery storage. Although more pilots and studies have to be carried out to find a proper business case, as the storage technologies involved are at the moment expensive and an accurate life cycle assessment and recycling plans should be envisioned.

Lastly, two new technologies were employed and tested at universities campuses. One of them is the solar charging station for electric bikes, demonstrated at UT. The other is a commercial hydrogen fuel cell electric vehicle, with ability to operate in vehicle-to-grid mode, demonstrated at The Green Village at TU Delft. Both of them were implemented successfully, resulted in many scientific papers. Further actions should be taken to commercialize these developments when they would become economically feasible.

In order to incorporate increasing renewable energies, electrification of vehicles, and satisfying heating demand the current energy system needs to be modernized. At the local level, home intelligence and smart grids can provide the integration of distributed renewable energy production and help stabilize the power grid. From experiences learned in smart grid pilots in The Netherlands, smart grid technologies are well established and can provide flexibility to both end-user and grid operator. These technologies fall basically within three main categories::

- **Advanced Metering Infrastructure:** It includes smart meters and energy management systems (EMS), which are essential to know how much energy was consumed and produced per households and/or appliance, either in the form of electricity, gas or heat.
- **Demand Response:** These include technologies such as smart appliances, energy storage systems, electric vehicles and in-home displays, which can respond to signals of the user and/or the grid operator to shift or reduce consumption.
- **Distributed Generation:** It includes micro generation systems, such as photovoltaic solar panels and micro-combined heat and power systems. Electric vehicles, either powered by batteries or fuel cells, operating in vehicle-to-grid also belong to this category.

Lessons learned from this project showed that the implementation of these smart grid technologies is completely feasible and that there aren't many technical barriers; They are already used in smart grid pilots, they operate good under different weather conditions and their efficiency in reducing consumption and/or increasing renewable energy integration is proven. New technologies are emerging that will improve smart grid operation and flexibility that they can offer to the energy system at even larger penetrations of renewable energy. For these technologies to be successful they will have to address the four dimensions of integration, as described below:

1) **Energy System Integration:** Smart grid technologies will have to focus on the interconnectivity of different energy networks, optimized integration of local renewables, day-to-day and seasonal energy storage, and integration of prosumers. Namely, we investigated, µ-CHP combined with PV in PMC and how it resulted in well balanced seasonal imported electricity (Gercek C. 2019). Further research and investments in smart grids should be focused on incorporating other green energy sources such as wind energy and biomass, as to diversify the local energy matrix. The choice of green energy matrix to be used in smart grids should be made based on the resources located in the near area, as to optimize the costs of its utilization. Coupled to this, a comprehensive exploration of modern energy storage systems is needed, either electrical, chemical or underground heat storage, and is related to the next dimension.

2) **Multi Energy Carrier Dimension:** This type of system based on multi-directional flows between (green) power, gases and heat, has the potential to offer greater flexibility, than a single carrier energy system. These carriers will be either heat, electrons, in the form of electricity, or molecules, such as hydrogen, methane, ammonia, etc. Heat Pumps offered a reasonable amount of flexibility with less amount of gas consumption compared to Dutch average (Gercek C. 2019). The two analyzed pilots; namely PMC and JEM used conventional gas when the temperature was below 5 °C, instead of biogas as latter was expensive, but the aim was and always should be going towards the usage of green energy resources. The integration of all these energy carriers will allow the energy needs of smart grids to be supplied 100 % by renewable energies, weather it is day, night, summer or winter. Storage can be used to increase the use of renewable on-site generation but to also perform demand response activities and provide flexibility to the grid operators.

3) **Cross Sectoral Dimension:** At the smart grid level, the power sector can be coupled to the heat and transport sector. Electrification is one way to obtain sector coupling. Renewable energy can be implemented in heat pumps to produce heat, to charge electric vehicles, or to produce hydrogen by electrolysis to fuel FCEVs and stationary fuel cells (Robledo et al. 2018). Use of renewable gases, such as green hydrogen is also a way to connect transport, heat and power sectors. Technologies such as hybrid heat pumps with boilers or fuel cells have the potential to couple both heat and electricity by combining different energy carriers, and thus will play a fundamental role in future smart grids, as shown on the analysis of hybrid heat pumps in PMC and conventional heat pumps in JEM- Meulenspie. As well, they eliminate the problem of high peak

electricity demand of heat pumps already mentioned. V2G technology, either with BEVs or FCEVs will also play a great role in the cross sectoral integration of smart grids.

4) **Digitalization Dimension:** Modernization of smart grids will include undoubtedly new digital technologies, such as cloud applications, block chain technology, smart phone applications(ex. in next chapter), data mining for predictive and data analytics, among others. These digital technologies will become central in smart grids in order to improve grid reliability, control operating costs and obtain personalized user experiences.

5 INNOVATIVE DESIGN OF SMART ENERGY PRODUCTS AND SERVICES

5.1 SEPS Design[11]

5.1.1 Introduction

Smart energy products and services (SEPS) could play an important role regarding the enchantment of active participation of end users in balancing energy demand and supply in the electricity network" (Reinders et al., 2016); as such they could be applied to create an environment where energy use is flexible, efficient, reliable, sustainable and cost-effective. Examples of SEPS include among others, smart meters, home energy management systems (HEMS) and solar-powered electric vehicles. The widespread implementation of these technologies in smart grid projects could enable a greater interaction between end-users, home appliances and energy suppliers, facilitating energy efficiency, local production and energy trading with the grid in order to improve the effectiveness of demand response strategies and reduce the required capacity for local energy storage (Obinna, 2017a).

The diagram in figure 5.1 shows the three layer model and conceptual SEPS design diagram of Stephan Übermasser and Angele Reinders, for the SEPS selection criteria. In this work, HEMS were specially chosen as they were suitable for to analyze the cycle of design and the diagram of selection criteria.

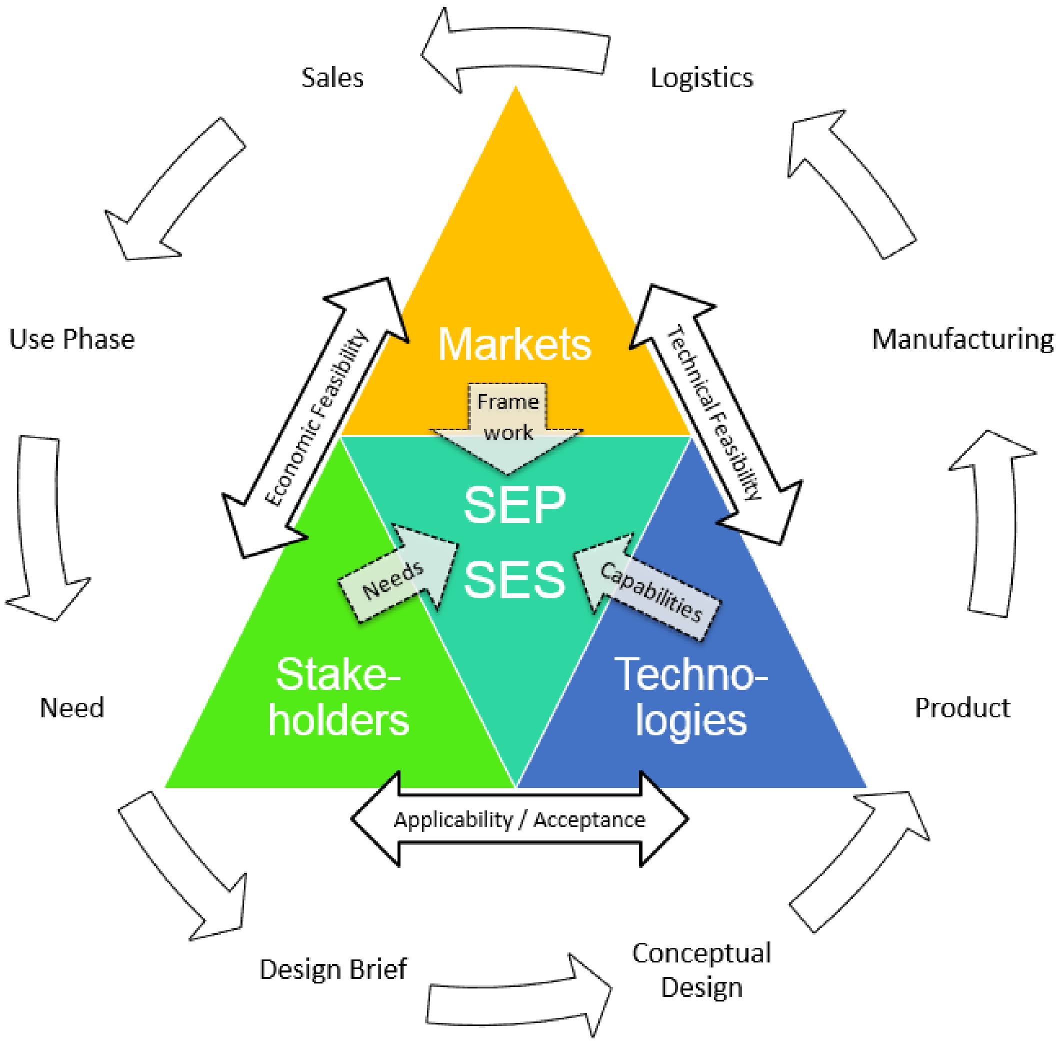


Figure 5.1. Three-layer model and conceptual SEPS Design diagram

[11] A significant part of this chapter has been written by Alonzo Sierra, Cihan Gercek and Angèle Reinders

This section explores how a design-driven approach to SEPS development may create a new perspective towards facilitating energy-efficient behavior from end-users. The section is structured as follows. In 5.1.2 the main barriers for SEPS design found in the literature will be explored, after which several design methodologies applied in academic SEPS projects will be evaluated in 5.1.3. This analysis will focus on the stages of the design process in which each method can be applied as well as on its perceived usefulness in the design process. In Section 5.1.4 three selected designs of SEPS will be prototyped and evaluated by user studies, monitored and simulated. The next sections will report about the functional prototyping, that will follow by end user and lab tests.

5.1.2 Key Barriers for Smart Energy Product Design

The main challenges for achieving a widespread use of smart energy products and services can be grouped categorized as :

- Diffusion process of new SEPS
- User-SEPS interaction
- Trust and privacy related issues

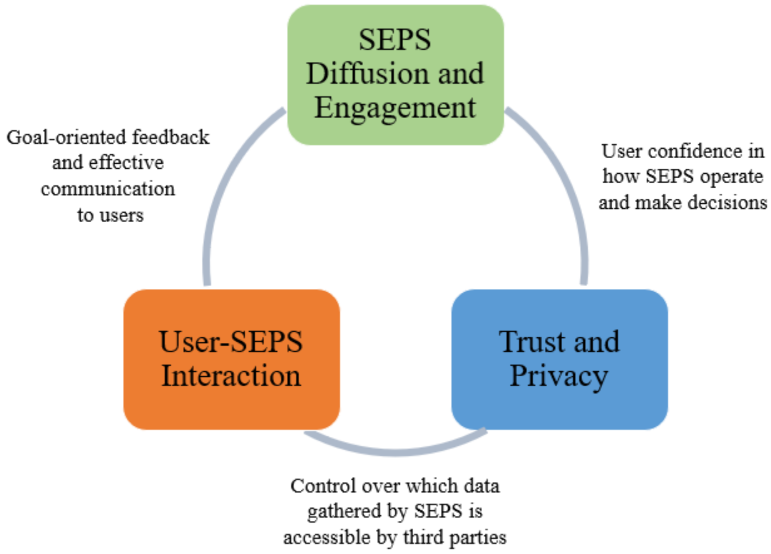


Figure 5.2. Current challenges for SEPS design and the relationships between them

5.1.2.1 Diffusion Process of New SEPS

The diffusion of smart products and services into the market is driven by two consumer behavior processes: the adoption of a new concept by users and their subsequent engagement with the concept through time. SEPS adoption stems from users realising the benefits of using energy more efficiently at home, the urgency of producing and using renewables or the increased comfort of having smart appliances (Geelen, 2014), after which they select a product or service that can capitalise on these benefits. User engagement takes place afterwards, and for this process to be successful, users must gradually become accustomed with the SEPS by starting with small and easy actions which gradually lead towards a desired behavior (Honebein et al., 2011).

While adoption and engagement are typically seen as processes taking place at an individual level, it is important to consider the social dimension of domestic energy consumption: people in a household interact with home appliances (and with each other) in many different ways, and no single member holds complete control over energy consumption(both magnitude and time) (Hargreaves et al., 2010a).

In addition to these two processes, can support the diffusion of SEPS in various ways, by the use of incentives which may either focus on rewarding certain actions (pull measures) or on penalising them (push measures) (Steg et al., 2018). Smart grid research has typically focused on economic incentives (Paterakis et al., 2017) (Palensky and Dietrich, 2011), but despite their importance, several authors point out the limitations of assuming end-users behave like a “homo economicus” which micro-manages resources in order to maximise an economic benefit (Christensen et al., 2016) (Verbong et al., 2013b). In

fact, savings from making a household energy efficient are usually not in line with user expectations and work best as an initial "eye-catcher" after which their appeal slowly fades away and other incentives start to become more important (Christensen et al., 2016), such as increased comfort (Gangale et al., 2013), increasing home security (Ford et al., 2017), increasing property value, forming part of a collective initiative and becoming independent of utility companies (Hansen and Hauge, 2017).
The consequences of using incentives to induce a specific response from users are often hard to predict, and the adoption of SEPS may sometimes result in unintended and counterproductive side effects. One of the these is the "rebound effect", where a household's energy consumption increases after smart energy technologies are installed (Geelen, 2014). This effect seems to take place when users feel that saving energy or producing renewable electricity justifies its use to make a household more comfortable (e.g. using the heating more frequently or leaving the lights on), and is further reinforced by unrealistically high expectations on financial savings (Christensen et al., 2016).
In addition to these user perceptions, the way in which a smart grid project is structured may unintentionally cause an undesired reaction from its users. Users from a smart grid pilot in Denmark, for instance, were found to increase their energy consumption because produced electricity was free to use only within the hour it was produced (Hansen and Hauge, 2017). This was perceived as giving energy for free to the utility company which made users try to consume as much self-produced energy as possible.

5.1.2.2 User-SEPS Interaction

The interaction between users and SEPS takes place in two directions (Christensen et al., 2016) (Geelen et al., 2013b) as shown in Figure 1 below.

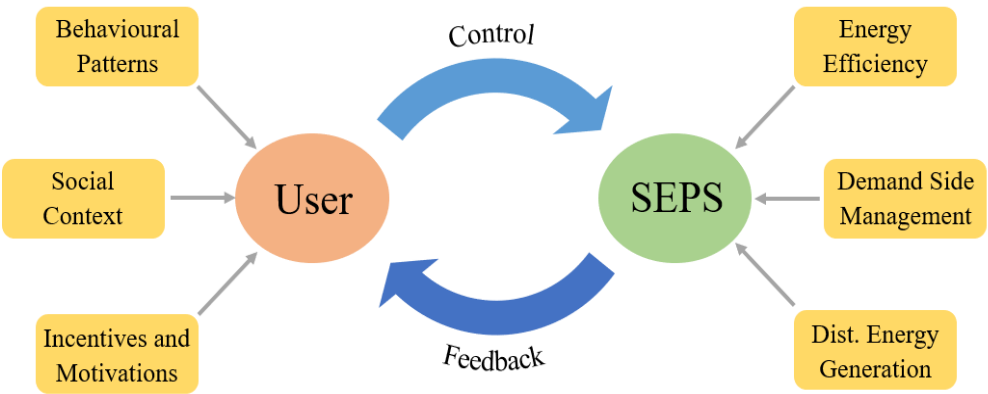


Figure 5.3The two directions of User-SEPS interaction

User to SEPS interaction typically refers to how the user controls the SEPS, but some authors suggest that more important than control itself is the user's perception of control over the product (Verbong et al., 2013b) (2013). While it might seem convenient to make appliances as 'smart' as possible so that the variability of user behavior is reduced, evidence suggests that end-users dislike devices which take the power of decision-making away from them. In the PowerMatching City project, which sought to optimise the match between supply and demand for an entire community, participants complained that the system operated autonomously and it was not always clear why some appliances were turned on or off at specific times. Furthermore, they expressed their desire for more influence and insight in the functioning of the system to "feel a part of it" (Obinna, 2017a). There are also cases in which automated operation has been positively viewed by users; participants in the SmartWash project appreciated their washer's capacity to autonomously run washing cycles during the day when they were not home and electricity prices were cheaper (Geelen et al., 2013b).
Both of these cases highlight the importance of giving users the choice on the level of control they personally would like to have. If too little control is offered users may feel powerless, whereas too much control makes the products too complicated to operate adequately. A possible solution is to develop systems that make decisions for the users, but still have the option to override this process and let users decide manually; Verbong et al. compared this to the 'sport' and 'comfort' settings in a car (Verbong et al., 2013b).
Interaction between SEPs and users refers to how users gain insights into their energy use and how these insights are interpreted. Effective communication with users may involve several channels such

as intuitive technology design and direct communication through messaging (Abrahamse et al., 2018), and can be presented in real-time or historically.

Real-time feedback has been found to be more effective since it is more visible and direct to users while also encouraging active experimentation by allowing them to clearly see the effects of appliance use in household energy consumption (Ehrhardt-Martinez et al., 2010). In general, data should be presented in a visual way rather than using numbers or text to facilitate its understanding by users. If visual feedback is not feasible, it might be useful to make comparisons to things people know or relate to such as converting an amount of energy in kWh to an equivalent number of lightbulbs or washing machine cycles. There is significant interest in this from users, with a survey by Obinna reporting visual feedback as the most desired feature for smart thermostats (Obinna, 2017a).

SEPS feedback may encourage goal-oriented collaboration between the product and the user through tutoring and assisting functions which convince users to pursue specific goals or achievements. Goals might be in the form of meeting a daily or weekly consumption target or scoring ‘green’ appliance usage (Geelen et al., 2013b). Comparing and/or ranking a user’s consumption within a reference group might also be an effective motivator (Obinna, 2017a), but special care should be taken in defining groups that are perceived by users as accurately representing them; location, age group or socioeconomic status are some of the criteria that could be considered for this purpose.

5.1.2.3 Trust and Privacy related issues

The acceptance of new SEPS greatly depends on the level of trust end-users have of the actors responsible for their development (Wolsink, 2012). It is crucial for these actors to avoid a technocratic, top-down approach where users are seen as barriers to making energy systems ‘smarter’, instead focusing on informing users about the benefits of using SEPS in a clear, transparent way so realistic expectations are made (Christensen et al., 2016).

In addition to trust between stakeholders, there has to be user trust in the SEPS themselves. Transparent and easy to understand communication is important to achieve this since users need to know what motivates a SEPS’s decision-making process. If too much information is given users will feel overwhelmed, while too little information generates a black box effect which might turn users away from any further learning.

Finally, SEPS are highly dependent on the collection and interpretation of data, and this data should be properly safeguarded or end-users will not be comfortable using these technologies in their homes. Users need to be assured that their data is managed safely and responsibly, with secure authentication and data encryption protocols being a basic requirement (Christensen et al., 2016). It is also important to clearly state what kind of information is being gathered and stored by SEPS; freedom over how much data users are willing to share with external parties may give them a higher sense of security.

5.1.3 Impact of Innovation Methods on Smart Energy Products and Services Design

To explore the impact of innovation methods, the co-design process and to capture different innovative ideas, master students of Industrial Design Engineering at the University of Twente were tasked with the following design assignment in a 10-week course called Souces of Innovation: “Design an innovative smart energy product-service for end-users of smart homes in residential smart grids” (“Sources of Innovation,” 2017). The SEPS concepts which were developed in this course offer the possibility of evaluating the impact of the tools and techniques used to create new smart products.

5.1.3.1 SEPS Design Categories and Representative Examples

A total of twenty SEPS concept resulting from this activity have been analyzed in this study. These concepts include solar/hydrogen powered mobility, smart appliances, home energy management systems (HEMS) and building-integrated photovoltaics (BIPV), among others. An example of a design from each category is presented below to illustrate some of the general features of each SEPS category (Figure 3 to 6):

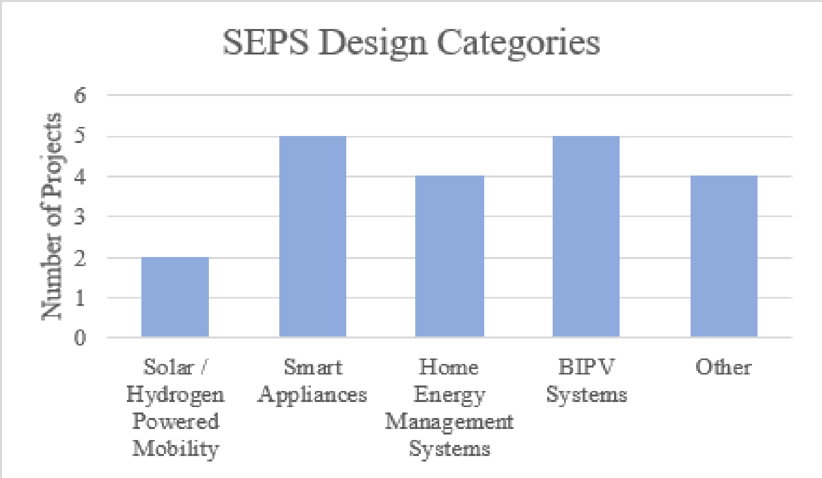


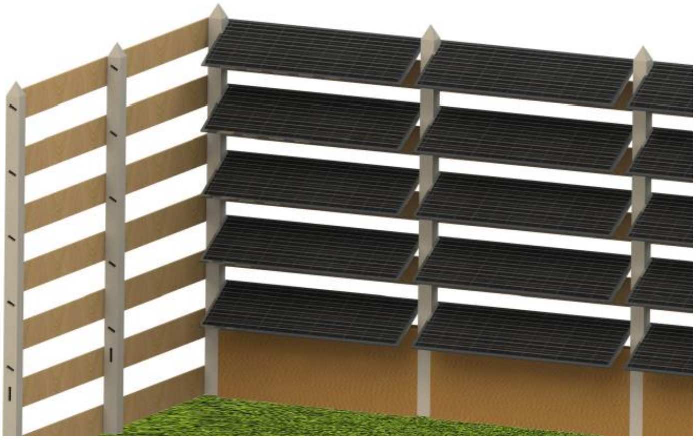
Figure 5.4 Current challenges for SEPS design and the relationships between them

Fig 5.4(a). shows an example of Solar/Hydrogen Powered Mobility: The ‘Batto Station’ is a recharging station where electricity from a PV system can be either stored in a Ni-Fe battery or used to produce hydrogen through electrolysis; the station can therefore charge both electric vehicles (EVs) and fuel cell vehicles (FCVs). Fig 5.4(b) shows Smart Appliances case: the smart kitchen designed by Colijn and Sevat consists of four kitchen appliances (dishwasher, refrigerator, stove and oven) fitted with intuitive user interfaces; these interfaces enable users to programme times of use and set operation variables such as a refrigerator’s temperature or a specific dishwashing cycle.
Fig 5.5(a). shows an exemplar project on Home Energy Management Systems. ‘CrystalLight’ is a smart home ornament which helps households use energy more sustainably by informing them through different light intensity levels how their energy use compares to that of their community; a dedicated mobile application can also provide users with further insights into their consumption patterns.
Fig 5.5(b). shows an application of BIPV Systems. The ‘Solar Fence’ consists of a series of photovoltaic (PV) panels arranged to resemble a wooden fence; the spacing between panels is intended to maximise renewable production while maintaining privacy for household members. The BIPV system is further fitted with a battery pack to store surplus energy which can be used at night.
And finally Fig 5.6. we illustrate what could be in the category ‘’other’’. SEPS designs which do not fit any of the previous categories include waste management systems, house weatherproofing techniques and local energy storage solutions. An example of the latter is the small-scale compressed air energy storage (CAES) system proposed by Fletterman and van der Sluis, which stores compressed air when there is surplus energy and decompresses it when household demand increases.

(a) (b)

Figure 5.5 Example of Solar/Hydrogen Powered Mobility and Smart Appliances respectively (a) Batto Station design prototype by Stoverink and Mellema, University of Twente, 2017 [24] (b) Smart kitchen design render by Colijn and Sevat, University of Twente, 2017 [24]

(a)



(b)

Figure 5.6 Example of Solar/Hydrogen Powered Mobility and Smart Appliances respectively (a) Batto Station design prototype by Stoverink and Mellema, University of Twente, 2017 [24] (b) Smart kitchen design render by Colijn and Sevat, University of Twente, 2017 [24]

Figure 5.7 CAES system design sketch by Fletterman and van der Sluis, Universitt of Twente, 2017 [24]

5.1.4 Innovation Method Analysis

All projects relied on using innovation methods from product design literature as a supporting tool in the development of new SEPS, and each of these methods was analysed to determine their perceived usefulness as stated by the students who applied them, as well as the type of bottlenecks they were most effective in solving. Table I shows the results of this analysis, including a brief description of each innovation method and some observations on their advantages and limitations for SEPS design. Please refer to (2013) for a more detailed description of these innovation methods.

Table 5.1Design Innovation Methods and their Application on SEPS Design

Innovation Method	Description	Observations
Innovation Journey (IJ) (Van de Ven et al., 2000)	This method conceives innovation processes as uncertain open-ended processes where certain patterns and key components can be identified to help designers "navigate along" the process.	The method is used to evaluate the product's evolution through time up to the present. Only a few projects ventured into clearly predicting next steps in product development
Delft Innovation Model (DIM) (Buijs, 2012)	This method visualises product innovation as a circular process consisting of five phases (product use, strategy formulation, design brief formulation, development and market introduction),	This method can be used to search areas for new SEPS concepts or features through SWOT analysis and mind maps. It is hard to apply this method in its entire scale since 3 of the 5 phases exceed the scope of conceptual design projects

	each with a set of required actions to create new ideas and concepts.	
TRIZ (Altshuller et al., 1996)	TRIZ is a Russian method which is used to study technological development as a sequence of transformations, each transformation resulting from solving a contradiction which hinders the product's adaptation to new market conditions.	Effective in inducing divergent thinking to produce breakthroughs in product design Offers many different tools (inventive principles, root conflict analysis, etc.) for identifying design contradictions, each tool suited to a different set of circumstances.
Platform-Driven Product Development (PDPD) (Halman et al., 2003)	PDPD focuses on defining a product platform for a given technology which balances the commonality potential and differentiation needs within a product family.	Used to visualise a range of similar products tailored to different targets while maintaining common elements Helpful in breaking a SEPS into its main modules or components which were shuffled around to create different members of a product family
Constructive Technology Assessment (CTA) (Kuhlmann et al., 1999)	This method maps the potential actors or stakeholders involved in the development of a particular technology and assesses how they might impact the design of resulting products and services.	Simulation of a stakeholder analysis taking place after the product's market release Main focus on predicting product acceptance by potential interest groups
Technology Roadmapping (TRM) (Wilyard and McClees, 1987)	TRM aims to forecast the evolution of a group of products and technologies, analysing the continuously developing interrelations between markets, technology, and business.	Predictions for future SEPS development, with the results shown in a much more visual way than IJ Typical timescale of 3-5 years Used to identify technologies or products which could become potential competitors
Innovative Design and Styling (IDS) (Eggink, 2009)	IDS focuses on how the design of a product may communicate its functionality or other ideas which users find attractive, and how styling should find the right balance between typical and novel product features.	Improving SEPS appearance and aesthetics to convey a clear message to users and make the product more distinctive. Limited impact for redesigning the appearance of already existing SEPS
Lead User Studies (LUS) (Franke et al., 2006)	This innovation method analyses the product and service needs of 'lead users': consumers facing needs that are months or years ahead of the bulk of the market.	Limited applicability since most of the designed SEPS do not have any users yet or if they do they are hard to contact within the frame of a student project. Better suited for company-scale analysis into products recently released or close to their launch date
Risk Diagnosing Methodology (RDM) (Halman and Keizer, 1994)	Relies on interviews, risk questionnaires and team meetings to identify and classify potential risks in the product development process.	Useful for identifying and addressing potential market risks before a SEPS design is launched into the market Focused on the latter stages of product development; better suited for an organisation with a dedicated product design team

Students were only allowed to use four of these methods in their project, so how often a method was selected for creating or improving a SEPS design may serve as an indicator of its perceived effectiveness. Figure 7 shows the frequency of use for each method in the analysed projects.

TRIZ and PDPD were the most used methods, having been applied to all twenty projects. The tools provided by TRIZ - particularly the inventive principles of segmentation, local quality and prior action - were often credited with key advances in the development of a SEPS concept, such as adding new functions or improving the user interaction mechanism. PDPD was successful in motivating the creation of several related concepts which focused on a different market segment or rearranged the main components of the original design in an innovative way.

The LUS and CTA methods, on the other hand, were applied the least, being present in only four and eight projects respectively. The reason for this might be the focus these methods place on the later stages of the product design process which is beyond the scope of this kind of academic projects and better suited for SEPS closer to their market release.

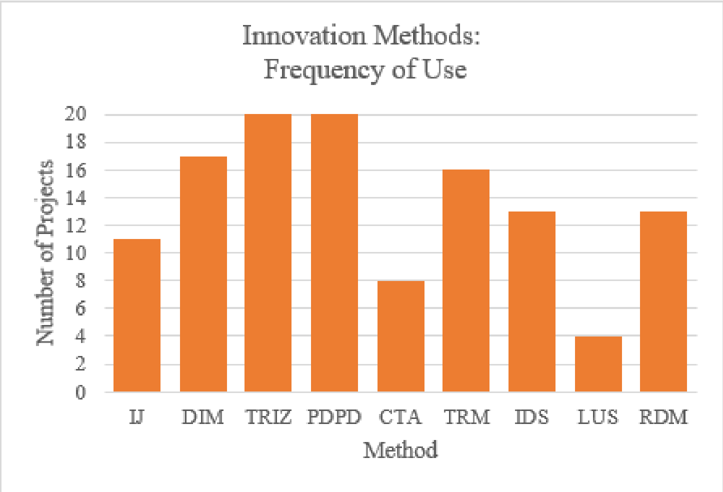


Figure 5.8 Number of mentions for each analysed innovation method

5.1.4.1 SEPS Ranking

In order to create a SEPS ranking, five *selection factors* were proposed to determine which designs are best suited for further development, including taking part in user tests in a real-life environment. These selection factors, which encompass technical, financial and design aspects, are described in further detail in Table 5.2 below. Each of these selection factors was graded from 1 to 10, and all factors were considered to have the same importance so no weighting was applied. Table 5.3 below shows the eight SEPS designs which received the highest score.

Table 5.2 Proposed factors for the pre-selection of SEPS concepts

Factor	Description
Technical Feasibility	Are the concept's underlying technologies at a high technology readiness level (TRL)? Is it possible to make the prototype functional in a real-life home environment?
Financial Feasibility	Can the prototype be built on time and within a reasonable budget?
User Interaction Potential	What level of interaction with the user can be achieved? Is there any feedback mechanism that influences a behavioural change from the user?
Suitability	Can the concept be implemented in a wide range of households? How well does it fit to the product/service categories defined by CESEPS?
Innovation	How original or innovative is the concept? How similar is it to existing SEPS?

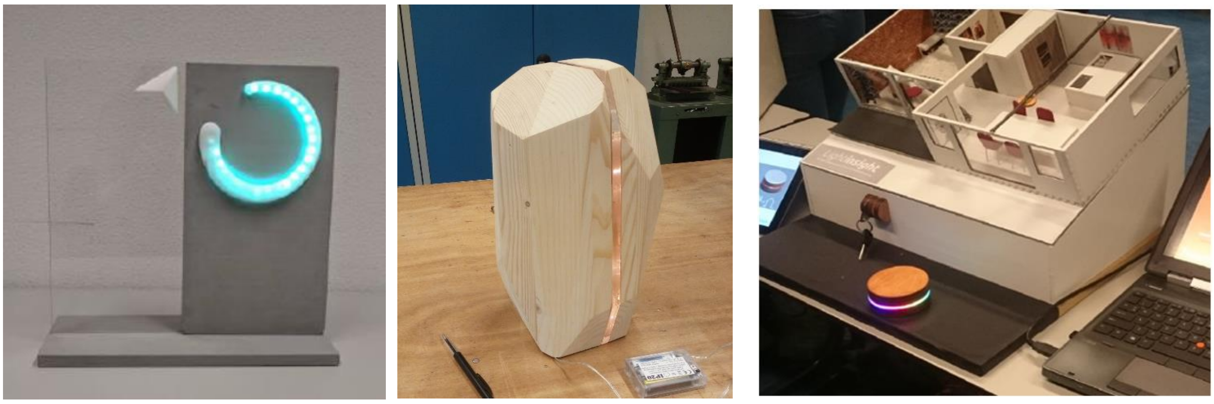
Table 5.3 Pre-selection of SEPS designs

SEPS Concept	Short Description	Product Category	Total Score
LightInsight	A dial which indicates through the use of different colours whether a household is buying or selling power from the grid, or if it is self-sufficient.	Home Energy Management Systems	41
CrystalLight	An ornament which gives insight on household energy consumption by making its light brighter or dimmer.	Home Energy Management Systems	40
Smart Plug	A power socket which shows the expected short-term power prices through a built-in LED interface together with a planning app.	Smart Appliances	39
Bodhi	An arrow-shaped 'smart window chip' with LEDs alternating between two colours to notify users if thermostat settings need to be adjusted to reduce energy consumption.	Home Energy Management Systems	38
HEMS Control	A wall-mounted HEMS control connected to a set of smart lights, with the possibility of connecting to other appliances and a PV system.	Home Energy Management Systems	37
Smart Switch	A modified power socket which collects power consumption data and sends it to a dedicated database for analysis before displaying results in a user app.	Smart Appliances	36
Smart Solar Car	A car with integrated PV with an energy management system which controls the car's batteries and the charging station to optimise vehicle charging.	Solar Powered Mobility	35
CAES System	A residential-scale compressed air energy storage system which is intended to be coupled with a PV array to reduce household dependence on the grid.	Other (Energy Storage)	34

Since all of these designs have similar scores, a final selection was done in order to reduce this list to only three concepts which were further developed and tested. The result of this selection, as well as a more in-depth description of the chosen SEPS concepts, will be covered in the next section.

5.1.4.2 Final Selection

From the pre-selected designs shown in Table 5.3, the three designs selected for further development and testing were **Bodhi**, **CrystalLight** and **LightInsight**. They are showed in Figure 5.9 SEPS (a)Bodhi (b)Cyristal Light and (c) LightInsight student prototypes.Figure 5.9 respectively. The reason for choosing these SEPS is that while all three belong to the same product category and are thus roughly comparable, they are still different enough from each other to contain distinct design features. The other pre-selected concepts were either too similar to already existing products or too difficult to test in households because of high costs or low technological readiness levels.



(a) (b) (c)

Figure 5.9 SEPS (a)Bodhi (b)Cyristal Light and (c) LightInsight student prototypes.

5.2 SEPS Functional Prototyping Process

The prototypes covered in section 3.3.2 were at an early development stage with very limited functionality so further changes were necessary in order to make them suitable for user testing in a real-life environment. The physical appearance of all prototypes was left mostly unchanged to preserve its original design features; modifications mostly focused on changing each SEPS's feedback algorithm to make it more suitable for a real-life testing environment as well adding new electronic components such as Raspberry Pi microprocessors. It is worth mentioning that from this section on, each prototype will continue to be identified by the original name it was given in the student projects.

5.2.1 Feedback Algorithms and Minor Prototype Modifications

The operating mechanism of all three SEPS concepts was modified, with the developed *feedback algorithms* either expanding on the initial concept or proposing an entirely new function for the SEPS. All three algorithms are based on assigning a specific type of LED colour or light intensity to different system states; here the term *system* refers to the production and consumption profiles in a given household as well as their changes in time.

This subsection will describe the feedback algorithms created for each SEPS, along with other small modifications made to the physical prototypes to house new electronic components and reduce their size or weight. The operation of these electronic components will be discussed in further detail in the next subsection.

A. Bodhi

New Feedback Algorithm - The original feedback for this SEPS was not very specific, only indicating whether users were doing something 'good' or 'bad' for their energy consumption habits. This simplistic approach would make any assessment into the effectiveness of this SEPS design of little interest so a more specific function was proposed instead.

Bodhi will now operate as an '*energy budget'* indicator, where users will set a daily or weekly energy target and the prototype will periodically show one of three different light colours to indicate how cumulative energy consumption is performing in comparison to the set target:

- *Aqua*: under budget during the last interval (i.e. using less energy than planned)
- *Purple*: on budget during the last interval
- *Orange*: over budget during the last interval (i.e. using more energy than planned)

Performance with respect to the defined energy budget will be expressed as a *budget ratio*, which indicates the relationship between actual and planned consumption during a given interval. This budget ratio will be reset after the end of each period, and will be calculated as:

$$R_B = \frac{E_{cum}}{{}^{j}/_{N} * B} \tag{10}$$

where R_B is the budget ratio, E_{cum} is the cumulative energy consumption in the current period, j is the interval number, N is the number of intervals in a period and B is the total energy budget for a given period in kWh.

An R_B value between 0.95 and 1.05 will thus indicate that users are roughly on budget (i.e. within ±5% of the target value); values greater than 1.05 will correspond to an 'Over Budget' state while values below 0.95 will indicate the system is ‘Under Budget’, as shown in

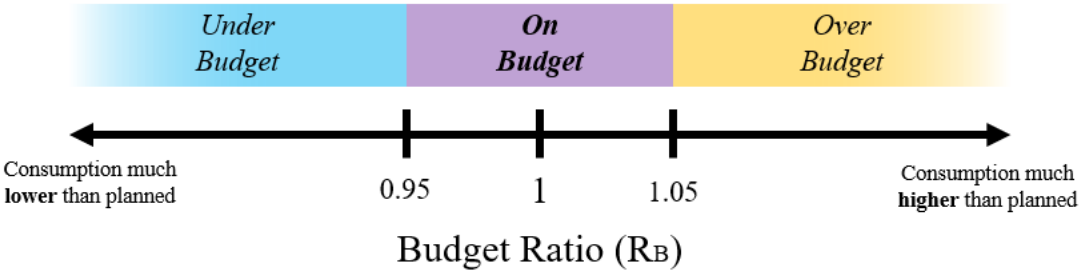


Figure 5.10 below.

Other Modifications - The student prototype was repainted and the acrylic glass pane was removed to reduce size and weight; the arrowhead was also placed next to the shaft to complete Bodhi’s shape as originally intended, as seen in Figure 5.11 below.

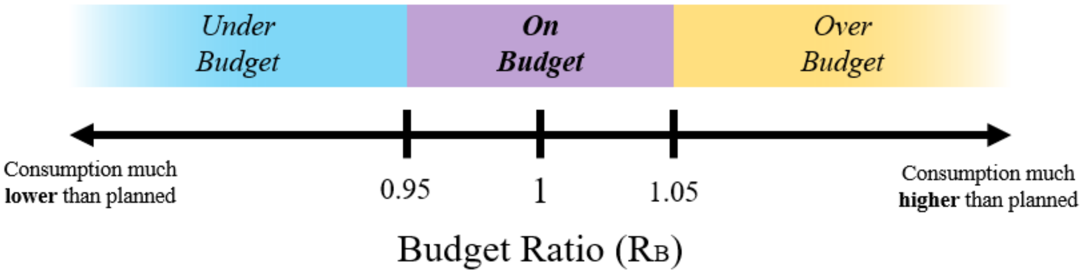


Figure 5.10 Bodhi LED feedback as a function of the Budget Ratio

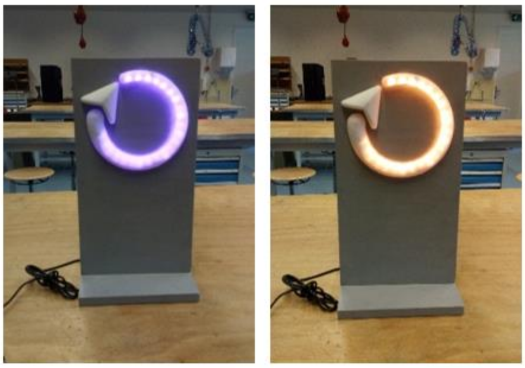


Figure 5.11 Bodhi modified prototype showing purple (left) and orange (right) lighting

B. CrystalLight

New Feedback Algorithm - The social and collaborative nature of the user interaction proposed for this SEPS would require testing on a much larger scale and is thus beyond the scope of this project. Therefore, a simplified alternative to this was created which will focus on reducing grid dependence by simulating a residential energy storage system.

CrystalLight will work in a similar way to a battery: each day, electricity produced by a household’s PV array will make its light grow stronger (‘charging’ the SEPS) while electricity consumption will gradually dim it. This way, a light still on at the end of the day will indicate that overall production exceeded consumption while no light will indicate the opposite. The battery’s charge (C_i) and state of charge (SOC_i) at each measurement interval will be calculated according to the following equations:

$$C_i = C_{i-1} + E_p - E_c \quad (11)$$

$$SOC_i = \frac{C_i}{C_{max}} \tag{12}$$

where E_p and E_c are the produced and consumed energy during a given interval and C_{max} denotes the total battery capacity in kWh. The battery state of charge will be converted into a brightness value between 0 and 100% for the prototype LEDs.

The battery SOC will be converted into a brightness value between 0 and 100% for the prototype LEDs. It is worth mentioning that if at any given interval C_i becomes negative, it will be automatically set to zero to simulate an 'empty' battery. Likewise, if SOC_i becomes greater than 100% charge will be set to C_{max} to simulate a 'full' battery.

Other Modifications – The prototype lacked sufficient inside space to house the required wiring and electronics so a cavity was made inside one of the solid wood pieces. A small hole for cables to go out through the back of the prototype was also added.

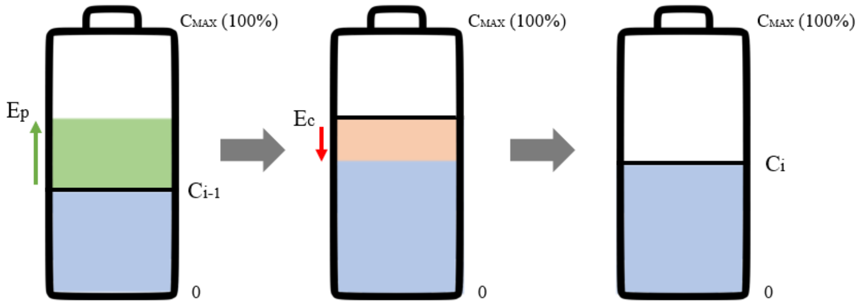


Figure 5.12 CrystalLight 'battery' charging algorithm; a new charge level is calculated by adding the energy produced (Ep) and subtracting the energy consumed (Ec) during a given interval

C. LightInsight

New Feedback Algorithm - From the three system states originally proposed for this SEPS, State 2 ("Grid is not used") was discarded since all households where tests will take place are grid-connected; two new states describing the transitions between State 1 ("Grid as an input") and State 3 ("Grid as an output") were added instead. The following colour scheme was introduced for the new system states:

- **Green**: energy production is greater than consumption.
- **Red**: consumption is greater than production.
- **Rainbow:** energy production is getting close to matching consumption; this should encourage users to transition to 'Green' by reducing their energy use by a small amount.
- **Yellow:** production is only slightly higher than consumption; this state should encourage a small reduction in energy use to prevent a shift to 'Red'.

These four system states will be determined by the relationship between produced and consumed energy. This relationship will be expressed as an ***energy ratio***, defined as:

$$R_E = \frac{E_p}{E_c} \tag{13}$$

In addition to the energy ratio itself, the direction in which this indicator is changing can be used to give users a more detailed insight into how the system is performing. To this end, two different colour schemes will be used depending on the direction R_E is changing (see Figure 5.13 below). For instance, at R_E values between 1 and 1.05 it is only necessary to show 'yellow' LED lighting if the energy ratio is decreasing since there is no risk of consumption overtaking production if the system moves on the opposite direction. Similarly, 'rainbow' LED lighting is only necessary when $0.95 \leq R_E < 1$ and the energy ratio is increasing.

To determine the direction in which R_E is moving, the energy ratio from the previous interval (*PR*) will be used; $PR < R_E$ will therefore indicate an *ascending* direction (i.e. towards the right side of the scale) while the opposite will indicate a *descending* direction (i.e. moving towards the left).

Other Modifications – The LightInsight Dial was extracted from the original prototype since user tests will only focus on this component; a wooden box for housing the new prototype's wiring and electronics was then built using laser cutting as shown in Figure 5.14below.

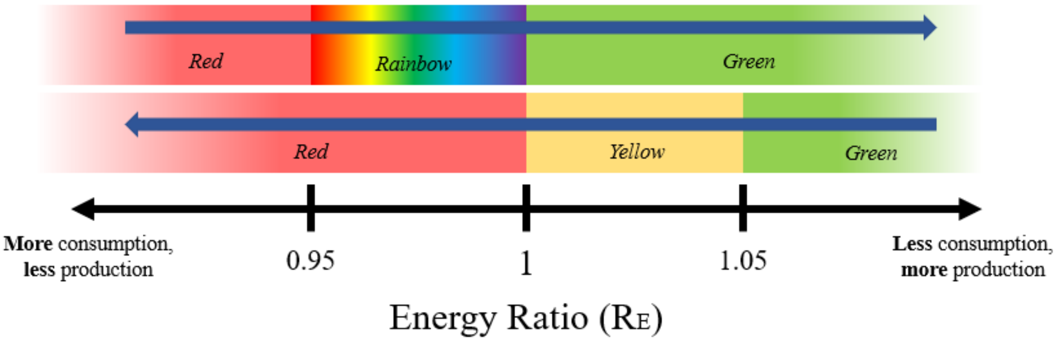


Figure 5.13 LightInsight LED feedback as a function of energy ratio, showing different colour schemes depending on whether R_E is increasing ($PR<R_E$, top) or decreasing ($PR>R_E$, bottom)

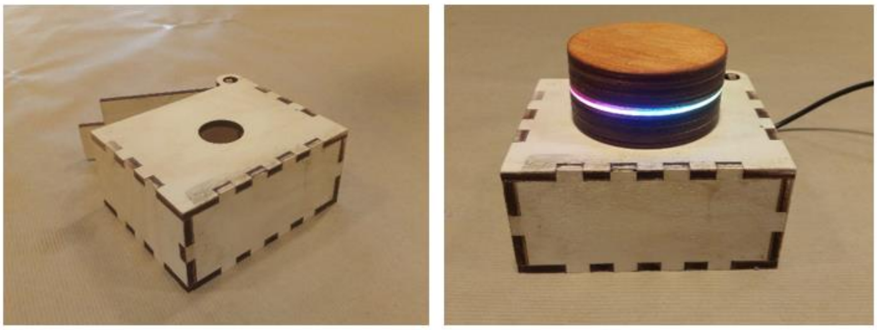


Figure 5.14 Wooden box created for housing LightInsight's wiring and electronics (left); LightInsight dial showing 'rainbow' LED lighting (right)

5.2.2 Prototype Reconstruction

During the remodelling process of the workshop where they were being stored, the Bodhi and Crystal-Light prototypes were accidentally discarded and new versions of the original concepts had to be created. These reconstructions are intended to replicate the original concepts as faithfully as possible, and only a few modifications were made to improve on minor design limitations found in the initial prototypes.

A. Bodhi

The original CAD files developed by Bodhi's designers were used to reprint the arrow display; its size was increased by 15% to ensure an easier fit for the LED strip, which was an issue in the previous version of the prototype. Additionally, the size of the new wooden base was increased in order to fit the rescaled display.

B. CrystalLight

While it was not possible to accurately recreate the original shape of this prototype due to its complexity and a lack of the proper materials, a new shape was made using thick plywood sheets stacked on top of each other as seen in Figure 5.15 below. The central acrylic layer was also made thicker in order to increase LED visibility and to ensure the electronics fit within the prototype without the need for adding an inside cavity.

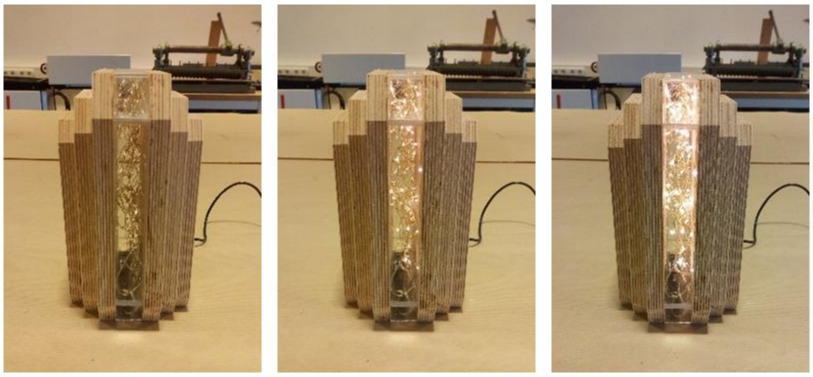


Figure 5.15 CrystalLight prototype reconstruction showing three different LED intensity levels

The final version of all three prototypes can be seen in

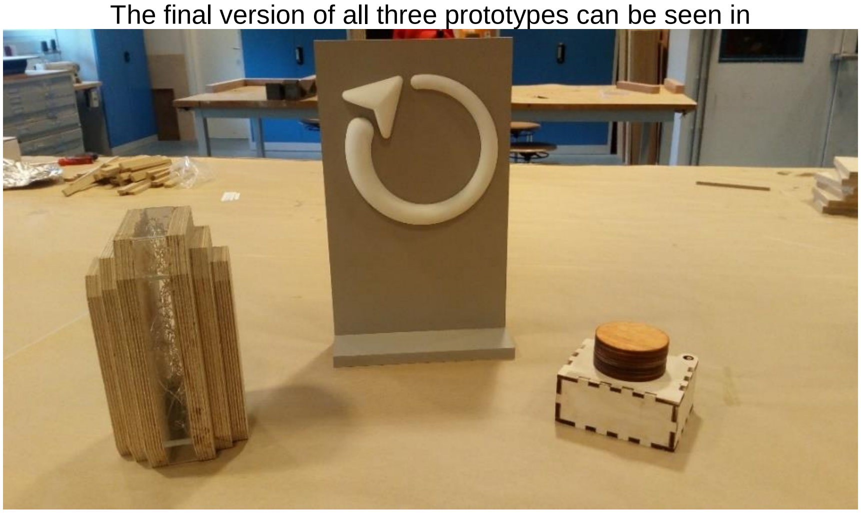


Figure 5.16 below; these will be the prototype versions implemented in the end user testing phase of this project.

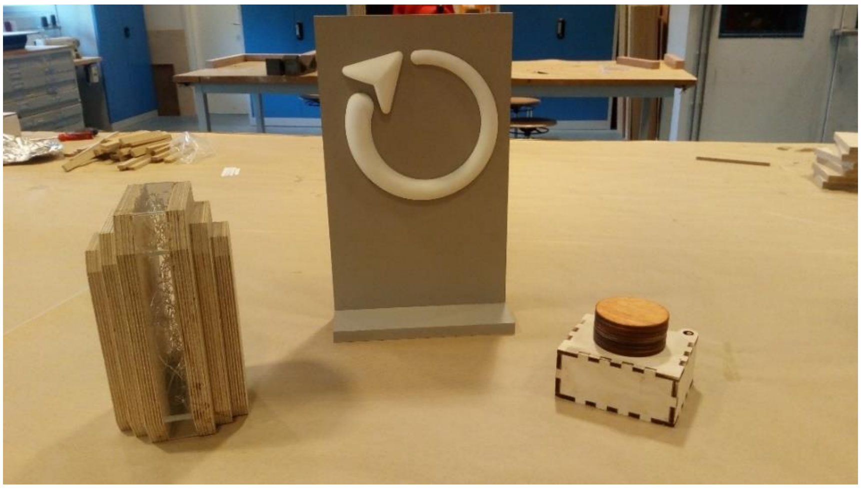


Figure 5.16 The reconstructed CrystalLight (left) and Bodhi (centre) prototypes with the previously modified LightInsight prototype (right)

5.2.3 Electronic Components and Prototype Automation

The autonomous operation of all SEPS prototypes was made possible through the use of Raspberry Pi microprocessors, where a Python script was created to periodically obtain data from a smart meter, execute the corresponding feedback algorithm and set LED properties accordingly. This process is illustrated by the flowchart shown in Figure 5.17 below.

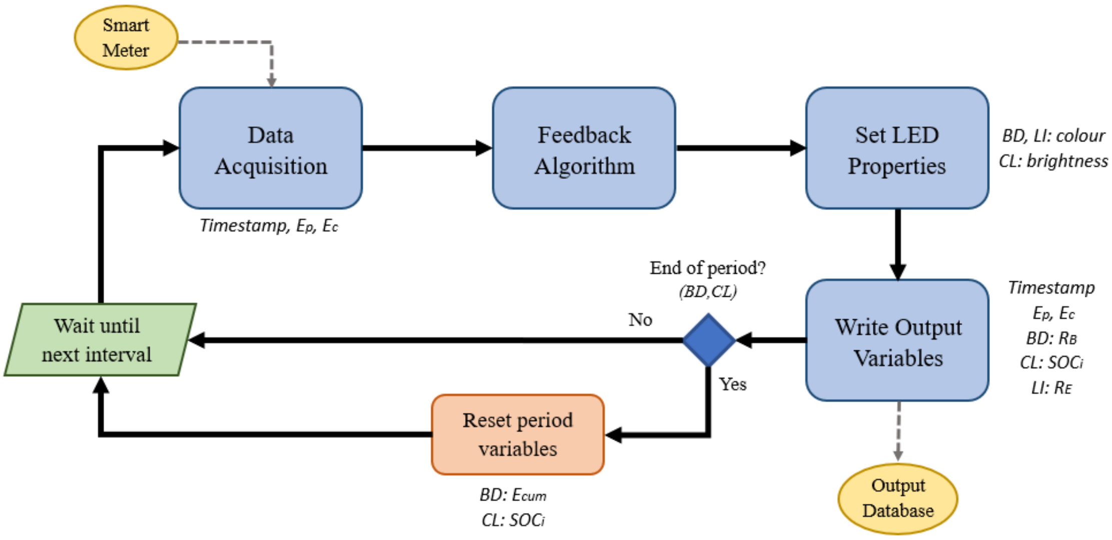


Figure 5.17 Flowchart showing the general operation of the Python scripts developed for the Bodhi (BD), CrystalLight (CL) and LightInsight (LI) SEPS prototypes

The Python scripts for all three prototypes consist of the following main components:
1) Data Acquisition: As a first step, the SEPS need to obtain real-time data on a household's energy production and consumption from its smart meter. This was done using the P1 Datalogger script developed by SmartMeter Dashboard (SmartMeter Dashboard, n.d.), which uses a smart meter's P1 port (see Figure 5.18 below) to periodically obtain telegrams containing energy data which are saved in a database file.

2) Database Management: Python's SQLite module was used to extract the timestamp, energy production and energy consumption from the aforementioned database file. An additional database file containing system outputs was also created. The two generated databases were remotely accessible through the use of the Dataplicity online software (Dataplicity, n.d.) which acts as a remote terminal for the Raspberry Pi unit. Remote data access was used to routinely verify if the system was performing as intended during the testing period as well as for updating the user interface presented to users; this will be described in further detail in Section 4.1.

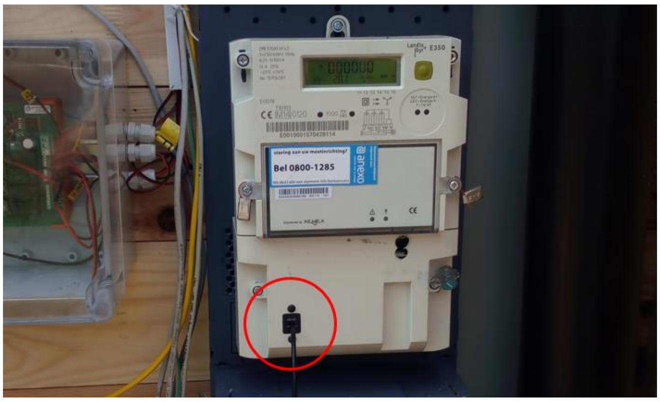


Figure 5.18 A smart meter and its P1 port (circled in red)

3) Feedback Algorithms: After obtaining energy consumption and production data, the feedback algorithms described in Section 3.4.1 were executed. For the Bodhi and LightInsight prototypes, this required installing an additional Python library to make the Neopixel LED strips compatible with the Raspberry Pi's operating system (DiCola, T., n.d.). The CrystalLight prototype, on the other hand, is able to work with the default libraries and thus set LED brightness using the Raspberry Pi's pulse-width modulation

(PWM) output pins.

4) Intervals and Periods. The actions described in the previous steps need to occur at fixed intervals since the data obtained from the smart meters is being constantly updated. To achieve this, a timer was started every time the feedback algorithm was executed; the interval length was set to 15 minutes to match the typical sampling frequency used in smart meters and PV systems. In addition to this timer, the feedback algorithms of the Bodhi and CrystalLight SEPS require resetting several variables at the end of a predetermined period (one week for Bodhi, one day for CrystalLight).

5.2.4 Conclusions on Concept Selection and Prototyping

In this chapter, the application of nine innovation methods in twenty industrial design projects was analysed to evaluate their impact in the design of new SEPS. Each of these methods tackled a different part of the design process: some methods helped visualise the product's development process to try to predict the next steps while others proved useful for finding 'breakthrough' ideas or refining the product's aesthetics.

TRIZ and platform-driven product development (PDPD) were two of the most used design innovation methods, with the former receiving the highest total score based on its perceived usefulness by students. The tools provided by TRIZ - particularly the inventive principles of segmentation, local quality and prior action - were often credited with key advances in the development of a SEPS concept, such as adding new functions or improving the user interaction mechanism, while PDPD was successful in motivating the creation of several related concepts which focused on a different market segment or rearranged the main components of the original design in an innovative way. On the other hand, methods such as Innovation Journey (IJ) and Risk-Diagnosing Methodology (RDM) had a much more limited applicability; the reason for this might be the focus these methods place on stages of the design process which exceeded the scope of these projects.

Some of the SEPS concepts developed in the aforementioned student projects were selected to be further developed and tested with potential end users. This selection was based on 5 factors: technical feasibility, financial feasibility, user interaction potential, suitability and innovation. Because of their high prototyping costs, low technology readiness level or similarity to existing SEPS, some concepts had to be discarded. The three designs selected were Bodhi, CrystalLight and LightInsight: besides receiving some of the highest scores according to the selection criteria mentioned above, these concepts were chosen because they belong to the same product category (thus being roughly comparable) while also containing distinct design features that can be evaluated during tests.

The functional prototyping of the selected SEPS concepts consisted of adding new electronic components and developing new algorithms for their operation, as well as minor modifications for reducing prototype size or housing the added components. These modified prototypes were later tested by end users in several households; the results of these tests will be described in the following chapter.

5.3 End User Testing

Following the functional prototyping process presented in the previous chapter, the developed SEPS prototypes were tested with end users in two different locations in the Netherlands: two studio apartments in Delft and a stand-alone house in Enschede. These tests evaluated the performance of each prototype through energy measurements and user interviews in order to determine whether they were successful in making household energy use more sustainable.
This chapter is structured as follows: Section 5.3.1 will describe the test goals and the test set-up, including some of the additional tools that were used to gather data and present information to users. Section 5.3.2 will present the results obtained from each test site as case studies, focusing on household energy measurements as well as on user insights. Finally, some conclusions on the end user testing phase will be presented in Section 5.3.3.

5.3.1 Test Goals and Testing Set-up

The end user tests had the following objectives:

- Determine users' main motivations for using smart energy products and assess whether these motivations changed after interacting with them.
- Measure the extent to which the use of the SEPS prototypes changed users' perception on their residential energy use, as well as evaluating whether this change is translated into a more efficient energy use.
- Finding out the influence product design had on the issues described above by identifying which design features had a positive effect on increasing user *interaction* with the product, as well as causing a *reaction* which altered household energy use.

In addition to the SEPS prototypes, other tools were used to obtain qualitative data and present information to users. The user testing plan, as well as a detailed description of these tools, will be presented in the following subsections.

5.3.1.1 User Testing Plan

End user tests were conducted in two phases: during the first phase, energy data was measured and provided to users via a user interface (UI), after which one of the prototypes was introduced for users to interact with during the second phase. Quantitative and qualitative data was gathered throughout both phases: *quantitative* data consisted on energy production and consumption values measured from household smart meters while *qualitative* data was obtained through user questionnaires and interviews.

Phase 1 – Reference Measurements and User Interface Feedback
As a first step, users were interviewed about their perceptions on energy use, whether they had any previous experiences with SEPS and their motivations for using them. After the initial interview, household energy production and consumption were measured constantly. End users were able to get basic feedback on their energy use through a dedicated user interface called *PowerTracker*; further details on the contents and structure of this interface will be presented in section 5.3.1.2.

Figure 5.19 below shows how energy production and consumption data was obtained by connecting one of the Raspberry Pi units directly to the household's smart meter using a P1 cable and executing the P1 Datalogger script described in Section 3.4.3; energy measurements were made on 15-minute intervals. Households with PV systems relied on actual generation measurements, while an approximation was done for households without them.

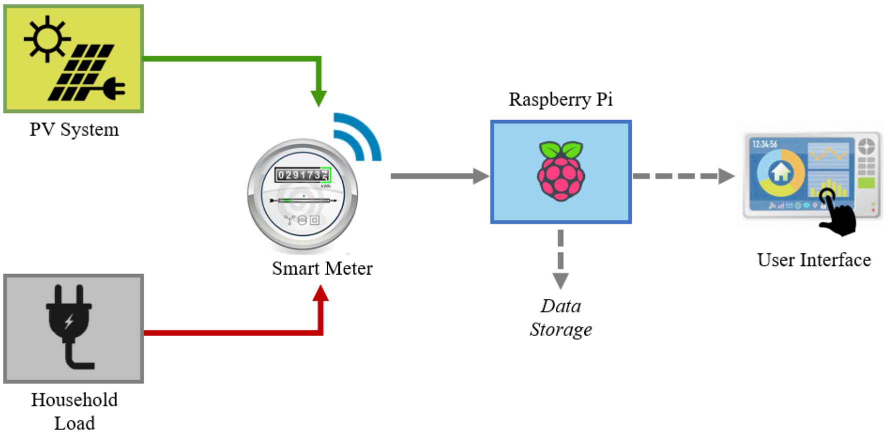


Figure 5.19. Testing Set-up for Phase 1 of the End user Testing

This phase was used to create a reference scenario by replicating the approach currently used by existing SEPS; the results obtained during this phase also served as a control for evaluating the effectiveness of each prototype in making household energy use more sustainable during the second phase.

Phase 2 – SEPS Prototype Testing
In this phase, users were presented with a brief description of the SEPS prototypes as well as a short demonstration of their feedback mechanism. A short series of questions on their first impressions of all three SEPS concepts were then carried out, after which one of the prototypes was selected and installed in a location chosen by the users themselves.
Following its installation, users were left to freely interact with the prototype for several days. During this testing period there was constant monitoring of energy consumption and generation in a similar way to the previous phase, with the prototypes capturing data from smart meters on 15-minute intervals. The prototypes also used this data to periodically set new LED properties and present feedback to users as seen on Figure 5.20 below.

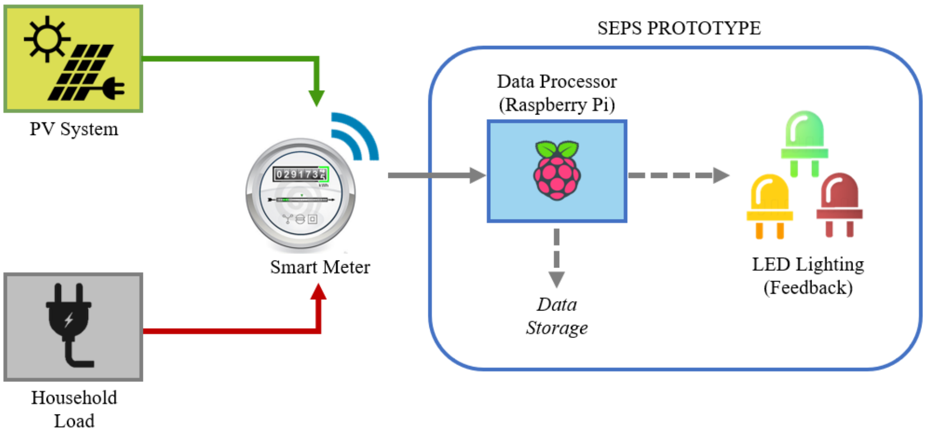


Figure 5.20 Testing Set-up for Phase 2 of the End user Testing

At the end of this testing period, the final part of the user questionnaire was conducted and additional observations on user experience were gathered through interviews. It is also important to mention that the UI first introduced during the previous phase was no longer implemented, meaning that the prototypes became the only feedback source available to users.

5.3.1.2 The PowerTracker User Interface

A simple user interface named *PowerTracker* was created to provide users with additional insights into their energy use at home by displaying relevant information on their daily or weekly energy production and consumption. *PowerTracker* was designed with the intention of showing relevant information in the

simplest terms possible, while still replicating the approach used by existing smart home technologies such as home energy management systems (HEMS) and smart thermostats.
PowerTracker was accessible to users as an Internet website during Phase 1 of the end user testing. An example of the interface is shown in Figure 5.21 below showing basic information from the current day/week on the left and a bar graph with daily production and consumption values on the right.

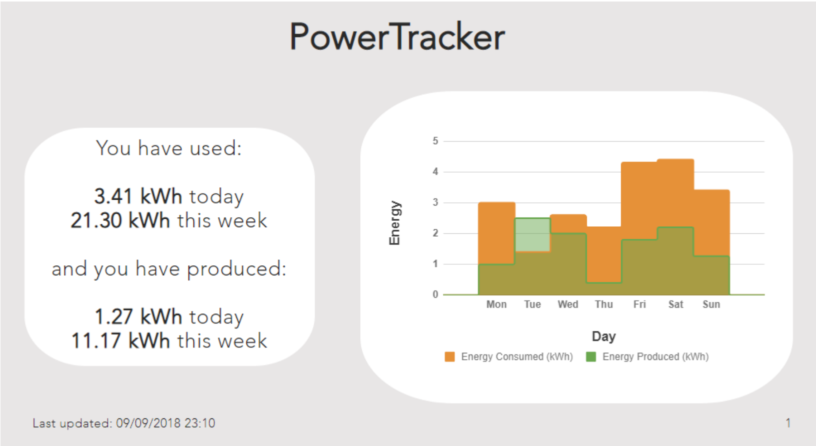


Figure 5.21 PowerTracker feedback interface, showing energy production in green and energy consumption in yellow.

5.3.1.3 User Questionnaire

A short questionnaire was used to obtain qualitative data on users' perceptions on energy use, their first impression of the prototypes and their experience while using them. This questionnaire consisted of the following sections:
A) Basic Information – This section describes the participant's age group and education level, as well as the type of housing and the number of people that live there.
B) Perception of Energy Use – This section evaluated participants' perception on how much energy they consume, when they consume it and on for which purposes. The tests will later corroborate or disprove these perceptions.
C) First Impression of SEPS – This part of the questionnaire was conducted after the initial demonstration of the prototypes and before one of them was selected for use. In it, participants were asked about the general attractiveness of each SEPS concept, identifying the features that made the concept more or less appealing to them.
D) Impression After Use – In this section, the participant's involvement with the prototype during the tests is evaluated by determining how often there was an *interaction* with the product and how often this was reflected in a *reaction* (i.e. a modification on normal energy use).
E) Conclusions – Finally, participants assess whether their initial perceptions and motivations for using these products changed as a result of the experiment while describing their general experience with the prototypes.

Some questions in this questionnaire were based on the user survey conducted by (Obinna, U., 2017); the full questionnaire text can be found in the Appendix B.

5.3.2 End User Testing Results: Case Studies

End user testing of the SEPS prototypes took place in two different locations: two studio apartments in Delft and a stand-alone house in Enschede. Since both the number of users and households where the tests took place is too small to be statistically significant, in this section each test site will be presented as a case study. Each case study will describe the results obtained during both end user testing phases, first analysing energy consumption and production data and then focusing on the insights gained from user interviews and questionnaires.

5.3.2.1 *Studio Apartments - Green Village, Delft*

The Green Village is an initiative by TU Delft and Stichting Green Village which aims to accelerate the development and implementation of innovations in renewable energy and sustainable development by creating a space where different stakeholders can test and showcase these innovations [57]. This location has many of these technologies (e.g. PV systems, smart meters, etc.) already in place which, together with the fact that there are several small households where residents can try out new product concepts, made it an ideal location for testing the developed SEPS prototypes.
Testing took place in the Sustainer Homes (shown in Figure 5.22 below), one of the sustainable building projects developed at this location. These one-person wooden modular studios incorporate several sustainable home technologies, including a building-integrated PV array which operates as a local energy source. Each of the two apartments is also fitted with a smart meter which served as the main data source for both the user interface and the SEPS prototypes during testing.

Figure 5.22 Sustainer Homes at the Green Village testing facility

The PV system was connected to the smart meter in the bottom apartment, so only this household had direct energy production measurements. The same production dataset also served as an input for the UI in the upper apartment during Phase 1, and was used to simulate a production profile for the SEPS prototype tested during Phase 2.

5.3.2.1.1 Phase 1: Reference Measurements

Figure 5.23 shows the production and consumption energy profiles in the top Sustainer Home for a 3-day period during this testing phase. All three days have a roughly similar profile, with energy demand showing a clear baseline load of around 0.1 kW and distinct sharp increases during the day, reaching peak loads of up to 1.7 kW around noon. Total energy consumption showed little day-to-day variation, averaging 4.5 kWh per day. Energy production profiles showed significant day-to-day variation, most likely due to weather conditions. Day 1 in Figure 5.23 shows an excellent match between supply and demand, but in the other two days this is not the case and peak production lags behind peak demand by a few hours.

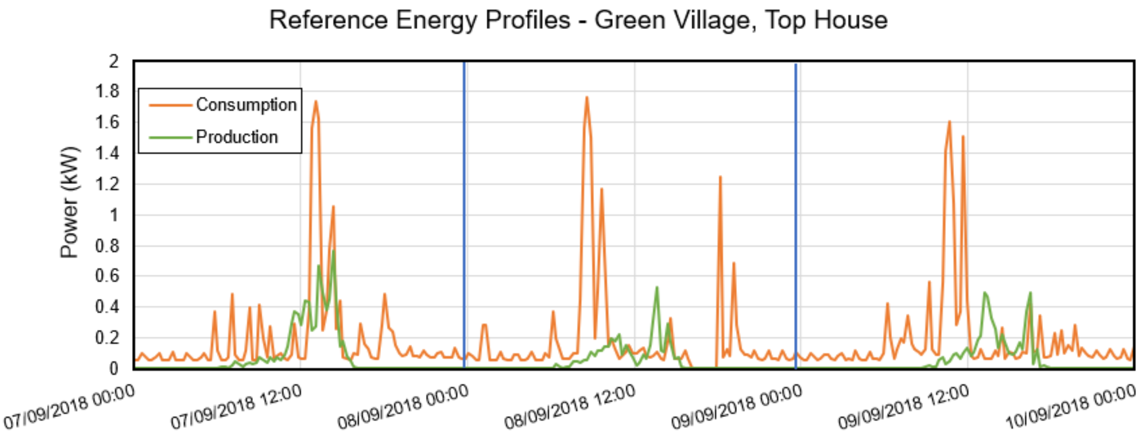


Figure 5.23 Reference phase 3-day energy profiles for the top Sustainer Home, showing consumption in orange and production in green

Energy profiles for the bottom Sustainer Home are shown in Figure 5.24 below. Baseline load is approximately the same as in the previous case; however, peaks in demand occur less often and rarely exceed 1 kW. Household energy consumption (averaging 1.66 kWh per day) is noticeably lower than on the top apartment, which can be explained by two factors. First, the shown interval took place during a weekend so it is possible that the user was not home for most of this period. Additionally, demand became noticeably lower when the PV system was generating electricity (particularly during Day 2); this might indicate that the meter reading measures the net energy flow from the household to the grid. If this is the case, an additional meter should be placed before the connection to the PV system so that household demand is measured independently from production.

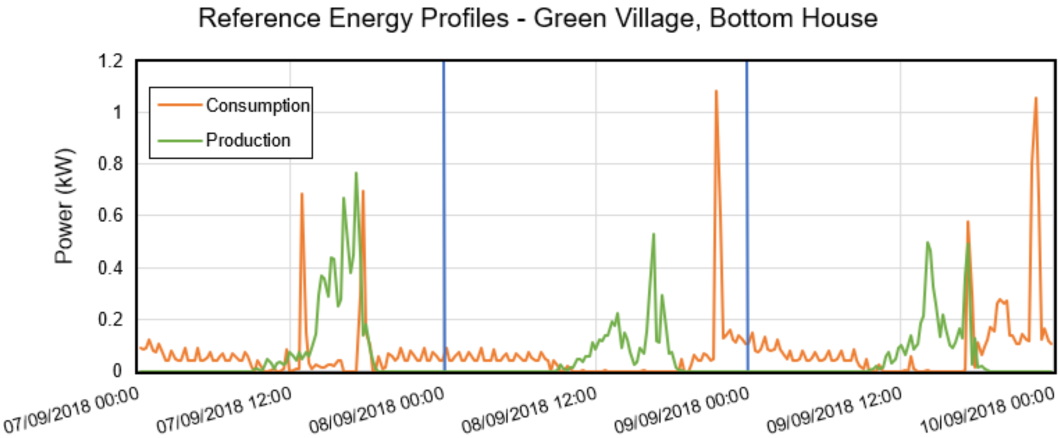


Figure 5.24 Reference phase 3-day energy profiles for the bottom Sustainer Home, showing consumption in orange and production in green

Energy measurements for both Sustainer Home apartments were carried out for a total of 5 days, but only a fraction of these results was presented in the figures in this section; complete energy profiles can be found in the Appendix C.

5.3.2.1.2 Phase 2: Prototype Testing

LightInsight was the SEPS prototype chosen for the top Sustainer Home, where it was installed in a table located between the kitchen and the living room as seen in Figure 5.25 below.

Figure 5.25 LightInsight prototype during the user testing phase

Figure 5.26 below shows the energy profiles for a 3-day interval during this testing phase. These profiles follow the same pattern observed in the first phase showing similar baseline and peak loads although in this case peaks in demand were more spread out and occurred at unusual times of the day, most noticeably during the early morning. This behavior goes against the prototype's intended effect of shifting load to times of high PV production.

Since this apartment's smart meter was not directly connected to the PV system outside, a simulated profile was constructed using data gathered during the previous phase. The simulated energy production consistently underperformed with respect to demand, which coupled with the spread in demand peaks translated into an even worse match between energy supply and demand. Surprisingly, both average load (25%) and peak load (3%) across the entire testing period increased from the previous phase when they were both expected to decrease. Due to the short duration of the tests, it is unclear if this change happened because of the introduction of the SEPS prototype or if other factors were involved.

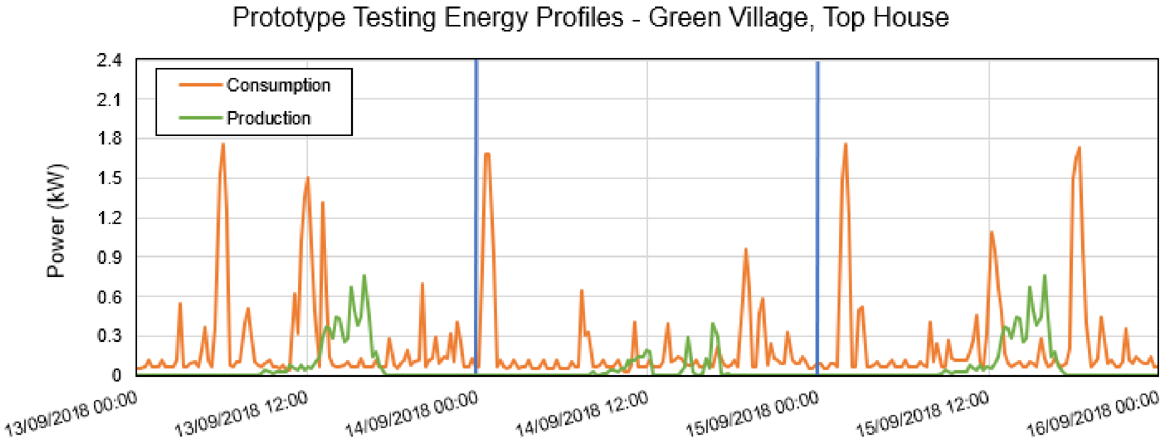


Figure 5.26 Testing phase 3-day energy profiles for the top Sustainer Home, showing consumption in orange and production in green

The performance of the LightInsight prototype during the same period was evaluated by plotting its energy ratio as seen in Figure 5.27 below. By mapping the LED colour shown by the prototype over this profile, it becomes clearly visible that the prototype showed red LED lighting for most of the day, with green lights appearing mostly during the early afternoon hours (12:00-17:00). In fact, analysing the entire testing period revealed that the 'red' system state constituted around 85% of the total intervals, with most of the remaining time spent on the 'green' system state. The 'yellow' and 'rainbow' transition states, at 2 (0.2%) and 4 (0.4%) intervals, almost never took place during this phase.

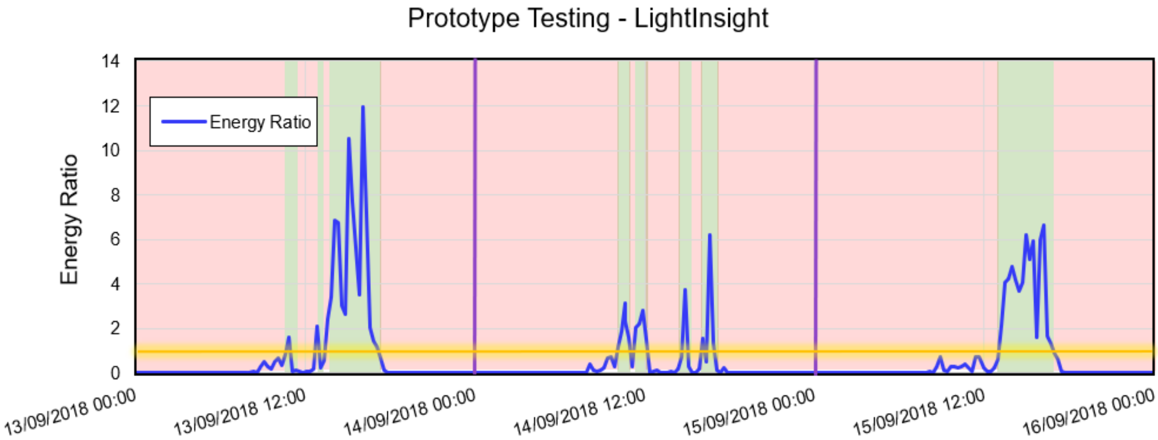


Figure 5.27 LightInsight 3-day performance during testing phase. Background colour corresponds to the light colour shown by the prototype LEDs; the yellow line indicates the balance point between energy consumption and production.

As was the case with data from the previous phase, complete energy and prototype performance profiles for this phase can be found on the Appendix C.

5.3.2.1.3 User Insights

During the initial interview, the user acknowledged she was unaware of how much energy she normally consumed, and estimated her household energy use as 'average' and taking place mostly in the afternoon (12:00 – 20:00). While the actual consumption of this household is slightly higher than the average consumption of a single-person household in the Netherlands [58], peak load was usually observed during the afternoon with a few exceptions where this occurred during the morning.

Furthermore, the user mentioned that her perceptions on energy use and her general routine remained unchanged both during and after the tests, although she indicated that she is now more aware of her energy use and of the times when production is high. This suggests that while the prototype was successful in providing insights into the user's energy use, it failed in changing user behavior.

While using the LightInsight prototype, the user clearly noticed lights were red most of the time which made her 'feel bad' about using energy. The user also reported feeling 'powerless' because the prototype's feedback partly depended on energy production which is entirely outside users' control. Transition states were barely noticed, with the user also pointing out that they were 'not very intuitive' and difficult to understand. Interestingly, green LED lighting pushed the user into 'consuming a bit more energy' than she would have otherwise which seems to indicate that a rebound effect took place; the observed increase in household consumption and the lack of load shifting towards high production times support this hypothesis.
Finally, the user also provided several suggestions for improving the product. These suggestions include:

- Prototype lighting can become irritating under certain circumstances; setting different light intensities at different times of the day (e.g. brighter during the daytime, dimmer at night) or adding the option to turn them off when users are not home or asleep could solve this issue.
- In addition to different light colours, other feedback mechanisms such as sound cues could notify users of a change between system states.
- Users are typically away from home for a significant part of the day so there should be some way to visualise how the prototype performed during this time. The user suggested adding a function in which each light in the prototype's LED ring represents a specific amount of time; for instance, a historical overview of the last 24 hours could be presented using each LED to represent a period of one hour.

The CrystalLight prototype was installed in the bottom Sustainer Home, with the user choosing to place the prototype in the kitchen as seen in Figure 5.28 below. However, due to a smart meter error which made it impossible to obtain constant energy measurements the planned testing did not take place.

Figure 5.28 CrystalLight prototype during the user testing phase

5.3.3 Stand-alone House – Twekkelerveld, Enschede

A stand-alone house located near the University of Twente was used as an additional testing location. In contrast to the Sustainer Home apartments described in the previous case study, this house does not have any 'smart' technology apart from a smart meter which makes it a more representative example of average households in the Netherlands. Although the house lacked a PV system, this had no impact on the obtained results because the prototype selected for testing at this location did not require energy production measurements.

Figure 5.29 Stand-alone house in Enschede where the end user testing took place

As with the previous case study, only part of the total measurements will be shown in the figures throughout this section; complete energy and prototype performance profiles can be found on the Appendix C.

5.3.3.1.1 Phase 1: Reference Measurements

Figure 5.30 below shows the consumption energy profile obtained in a 3-day period during this testing phase. A baseline load of around 1 kW was observed which is significantly higher than the base loads measured in the Sustainer Homes; a likely reason for this is that, in addition to a larger household size (5 household members), this house lacks the energy-efficient design used for building these apartments. Total energy use during the measuring period was remarkably consistent, showing only slight deviations from the average consumption of 32.1 kWh per day. The distribution of load peaks was also relatively constant, reaching a maximum of around 3 kW during the early afternoon.

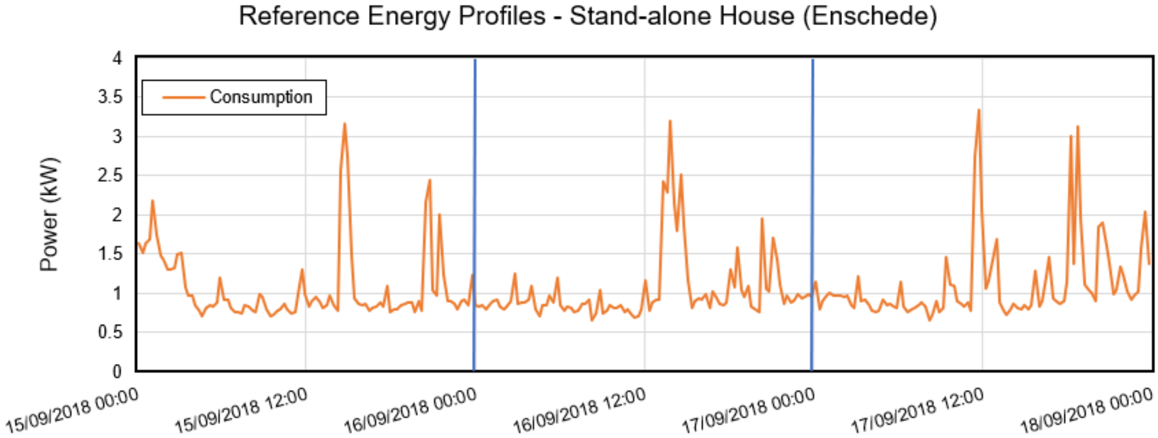


Figure 5.30 Reference phase 3-day energy profiles for the stand-alone house

5.3.3.1.2 Phase 2: Prototype Testing

Bodhi was the prototype tested in this household; users decided to have the prototype placed in the living room as seen in Figure 5.31 below. Based on the energy consumption observed during the previous phase, a budget of 30 kWh per day was set for this test.

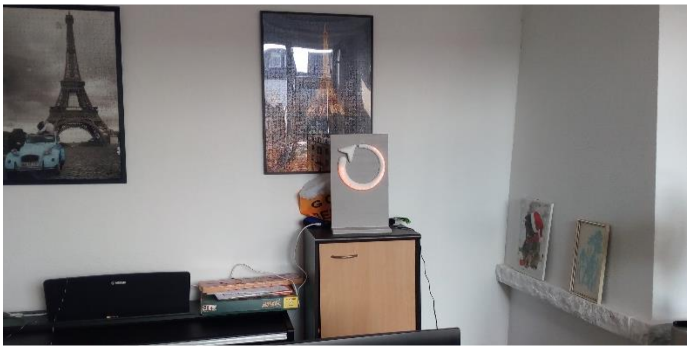


Figure 5.31 Bodhi prototype during the user testing phase

Figure 5.32 shows the energy profiles during the prototype testing phase. While both the base and peak loads observed in this period were only slightly lower than during the reference measurements, overall energy consumption saw a significant decrease averaging 23.4 kWh per day (27% less than on the previous phase). Furthermore, no load shifting seems to have occurred since energy demand still peaked during the early afternoon.

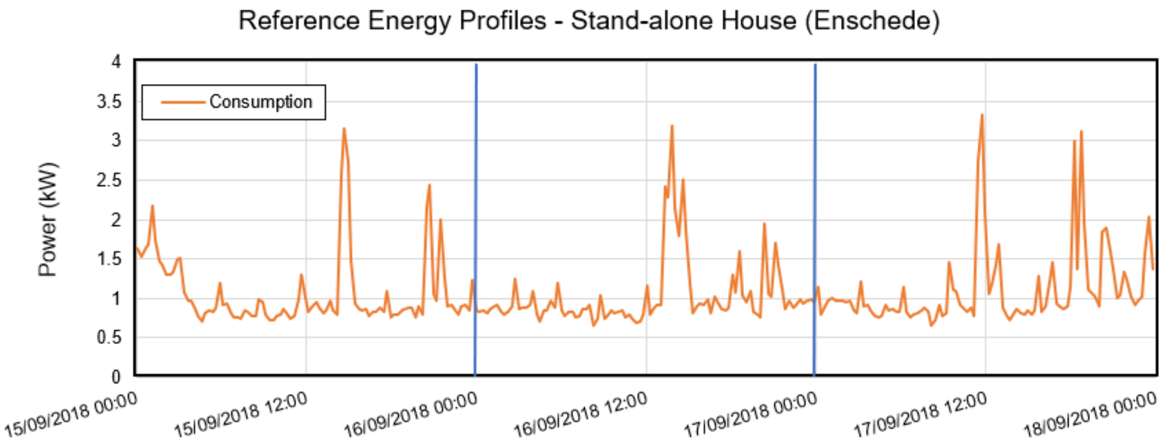


Figure 5.32 Testing phase 3-day energy profiles for the stand-alone house

Analysing prototype performance during this period revealed that the energy budget set in Bodhi's feedback algorithm greatly overestimated the actual energy use during testing. In the 3-day period shown in Figure 5.33 below, consumption during Day 1 was much higher than expected at first but then sharply decreased, transitioning through all three system states and remaining on the 'Under Budget' state (corresponding to aqua LED lighting) for the rest of the day and the next two days as well. Due to the short length of the testing period, it is hard to determine whether this decrease in consumption can be attributed to the prototype or if there was influence from other factors.

With the exception of the first half of Day 1, all budget ratio profiles follow a similar pattern showing an overall increasing trend. By comparing these profiles with the consumption data previously shown in Figure 5.32 it is possible to see that intervals where this indicator sharply increases match peaks in household load; these intervals are followed by gradual decreases in budget ratio as energy use reverts back to the baseline load.

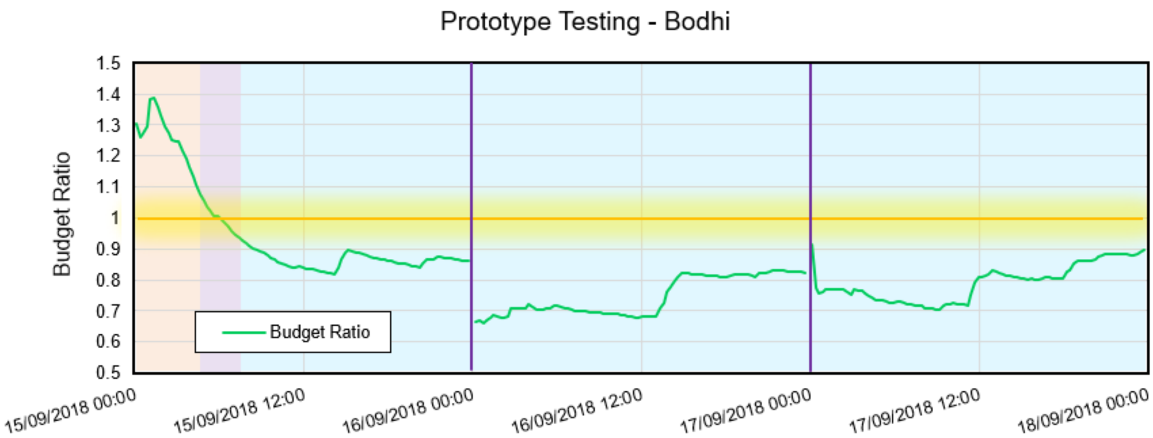


Figure 5.33 Bodhi 3-day performance during testing phase. Background colour corresponds to the light colour shown by the prototype LEDs; the yellow line indicates the balance point between actual and planned energy consumption.

5.3.3.1.3 User Insights

All five members from this household were interviewed during both testing phases. When asked about their motivations for using SEPS, almost all respondents ranked the suggested incentives differently: peer pressure was the top ranked incentive, followed by comfort and environmental concerns. Saving money was ranked last, most likely due to the fact that respondents' housing contract has energy costs already included in their monthly rent.

As part of the user questionnaire, all respondents were also asked to evaluate how often they *interacted* with the user interface and the SEPS prototype, and whether this interaction resulted in a *reaction* from them. The answers to these questions (shown in Figure 5.34 below) revealed a significant difference in the interaction with each device; while 3 out of 5 respondents admitted checking the UI less than once a week, nearly all respondents interacted with the prototype on multiple occasions each day. There was also a noticeable improvement in the reaction to feedback as well, with the majority of users never reacting to UI feedback but all respondents reacting at least occasionally to feedback from Bodhi.

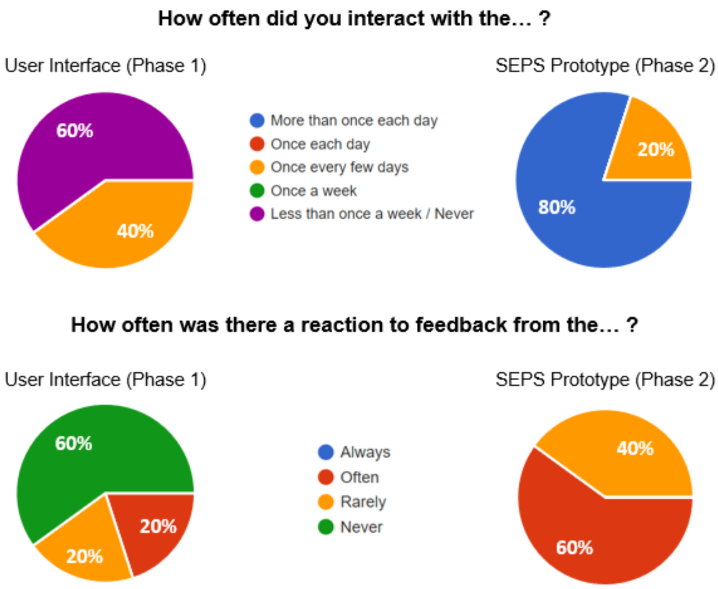


Figure 5.34 User response to the user interface and the SEPS prototype during testing

All respondents stated they would keep the SEPS at home either because it would help them 'use energy in a smarter way' (3 respondents) or because 'of the way it looks' (2 respondents). When asked about attractive product features, expected ease of use and the feedback mechanism were preferred the most, slightly more than the product's appearance.

The prototype's aqua lights were interpreted as a sign that "everything was alright" and no action was needed, while orange or purple lights pushed users to use less energy either in that moment or later on. Interestingly, the most frequent reaction to this type of feedback according to all users was turning lights off which typically represent only a small fraction of a household's total consumption. This highlights the importance of giving users more detailed information on which appliances consume the most energy so they can take better-informed decisions on how to reduce their energy use.

Regarding their perception on energy use, most respondents initially estimated their consumption as 'high', changing to 'average' at the end of the testing period. At an average 29 kWh consumed per day, this household's energy demand seems to be significantly higher than that of the average 5-person household in the Netherlands [58], indicating that despite the observed reduction in consumption the prototype feedback might have given users an incorrect impression on their energy use.

Some of the suggestions made by users to improve the prototype include:

- In addition to different light colours, other feedback mechanisms such as sound cues could notify users of a change between system states. This idea was also suggested by the user from the previous case study.
- The number of lights turned on in the LED strip could be used to provide additional information. Users also suggested placing lights inside Bodhi's arrowhead so that the prototype's shape is easier to identify, especially at night.

5.3.4 Conclusions on End User Testing

Two of the three developed SEPS prototypes were successfully tested by end users in order to evaluate their impact in helping achieve a more sustainable energy use in their homes. The energy data measured during these tests, as well as the insights gained through user interviews and questionnaires, offer valuable information on some of the design factors that supported or discouraged this change.

Residential energy consumption depends on many factors which become evident over long periods of time; such factors include, among others, the influence of weather and the gradual decrease in interest new products can experience with time as users get accustomed to have them at home. The size and length of the tests performed were insufficient for a complete analysis of these factors, but despite these constraints it was possible to identify some of the underlying trends behind this process.

One of the main challenges found during these tests was the complexity of testing in real households, which are relatively uncontrolled environments where much depends on people's daily routine patterns. Furthermore, the higher the number of people living in a household, the more complex the interactions with home appliances (and between household members) become. People had different levels of engagement with the tested technologies and different motivations for doing so, and any changes to their usual behavior were hard to achieve.

Although the tested SEPS concepts were designed to be simpler and more intuitive than conventional smart home technologies, users still struggled to understand how they worked at first but with time they gradually learned how to interpret feedback from the prototypes. Insights into energy production and consumption, both through the *PowerTracker* user interface and the SEPS prototypes were appreciated by users, but proved insufficient for helping them find the best way to reduce the amount of energy they were consuming. This demonstrates the need for providing end users with more detailed information on how they consume energy at home so they can be more effective in making their energy use more sustainable.

Testing the LightInsight prototype revealed that this SEPS proved ineffective in changing energy use, with no shifting towards high PV production times and consumption increasing instead of decreasing. The proposed transition states for this SEPS concept were unable to push users in the right direction due to their limited presence during testing, and the prevalence of red LED lights seemed to discourage user engagement with the prototype**.** Furthermore, users realised energy production was not in their control which made them feel ‘powerless’ even though they still had some influence on prototype performance by modifying their consumption.

End user tests on the Bodhi prototype, on the other hand, resulted in a significant decrease in average daily consumption although no load shifting was observed. This household had a larger number of members which added more complexity for determining what caused the observed changes. The chosen energy budget also proved to be a key factor during testing since an overestimation in the predicted consumption for the prototype testing phase resulted in a single system state dominating most of the testing period; this underscores the importance of developing an algorithm which adapts to changes in user consumption in order to consistently set a more accurate energy budget.

5.4 SEPS Validation and Use Scenario Simulations

After conducting the end user testing described in the previous chapter the operation of the SEPS prototypes was further tested at the Austrian Institute of Technology (AIT). These tests aimed to validate prototype operation using the high-precision testing equipment available at the site, as well as extending the range of conditions for prototype performance testing by modelling situations which were not possible during the end user tests.
This chapter is structured as follows: Section 5.1 will describe the testing plan for the SEPS validation and use scenario simulation tests, with Section 5.2 presenting the results obtained in each testing phase. Finally, some conclusions on these tests will be presented in Section 5.3.

Figure 5.35 SmartEST Laboratory installation at the Austrian Institute of Technology (AIT), where SEPS validation took place

5.4.1 Testing Plan

The tests performed on the three SEPS prototypes sought to achieve the following goals:

- Validate prototype operation using equipment from the Smart Electricity Systems and Technology Services (SmartEST) Laboratory. This will confirm that the scripts developed for each prototype work adequately, further supporting the results that were previously obtained during the user tests.
- Extend the range of conditions where the prototypes' performance was evaluated by modelling situations which were not possible during the end user testing. This can be achieved by using datasets from previous experiments to create several scenarios, each representing a particular set of conditions.

Testing each SEPS prototype consisted of two main phases, with each testing phase tackling one of the goals mentioned above.

5.4.1.1 Prototype Validation

During this testing phase, an emulated PV source and an RLC controllable load were used as production and consumption inputs to simulate different system states which were interpreted by the prototype's feedback algorithm in order to set its LED properties accordingly, as seen in Figure 5.36 below. This was achieved through the following process:

- Energy **generation** was modelled using a DC voltage/current source simulating a PV system. Energy **consumption**, on the other hand, was modelled using an RLC controllable load which consumed the generated power or drew power from the local grid whenever consumption exceeded generation.
- The main measurement system then estimated power flows in the system by constantly measuring voltage and current values in the aforementioned circuit. These measurements were periodically passed on to the SEPS prototype using the lab's communication infrastructure, consisting of a custom-built communication middleware application which linked both components.
- The prototype performed the necessary calculations to determine LED properties following the feedback algorithms described in the previous testing phase.

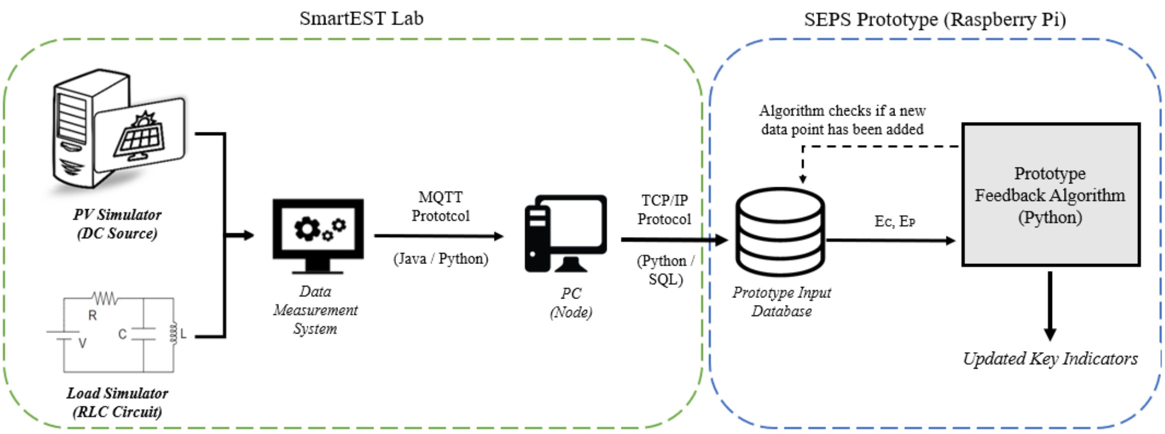


Figure 5.36 Test Set-up for the SEPS Validation testing

A different testing sequence was created for each prototype to make sure that all system states were tested:

- **Bodhi**: After setting an arbitrary energy target, a relatively low load was first simulated to set the system in the ‘under budget’ state. The load was then increased so that the cumulative consumption roughly matched, then exceeded the planned budget. Since this prototype does not require energy production data, the PV simulator was not used.
- **CrystalLight**: After setting an arbitrary maximum charge, a ‘charge-discharge’ cycle was modelled by first setting the load at a lower value than PV production until the prototype reached its maximum ‘charging’ capacity. The load was then increased so that consumption exceeded production, gradually ‘discharging’ the prototype until a full discharge was reached.
- **LightInsight**: The two colour schemes previously presented in Figure 3.21 were tested by setting PV production at a constant level and gradually decreasing the RLC load from a relatively high value to a low value, after which the load was increased until the initial point was reached again.

5.4.1.2 *Use Scenario Simulation*

The algorithm used by each prototype to determine LED output properties was further tested by using production and consumption profiles to model different use scenarios. Since the prototypes were designed to periodically read the required data from smart meters, a simple script was created which replicated this process by adding a new data point to the prototype’s main database file at regular intervals. This data point, consisting of a pair of energy consumption (E_c) and energy production (E_p) values, served as the main input for the prototype’s feedback algorithm which calculated the key indicator variable(s) used to set new LED properties.

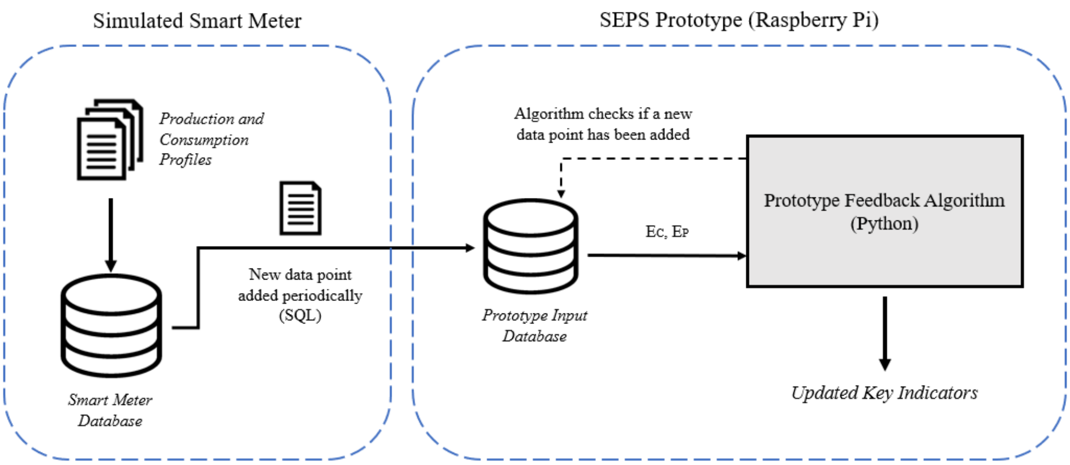


Figure 5.37 Test Set-up for the Use Scenario Simulation testing

Several prototype use scenarios were created by using existing experimental datasets to combine summer and winter load curves with PV production data reflecting ‘adequate’ or ‘inadequate’ performance according to weather conditions; all sources have 1-min resolution and cover a 24-hour period. The four modelled scenarios are:

1. **Summer Load Profile, Inadequate PV Production:** The household in this scenario has an average load of 0.89 kW, with a series of pronounced peaks taking place during the daytime reaching a maximum of around 5 kW. Energy generation is significantly lower than consumption, averaging only 24% of the household load throughout the day.

2. **Summer Load Profile, Adequate PV Production:** Household load remains unchanged from the previous case, but PV production is on average nearly 50% larger than the load throughout the day.

3. **Winter Profile, Inadequate PV Production:** Household load is on average 10% larger than during the summer, with peak loads reaching up to 7 kW during the early afternoon. PV generation is very poor, significantly trailing behind energy consumption the entire day.

4. **Winter Profile, Adequate PV Production:** Household load remains unchanged from the previous case, but in this scenario energy production exceeds average consumption during the late morning and early afternoon hours.

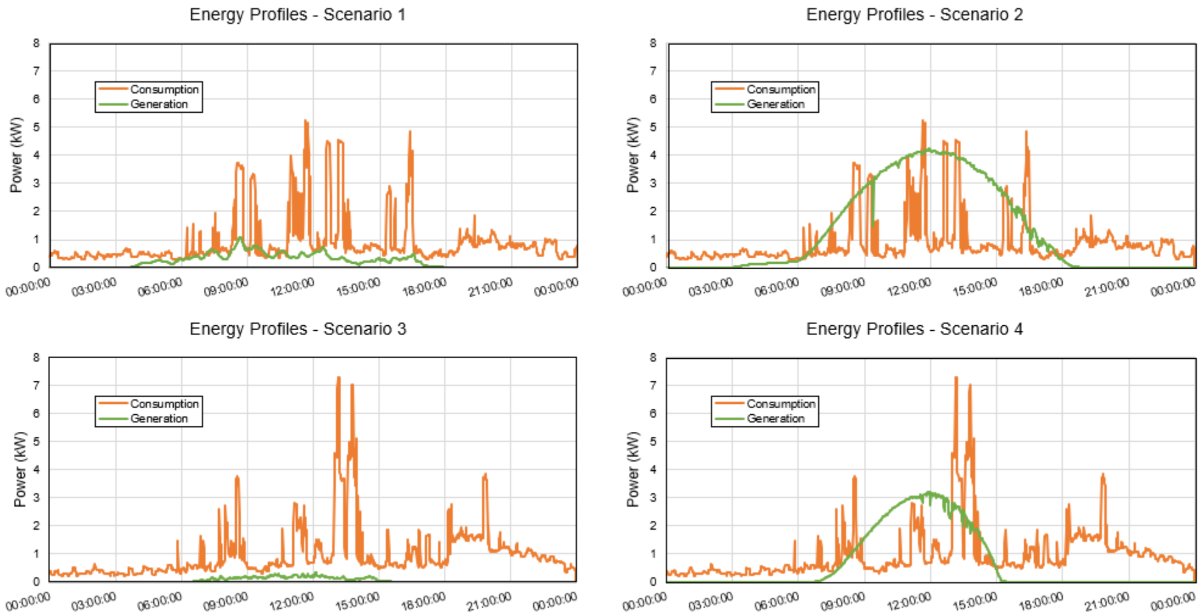


Figure 5.38 Energy profiles for the four modelled scenarios, showing consumption in orange and production in green. Clockwise from top left: Scenario 1 (Summer Load, Inadequate PV), Scenario 2 (Summer Load, Adequate PV), Scenario 4 (Winter Load, Adequate PV), Scenario 3 (Winter Load, Inadequate PV).

5.4.2 Validation and Simulation Results

This subsection presents the results obtained during each of the two testing phases described above. Section 5.2.1 focuses on the validation of the prototypes’ feedback algorithms and general operation while Section 5.2.2 describes the results of each of the four modelled use scenarios, as well as a brief sensitivity analysis on key prototype parameters.

5.4.2.1 Prototype Validation

As described in Section 5.1, several components from the SmartEST laboratory were used to simulate production and consumption inputs in order to perform a simple test sequence for each prototype encompassing all of its system states. Figure 5.39 below shows the laboratory infrastructure and some of the user interfaces used during this phase.

Figure 5.39 SmartEST lab equipment during the testing phase. Clockwise from top: General test set-up (PV simulator can be seen on the left), data measurement interface, PV simulator interface.

The test sequences for all three prototypes successfully generated a set of production and consumption measurements which were converted to a progression of different LED properties. The results for each test sequence (visualised as a picture time-lapse) are described in further detail below:

Bodhi – Figure 5.40 shows how the prototype's lighting reacted to a gradual increase in cumulative energy consumption relative to an arbitrary energy budget, going from the 'under budget' state (left) to the 'on budget' (centre) and 'over budget' (right) system states.

Figure 5.40 Time-lapse showing Bodhi's lighting transitions through all three system states

CrystalLight – Figure 5.41 below shows different stages of the modelled charge/discharge cycle, where the prototype's LED brightness gradually increased before reaching its maximum intensity level, then becoming dimmer until the 'full discharge' state was attained.

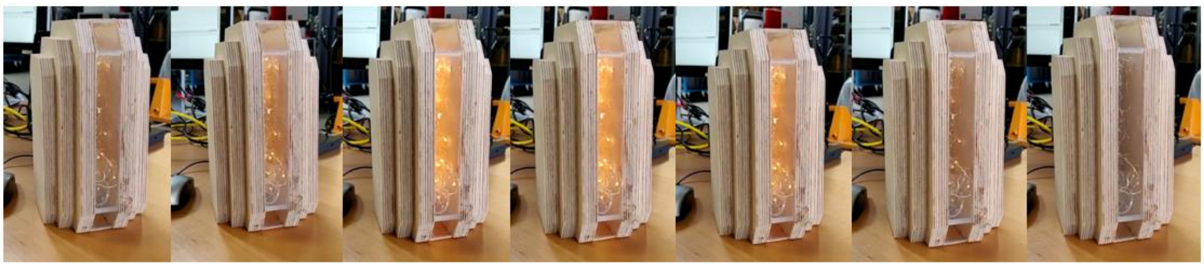


Figure 5.41 Time-lapse showing CrystalLight at different stages of a charge-discharge cycle

LightInsight – Both colour schemes previously shown in Figure 3.21 were evaluated, first increasing the value of R_E from 0.9 to 1.1 (Figure 5.42, pictures 1-3) and later decreasing it (Figure 5.42, pictures 3-5) back to its initial value.

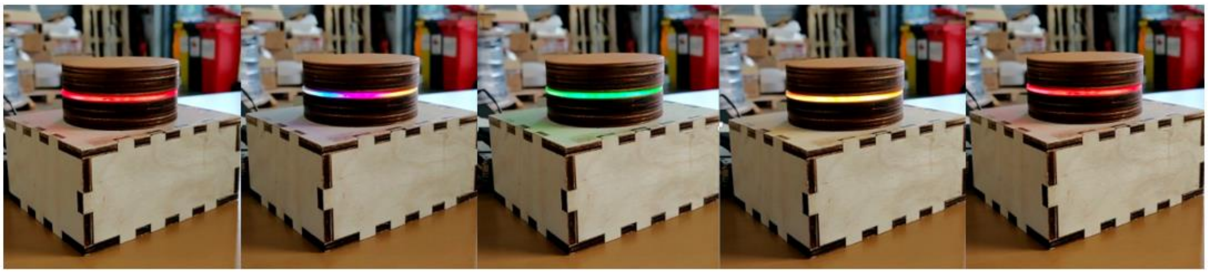


Figure 5.42 Time-lapse showing each of LightInsight's system states

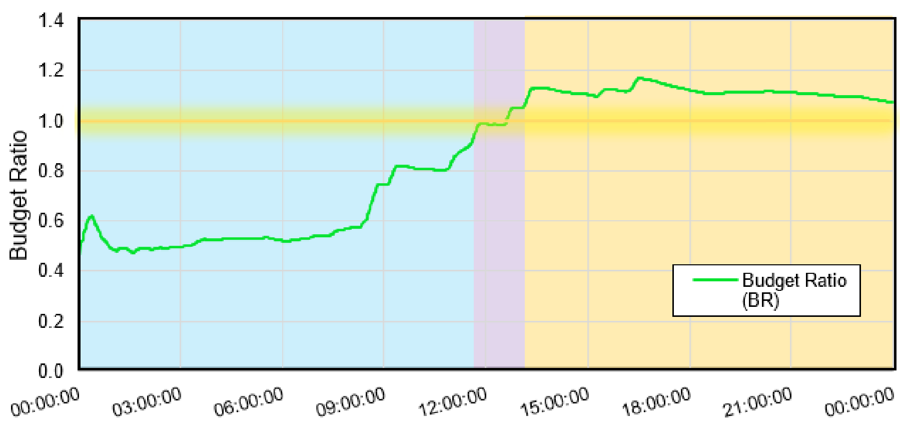
5.4.3 Use Scenario Simulation

This subsection presents the simulation results for the four modelled use scenarios, each covering all three prototypes, followed by a sensibility analysis which evaluated the impact key parameters such as *energy budget* (Bodhi), *battery capacity* (CrystalLight) and *transition range* (LightInsight) have on prototype feedback.

5.4.3.1 Scenario 1 – Summer Profile, Inadequate PV Production

Bodhi – The value of Bodhi's budget ratio throughout the day (see

BD Prototype - Scenario 1



below) showed a smooth transition through all three system states, starting significantly under budget (R_B < 0.95) and staying 'on budget' for a short interval before performing consistently over budget (R_B > 1.05) for the rest of the day. This is partly due to the shape of the budget ratio curve itself, which shows a clear upward trend lacking intervals with significant decreases in R_B, but the selected value for *B* also has significant impact on when these transitions take place; the effect of changing this parameter will be analysed in further detail later on.

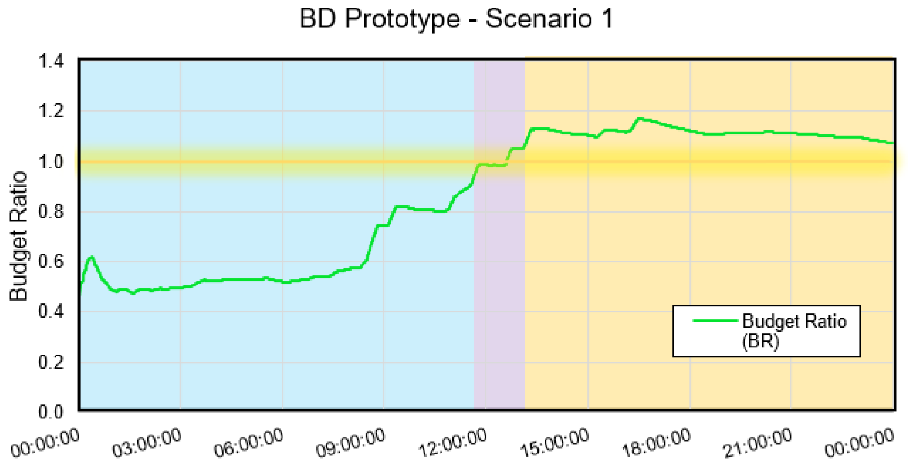


Figure 5.43 Bodhi (BD) prototype performance for Scenario 1. Background color corresponds to the light color shown by the prototype LEDs; the yellow line indicates the balance point between actual and planned consumption.

CrystalLight – This prototype spent the vast majority of the day at full discharge, only charging during a few short intervals between 7:30 and 11:00 where the maximum charge, set at 15 Wh, was quickly reached and then consumed. This should not be surprising considering that energy consumption consistently outperforms production in this scenario (see Figure 5.38, top left).

LightInsight – The 'red' LED state (i.e. consumption overtaking production) took place around 93% of the time, the only exception being several short periods in the morning as seen in Figure 5.45 below. These periods match the periods of fast charging previously seen for the CrystalLight prototype, with higher E_R values corresponding to faster 'battery' charging. The two proposed transition states (corresponding to 'rainbow' and 'yellow' LED lighting) were extremely rare, each occurring less than 1% of the time. This is due to the way R_E changed abruptly from one interval to the next, seldom falling within the transition range ($0.95 < R_E < 1.05$) which is caused by changes in consumption rather than production.

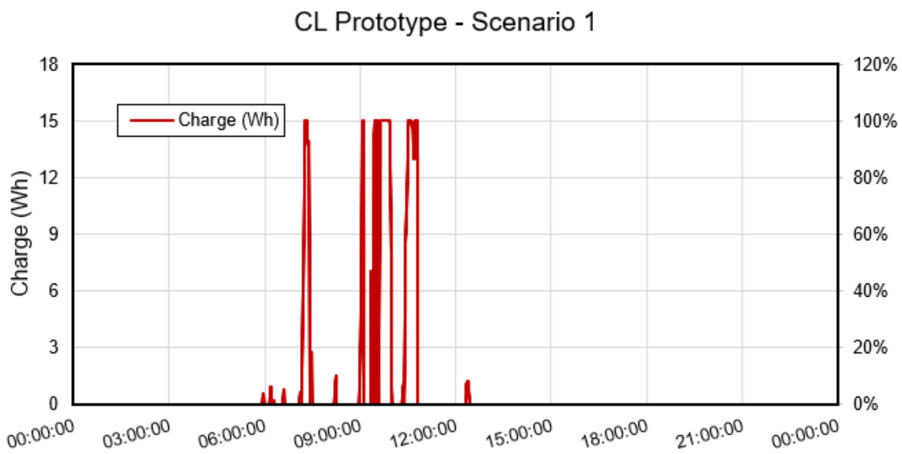


Figure 5.44 CrystalLight (CL) prototype performance for Scenario 1; LED intensity (corresponding to the prototype's state of charge) is shown on the right.

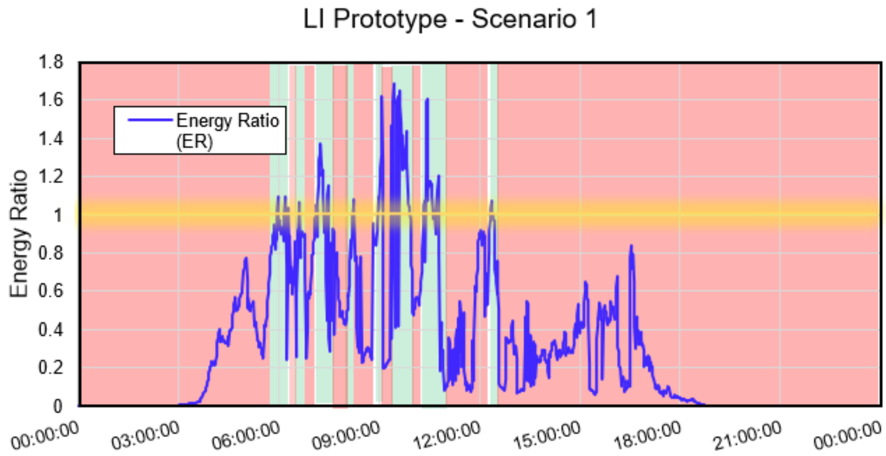


Figure 5.45 LightInsight (LI) prototype performance for Scenario 1. Background colour corresponds to the light colour shown by the prototype LEDs; the yellow line indicates the balance point between energy consumption and production.

5.4.3.2 Scenario 2 – Summer Profile, Adequate PV Production

Bodhi – Since the performance of this prototype depends on energy consumption only, results are exactly the same as those presented in Scenario 1.

CrystalLight – In this scenario, fast charging took place from 7:00 to 10:00, with the prototype fully ‘charged’ (C_{max} = 5000 Wh) for around five hours before gradually discharging for the rest of the day. As expected, performance was significantly better than in the previous scenario; the only times in which a full discharge occurred were the early morning hours where PV production had not yet started.

LightInsight – As expected from the increase in PV production, ‘green’ periods were much more frequent in this scenario, now amounting to around 40% of the day and lasting longer on average. The energy ratio was also significantly higher both on average (R_E = 1.7 compared to 0.3 from Scenario 1) and on its maximum range, with values exceeding R_E = 10 on several occasions. Transition states occurred even less frequently than on Scenario 1, both accounting for only 0.9% of the total intervals.

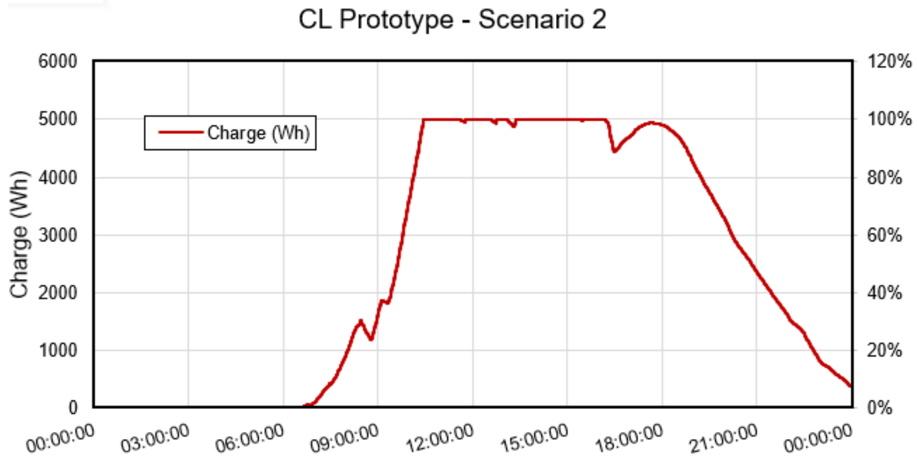


Figure 5.46 CrystalLight (CL) prototype performance for Scenario 2; LED intensity (corresponding to the prototype’s state of charge) is shown on the right.

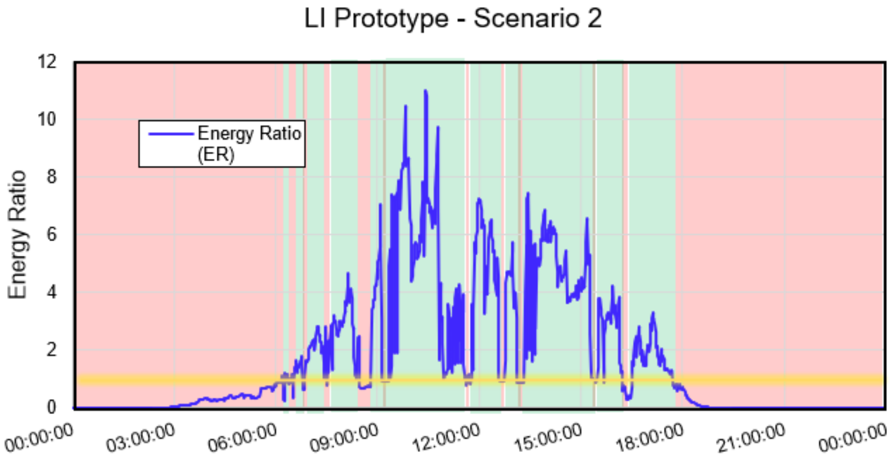


Figure 5.47 LightInsight (LI) prototype performance for Scenario 2. Background colour corresponds to the light color shown by the prototype LEDs; the yellow line indicates the balance point between energy consumption and production.

5.4.3.3 Scenario 3 – Winter Profile, Inadequate PV Production

Bodhi – This scenario presented a similarly increasing trend for the budget ratio throughout the day while showing even smaller decreases in R_B than the previous two cases. Once again, the energy budget was exceeded by the end of the day, although this occurred much later than during the summer; as was the case before, this greatly depends on the selected energy budget.

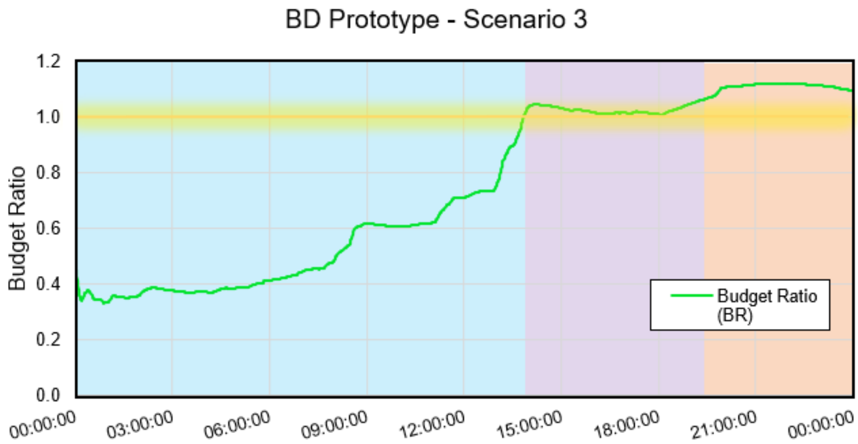


Figure 5.48 Bodhi (BD) prototype performance for Scenario 3. Background color corresponds to the light color shown by the prototype LEDs; the yellow line indicates the balance point between actual and planned consumption.

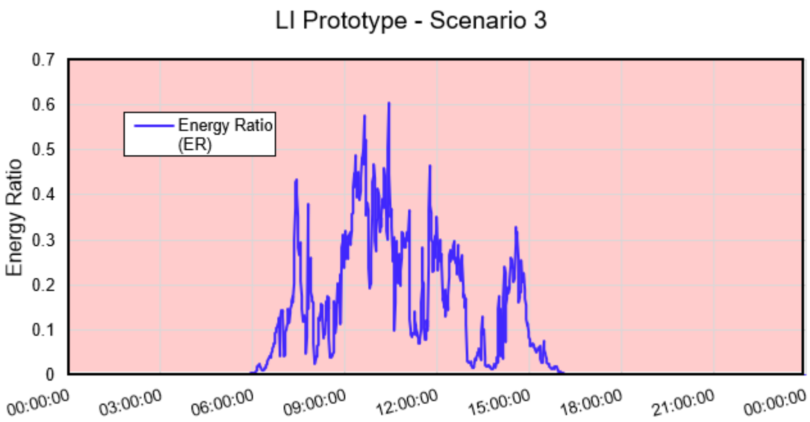


Figure 5.49 LightInsight (LI) prototype performance for Scenario 3. Background color corresponds to the light color shown by the prototype LEDs; the yellow line indicates the balance point between energy consumption and production.

CrystalLight – The combination of poor PV production and a high energy demand resulted in the prototype being fully discharged for the entire day; this means that from the user's perspective the lights would be constantly off.

LightInsight – The performance of this prototype confirms the observations made for CrystalLight; 'red' lights were shown the entire day with RE failing to approach the balance point; a maximum energy ratio of only 0.6 was reached.

5.4.3.4 Scenario 4 – Winter Profile, Adequate PV Production

Bodhi – Since the performance of this prototype depends on energy consumption only, results are exactly the same as those presented in Scenario 3.

CrystalLight – In a similar way to Scenario 2, the prototype went through a charge-discharge cycle during the daytime, with a second shorter charging phase in the early afternoon. The discharge phases were faster in this case, with the 'battery' emptying completely by 18:00. Maximum charge was set at 4000 Wh, which explains why the charging phase abruptly stopped at around 11:00; the effects of setting different values for this parameter will be explored during the sensitivity analysis later on.

LightInsight – This prototype showed similar behavior to that of CrystalLight, with a few hours around noon where 'green' state occurred with little to no interruption. Transition states were less frequent than in any other scenario, with only two 'yellow' intervals (0.14%) and one 'rainbow' interval (0.07%) during the entire day. Overall performance was significantly better than in Scenario 3 as expected but a better performance than in Scenario 1 was also achieved, showing that good PV production has a more significant impact in prototype feedback than an increase in household consumption.

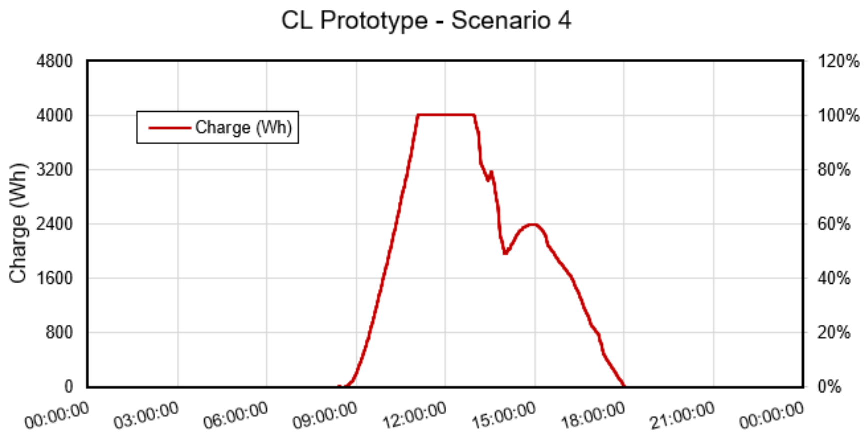


Figure 5.50 CrystalLight (CL) prototype performance for Scenario 4; LED intensity (corresponding to the prototype's state of charge) is shown on the right.

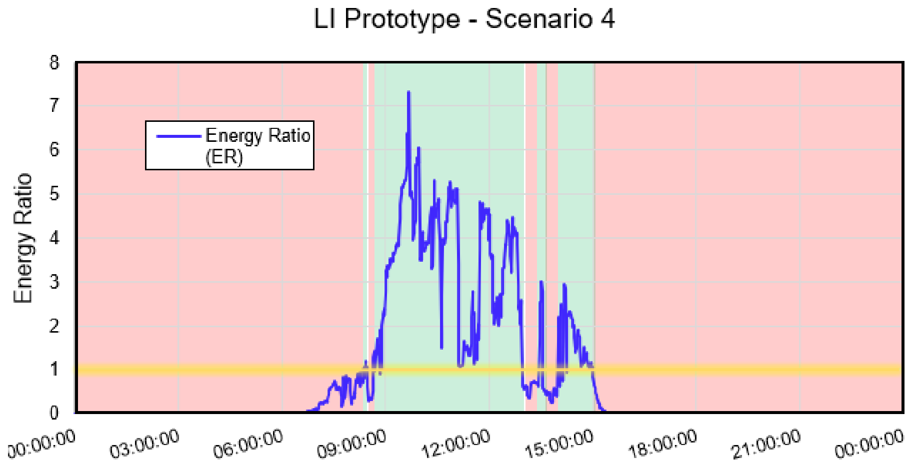


Figure 5.51 LightInsight (LI) prototype performance for Scenario 4. Background color corresponds to the light color shown by the prototype LEDs; the yellow line indicates the balance point between energy consumption and production.

5.4.3.5 Sensitivity Analysis on Key Prototype Parameters

The performance of all three SEPS concepts is partly dependent on some arbitrarily set variables, so a sensitivity analysis was performed in order to evaluate the impact changing key parameters such as *energy budget* (Bodhi), *battery capacity* (CrystalLight) and *transition range* (LightInsight) have on prototype feedback. A different scenario was selected for each prototype to assess the response of LED feedback to changes in each of these three variables:

1. Bodhi – Energy Budget (B)
Figure 5.52 shows how increasing or decreasing the previously selected energy budget for the summer load profile (Scenarios 1 and 2) resulted in a significant variation in the LED colours shown by Bodhi throughout the day, either modifying the length of each system state (Figure 5.52, bottom right) or not reaching one of the system states altogether (Figure 5.52, bottom left). The shape of the R_E curve is roughly the same for all three cases; the main difference lies in the fact that a lower budget shifts the curve upwards and a higher budget shifts it downwards. As a result, the curve crosses the balance threshold (indicated by a yellow line) at a different point of time.

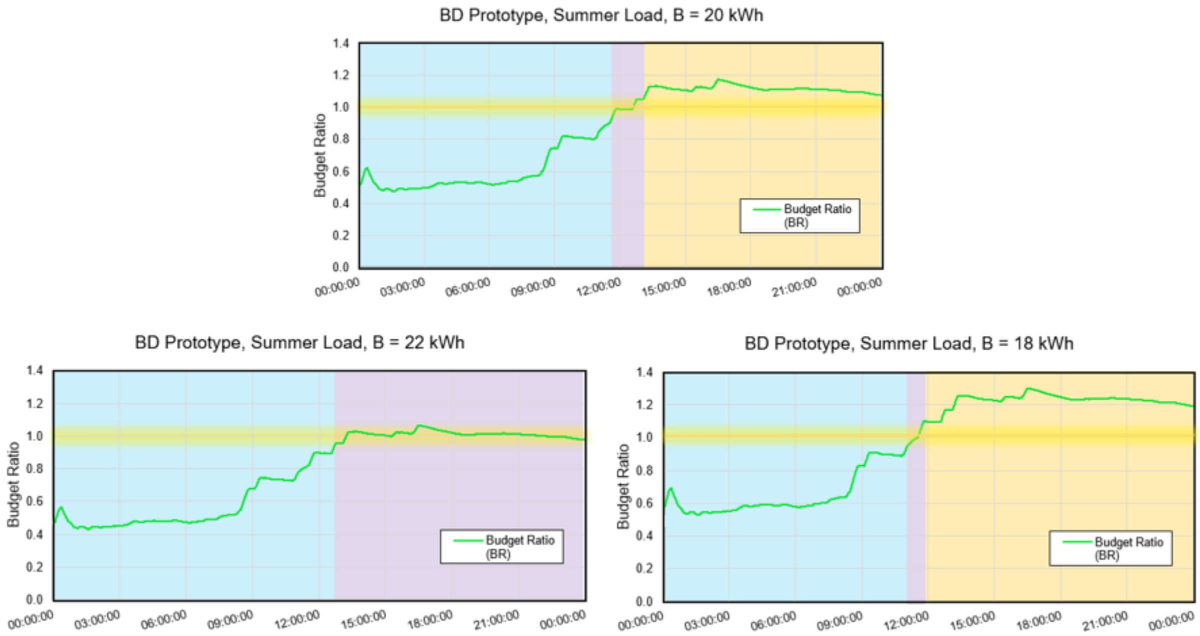


Figure 5.52 Bodhi sensitivity analysis using the summer use scenarios. Top: benchmark case (B = 20 kWh), bottom: 10% increase on B (left), 10% decrease on B (right).

2. CrystalLight – Battery Capacity (C_{max})
Scenario 4 was chosen to evaluate how the charge profile for this prototype reacts to changes in its maximum allowed charge. Figure 5.53 below shows the charge profiles for four different C_{max} values including the benchmark case (top right, C_{max} = 4000 Wh) and a limiting case where all of the produced energy is 'stored' in the battery (i.e. an "infinite capacity" scenario). There was a clear variation between all four profiles, with a lower C_{max} value correlating to a more pronounced charge 'clipping' when the full charge was reached. In all profiles the charging phase started exactly at the same time but discharging occurred at different intervals: the more energy stored, the later the discharging will take place. Since CrystalLight uses a simulated 'battery' rather than a physical one, there are no practical limitations for the value C_{max} can have. A higher C_{max} enables the prototype to 'store' more of the surplus energy but increasing this variable indefinitely can become counterproductive if the average LED intensity (corresponding to the state of charge) becomes too low and it becomes difficult for users to notice the prototype lighting. The ideal value for this parameter therefore lies around the highest point observed in the "infinite capacity" curve (Figure 5.53, bottom right), for values higher than this no additional energy will be stored and the average state of charge will only decrease.

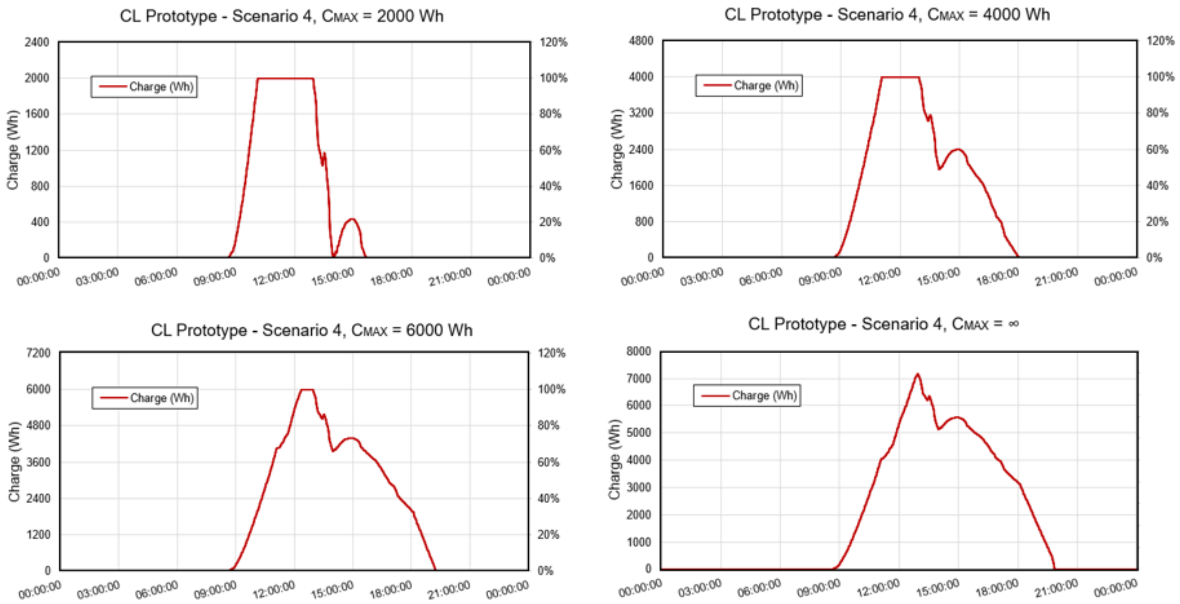


Figure 5.53 CrystalLight sensibility analysis in Scenario 4, showing increasing values for C_{MAX} and an "infinite capacity" case where all surplus energy is stored.

3. LightInsight – Transition Range

The prevalence of transition states (corresponding to yellow and rainbow LED lighting) depends on the size of the 'transition range' where these states can occur. Table 5.4 below shows the frequency for each system state with four different transition ranges.

Table 5.4 LightInsight sensitivity analysis showing the number of intervals and frequency for each system state with four different transition ranges, including the benchmark range (highlighted in green). All transition ranges are expressed as an interval defined around the balance point ($R_E = 1$).

System State	Transition Range							
	± 5%		± 10%		± 15%		± 20%	
	Intervals	*f*	Intervals	*f*	Intervals	*f*	Intervals	*f*
Red	1336	*92.78%*	1317	*91.46%*	1296	*90.00%*	1289	*89.51%*
Green	84	*5.83%*	80	*5.56%*	76	*5.28%*	73	*5.07%*
Yellow	9	*0.63%*	13	*0.90%*	17	*1.18%*	20	*1.39%*
Rainbow	11	*0.76%*	30	*2.08%*	51	*3.54%*	58	*4.03%*

The four analysed scenarios show that increasing the transition range has a positive impact in making transition states more frequent, although the extent at which this happens is still limited. In any case, an increase in the transition range presents a clear trade-off: while the aforementioned states may occur more frequently, users will need to change their consumption-production balance by a much larger amount to switch from one state to another which could prove too difficult to achieve in some circumstances.

5.4.4 Conclusions on SEPS Validation and Use Scenario Simulations

The operation of all three SEPS prototypes was successfully validated using equipment from the Smart-EST Lab, confirming that the scripts developed for each prototype can correctly interpret energy consumption and production inputs in order to give users simple, clear feedback into their household energy use. In addition to the prototype validation, four different use scenarios were modelled to visualise prototype performance in a wider range of testing conditions than those previously encountered during end user testing. This section will present several conclusions based on the results obtained for each testing phase.

The test sequences for all three prototypes were translated into a clear lighting sequence which confirmed that their feedback algorithms operate correctly, further supporting the results previously obtained in end user tests. It is worth noting that the tests only validated the operation of the *prototypes*, not the smart meters they will rely on for obtaining data from users' households. The test set-up used a highly accurate measurement system to provide the required inputs instead of a smart meter; this means that in practice feedback accuracy will mostly depend on the accuracy of the smart meters themselves.
It is also important to point out that one of the main challenges encountered during the laboratory tests was transmitting data from the measurement system to the prototypes. This issue was also encountered during end user testing, where data from household smart meters had to be periodically passed on to each prototype, and underscores the importance of reliable communication protocols as well as adequate database management and storage.
Regarding the *simulation of use scenarios*, the behavior of some prototypes roughly matched the patterns observed during end user testing (e.g. LightInsight), while others showed more significant variations (e.g. Bodhi). In either case, the operation period analysed in these simulations was of one day only which is a relatively short period of time so it is not possible to conclude whether they significantly represent the simulated conditions. Furthermore, the modelled scenarios lack the impact of user response to prototype performance which is one of the central design components of these SEPS concepts. Despite these limitations, the modelled scenarios provide valuable insights into some of the issues these SEPS could encounter in these situations. For instance, both the CrystalLight and LightInsight prototypes would show no changes in feedback during winter days with poor PV production so an alternative algorithm should be designed to ensure some other useful information is shown during these periods.

A sensitivity analysis provided additional information into the impact some key parameters have on prototype feedback. The three parameters analysed need to adapt to some extent to user behavior or system performance; for instance, Bodhi's energy budget should motivate users to decrease their cumulative consumption by a certain amount while CrystalLight's battery capacity performs best when matching the maximum stored charge during a given day. Estimating these parameters using historical data or forecasting could significantly improve the quality of feedback presented to users.

5.5 General Conclusions : SEPS Design Guidlines

Based on the observations made for the tested SEPS prototypes and the key factors identified in the previous section, a series of general conclusions on how to design SEPS more effectively will be proposed in this section. These conclusions will be presented as a set of guidelines for designing future SEPS which can be successfully accepted and implemented by end users**:**

1. **If you think it's simple, it might not be simple enough**
   Sustainable energy use at home is a relatively new concept and most users will probably be unfamiliar with many of its underlying technologies and principles; this will be particularly the case with users from a non-technical background. For this reason, SEPS design should focus on simple solutions that can be easily understood and applied by a wide range of users while still achieving their intended purpose. One way to do this is to think of concepts that have a more limited scope at first and gradually become more complex as people get acquainted with them and learn how to use them more effectively.

2. **Consider the complexity of energy use in households**
   The tests carried out during this project showed that households are uncontrolled environments with a significant number of factors impacting energy use, such as the number and type of appliances they contain, weather conditions and the daily routines of their inhabitants. SEPS will therefore need to be able to adapt to this broad range of conditions by either reducing total energy use or shifting demand to times of high renewable production. Of these two goals, load shifting seems to be more difficult to achieve, mostly because the use of several household appliances (e.g. EVs, washing machines, kitchen appliances) has a strong dependence on the time of day. However, since these appliances consume a significant fraction of a household's total energy, any steps towards these goals could have a considerable impact in making the residential sector more sustainable.

3. **Adapt to a wide range of behavioral patterns and interpersonal dynamics**
   Energy use in households with multiple members also involves complex interpersonal dynamics where no member holds complete control over how energy is used. In addition to households with different attributes, SEPS need to be flexible enough to adapt to households with groups of different sizes and structures (e.g. families, couples, etc.) and to users with different routines and behavioral patterns. The incentives used to encourage sustainable energy use need to be flexible as well since some users in a household are likely to respond better to a given incentive while the rest will not.

4. **Think about potential rebound effects and long-term impacts**
   SEPS have been proven to cause a 'rebound effect' where the same incentives that push people to use energy more sustainably in some cases might push them in the opposite direction in others. This was observed, for instance, during end user tests where one of the prototypes encouraged users to increase their energy use instead of decreasing it. SEPS design needs to anticipate these situations and prevent them from taking place. In addition to rebound effects, it is important to consider there can be long-term outcomes which may take weeks or even months to become apparent; these include seasonal energy use patterns and decreasing SEPS engagement over time, among others.

5. **Include other disciplines and involve potential users early on in the design process**

   The design innovation methods analysed in this project provide useful tools for helping designers develop new SEPS, but this process needs to get potential end users involved as early as possible. Focus groups, interviews, user testing and similar techniques can prove key in bridging the gap between what designers have in mind when creating SEPS and what users expect from them. Furthermore, the development of smart home technologies is a wide topic spanning many different research fields so it is important to adopt a more multidisciplinary approach in their design. Disciplines like computer science, electrical power engineering and behavioral sciences can all provide a better understanding of how to make more effective SEPS and ensuring active involvement from users, making them a valuable addition to the design process.

6. **Give users (the feeling of) control**
   The literature review and the presented experimental work revealed the importance of control (and its perception) in increasing user involvement with SEPS. For instance, user tests showed that one of the issues with SEPS involving energy production is that users felt they had no influence in its performance; this perception can have a long-lasting impact in how, and if, users engage with the SEPS. SEPS must be designed so that users feel in control while trying not to overwhelm them with constant decision-making; a possible solution to this is to design SEPS that can switch between different levels of autonomy so that different functions can be automated if users decide to delegate more decisions to the SEPS.

7. **SEPS appearance has a big impact (but it may not last for long)**
   As with any other product or service, the visual appearance of SEPS plays an important role in capturing users' interest and determining how much they interact with it. The visual appeal of SEPS also seems to have the added benefit of constantly reminding users of being more sustainable at home, as observed during the prototype tests. However, this interest will decrease with time as users become accustomed to have the SEPS around which underscores the importance of finding how to keep people engaged with the product after the initial interest fades off.

8. **Data acquisition and management are essential**
   Many SEPS depend on measuring variables such as energy flows, temperature and time of day, which are then used to determine the actions the SEPS needs to perform. For this reason, it is essential to consider how (and what kind of) data will be obtained, processed and managed and which tools will make these processes possible. Additionally, data access policies should be assessed as well, both regarding which information should be presented to users as well as how and who will store this information.

9. **Use information to guide users in the right direction**
   While user awareness will most likely increase with basic insights into energy use, this information alone is not enough for users to decide how to change their energy consumption. More in-depth knowledge (e.g. how much energy a given appliance or device uses) could provide users with the right tools to achieve this but it is important to avoid making this information too technical while still providing enough context for users to use it adequately; advice and should ideally become more elaborate with time as users become familiar with the SEPS.

   In addition to the nature of the information provided, how this information is provided is also important. Real-time data has the advantage of being more visible to users, encouraging experimentation from them to see the response of different actions on SEPS performance. Historical data might also be helpful for evaluating the impact of SEPS on the longer term, but its usefulness is more limited.

10. **Seek to foster interaction between stakeholders**
    SEPS have the potential to involve many different stakeholders apart from the users themselves: energy companies, local authorities and other households all have a key role in making the residential sector more sustainable. SEPS designers should try to build synergies between stakeholders so that they work together towards achieving the goal of a given SEPS. These synergies should not be limited to the design or use of SEPS either; collaboration between stakeholders can result in more successful diffusion strategies for persuading users to adopt a new SEPS as well. A key element for establishing these partnerships is determining who bears the main responsibilities, costs and potential benefits of sustainable energy use; this will help identify the motivations and concerns of each interest group.

11. **Manage user expectations**
    Many existing SEPS have focused on setting high expectations on their performance, particularly regarding energy savings and the financial gains associated with them. While this might in principle make the SEPS more attractive to potential users, if these expectations are not met users will be disappointed and discouraged from using this (or any) SEPS in the future. For this reason, special care should be taken in setting clear, more realistic expectations that focus on several potential benefits. It is important to consider that people will have different levels of commitment with SEPS and different motivations for using them beyond financial incentives or comfort.

12. **SEPS can focus on more than sustainability**
    Smart home technologies can achieve other objectives beyond a more sustainable energy use, such as increasing user comfort, improving home security and reducing dependence on energy companies. These objectives can also be used as incentives for attracting potential users or increasing user engagement with SEPS at home but this does not mean that that the sustainability goals of SEPS should be sidelined: sustainable energy use still needs to play a central role in SEPS design even if it is not the main selling point from the user's perspective. The key to achieving this balance is to find how to align these objectives with sustainable behaviors so that both goals are reached simultaneously.

The presented guidelines can be classified into four main SEPS design areas: *technology and design*, *information*, *co-evolution* and *users*. Applying each guideline requires a different interaction between these areas as seen in Figure 5.54 below.

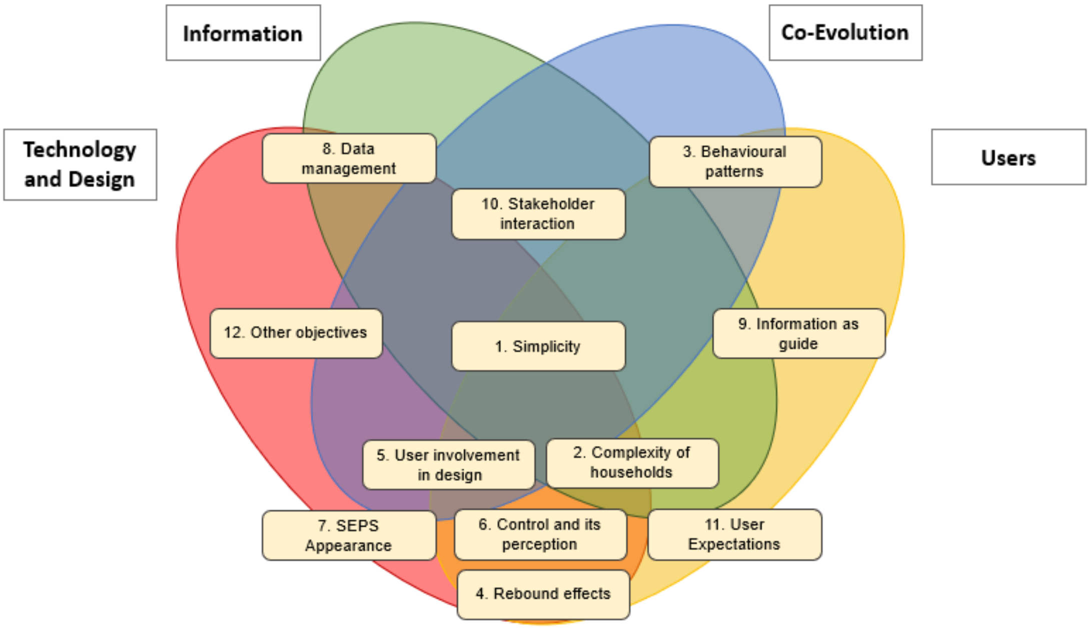


Figure 5.54 Summary of design guidelines and their relationship with the four SEPS design areas

5.6 Conclusions

In this section, the results obtained in the end-user tests, prototype validation and use scenario simulations of the developed SEPS prototypes will be analysed in order to identify some of the key factors that determined whether they were successfully implemented by end-users for making residential energy use more sustainable. Based on these conclusions which are specific to the tested SEPS, a set of guidelines for 'good' SEPS design will be proposed. These guidelines are intended to serve as general recommendations for designers to apply in the design of any future SEPS.

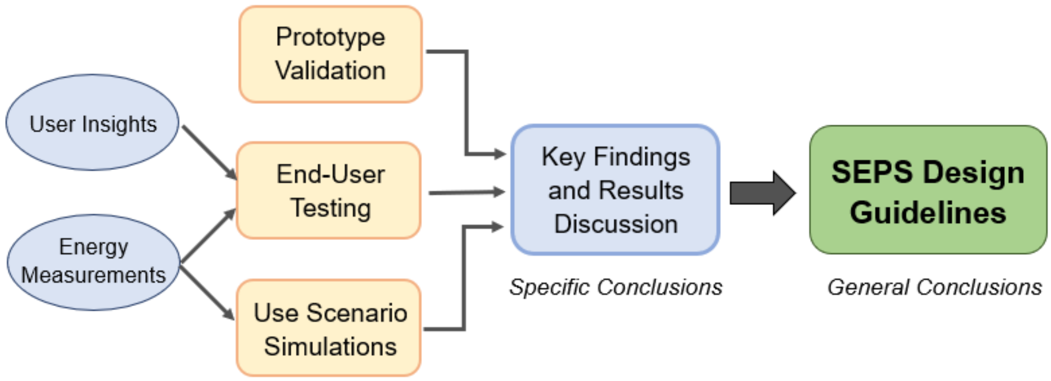


Figure 5.55 Final analysis and conclusions flowchart

In this chapter, the key insights gained from the experimental work will be discussed in Section 6.1 along with the identification of factors which determined the success or failure of the tested SEPS prototypes. This section will present the list of SEPS design guidelines proposed as a result of this analysis, while Section 6.3 will introduce several topics recommended for further research.

5.6.1 Key Findings and Results Discussion

This section will summarise some of the key insights and limitations observed during the end user testing and validation tests of the three developed SEPS concepts as well as discussing the factors that determined whether they succeeded in their purpose.

During the end user tests, users were observed to have different levels of engagement with the tested SEPS and different motivations for doing so, and any changes to their usual behavior were hard to achieve. The number of people living in a given household also had a strong impact on the relationship between users and the SEPS: the higher the number of people living in a household, the more complex these interactions became.

Although the SEPS prototypes tested were intended to be simpler and more intuitive than conventional smart home technologies, users initially struggled to understand how they worked but eventually learned how to interpret the feedback shown by the prototypes. The insights into energy production and consumption offered through the user interface and the prototypes proved insufficient for helping users find the best way to change their behavior, demonstrating the need for providing end users with more detailed information on their energy use at home.

Two of the three developed prototypes were tested by users: the LightInsight prototype was tested in one of the studio apartments in the Green Village while Bodhi was tested in a stand-alone house in Enschede. The LightInsight prototype proved ineffective in changing energy use, with no significant shifting towards high PV production times and consumption increasing instead of decreasing (Figure 5.56, left). Furthermore, users realised energy production was not in their control which made them feel 'powerless' even though they still had some influence on prototype performance by modifying their consumption.

End user tests on the Bodhi prototype (Figure 5.56, right), on the other hand, resulted in a significant decrease in average daily consumption although due to the length of the testing period it remains unclear whether this was caused by the SEPS or if other factors had an influence. The energy budget proved to be a key factor since the selected budget led to a single system state dominating the majority of of the testing period; this underscores the importance of developing feedback algorithms which adapt to changes in user consumption in order to set more accurate values for this parameter.

It is important to consider that the results obtained during these tests were limited both by the short duration and the small sample size used, which may have been unable to identify some long-term trends or behavioral patterns. Conducting more extensive testing would help obtain more representative insights into residential energy consumption to further improve SEPS effectiveness.

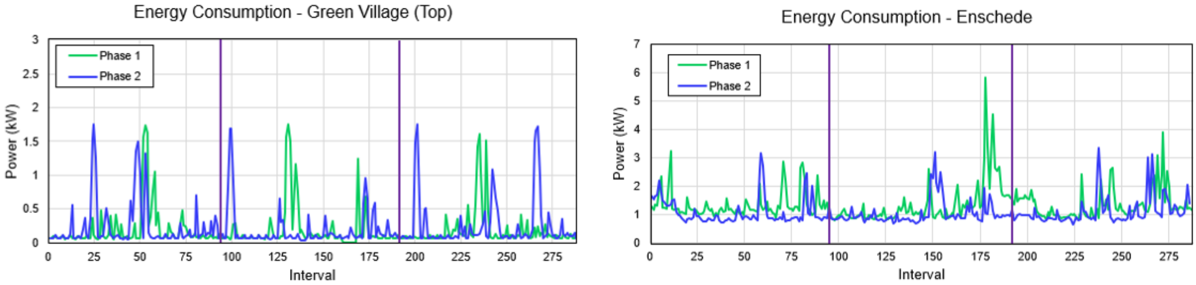


Figure 5.56 Energy consumption profiles from the Green Village (left) and Enschede (right) testing sites, with Phase 1 results shown in green and Phase 2 results shown in blue

In addition to end user testing, the prototype algorithms were validated using a simulated PV generator and a controllable load. These tests confirmed that all three prototypes correctly interpreted energy production and consumption data in order to set their LED properties according to a particular system state.

Several use scenarios for each SEPS were simulated as well, which helped visualise how the prototypes would perform in situations not seen in end user tests and some of the potential issues that could limit their effectiveness. For instance, both the CrystalLight and LightInsight prototypes would show no changes in feedback during winter days with poor PV production so an alternative algorithm should be designed to ensure some other useful information is shown during these times. A sensitivity analysis on some of the key SEPS operation parameters further showed that these variables need to adapt to user behavior or system performance to improve the quality of feedback presented to users.

While these results offer a good first approach for evaluating prototype performance, just like with the end user testing these simulations only covered a very short period of time due to limited data availability; using larger datasets to simulate longer periods of time would provide a more accurate representation of the modelled operating conditions.

Based on this analysis, it was possible to identify several factors that determined whether the prototypes succeeded or failed in achieving their purpose during the end user and validation tests:

- **Ease of Use**: This refers to both the difficulty of the learning curve users went through to understand how the prototypes worked and the degree of control required from users needed to operate them.
- **User Attributes:** These include the number of household members, the relationship between them and each member's motivations while using SEPS.
- **Data Source**: The three SEPS concepts relied on smart meters to obtain energy data, meaning that feedback greatly depended on the accuracy and reliability of the smart meters themselves.
- **Visual Appeal**: The prototypes' appearance (as well as their location) had a significant impact on how often users interacted with them and whether there was a response to this interaction.
- **Feedback**: The amount of information provided to users, as well as the knowledge required to put it in context, was crucial in determining how users reacted to SEPS during tests.
- **Flexibility:** the tested prototypes had to operate in different use conditions which depended on a wide range of variables and changed constantly with time.

6 DISCUSSIONS, CONCLUSIONS AND RECOMMENDATIONS FOR FUTURE RESEARCH

6.1 Discussion, conclusions and recommendations for future research

TThe ERA-Net Smart Grids Plus project CESEPS “Co-evolution of smart energy products and services” took place between the beginning of 2016 and ended in January 2019. This project which comprised a transnational collaboration between the Netherlands and Austria envisioned to explore existing smart grid environments by evaluating the performance of smart energy systems in relation to the energy products and services used as well as stakeholder processes and end-users perceptions. This has been done for real cases with actual users, called smart grid pilots, and for newly designed pilots on campuses and also with the support of a virtual context by use of a co-simulator in one of the labs of the partners. The research was embedded in the three-layer framework of the European ERA-Net Smart Grids Plus program and as such interdisciplinary by nature. The three layers focused the research on new energy technologies, markets and stakeholders in the context of smart grid environments. In practice the three layers were embedded in several work packages (WP’s) which cover the complete smart grid environment according to this model, namely WP2 on Marketplaces, WP3 on Stakeholders, WP4 on Technologies and WP5 on Smart Energy Products and Services.

The multidisciplinarity of this project led to many diverse results originating from data analyses of measurements in smart grid pilots, interviews and surveys of stakeholders and end-users, simulations of energy systems in the context of energy markets and product design activities for the development of smart energy products. This myriad of results has been presented in this report however in this final section we would like to summarize the most important findings, namely:

WP2 on Marketplaces: National regulations, policy and market incentives play a major role in inertia around implementation of mature smart grid solutions in both Austria and the Netherlands. Therefore based on our research we advise to pay more attention to reducing cross border barriers in Europe around energy regulations and energy policy. This will involve multiple stakeholders.
WP3 on Stakeholders: Public organizations and grid operators, play a more dominant role than energy companies in smart grid development, but the expectations of DSOs and consultants about a flexibility market have so far remained unfulfilled. End users are very interested in renewable energy but in order to develop successful smart grid environments, we shouldn’t address users not just as energy consumers, but also as managers of local energy systems, meaning they would gain decision making power, to learn about their role as empowered co-providers.
WP4 on Technologies and Methods: Based on the research conducted in this project we can conclude that from a technical point of view the new smart energy systems which have been applied in various pilots perform well and reliably and can therefore be used as expected for distributed power generation as well as demand side management. Hence they can contribute to self-sufficient renewable energy systems. Flexibility in relation to the local use of renewable energies has been extensively discussed in this report. By applying energy storage at a community level and by regionally sharing renewable energy, the flexibility of local power grids can become very high.
WP5 on Smart Energy Products and Services: Smart energy products and services should provide the feeling to end users of being part of the renewable energy systems rather than having an interaction with black box technologies. Therefore we recommend to develop energy systems, products and services that consumers want to use and can understand.

During the project the three layer model helped to form a common language between different disciplines, and increased the knowledge about different aspects of smart grids. The renewable energy transition is a multidisciplinary problem with various stakeholders, with considerable dependencies on geography and regulations, which require complex and complete solutions in order to become feasible and widespread applicable. Therefore, we would like to recommend that multidisciplinary approaches such as the three layer model will become more established in the development of smart grid environments.
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Disclaimer

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Angèle Reinders studied Experimental Physics at Utrecht University, where she also received her doctoral degree in Chemistry in 1999. She's a co-founding editor of IEEE Journal of Photovoltaics and involved in various Photovoltaic Specialists Conferences which she chaired in 2017. In the past years she has published two books namely "The Power of Design: Product Innovation in Sustainable Energy Technologies" and "Photovoltaic Solar Energy: From Fundamentals to Applications" and she has authored more than 100 peer-reviewed papers.

Cihan Gercek is a postdoc researcher and the assistant manager of CESEPS at University of Twente. He had received his PhD in Electronic Systems from the University of Lorraine and Institute Jean Lamour (CNRS) and his MSc in Electrical Engineering from the University of Lyon. His interdisciplinary research involves analysis of big data originating from the performance of existing smart grid pilots and design-driven research on smart energy products and services. His aim is to boost the energy transition, the smart energy innovation process and the smart grids respond to the demands of stakeholders in terms of performance, cost-energy efficiency, reliability and end users' comfort.

Carla Robledo is a postdoc researcher with solid academic preparation holding a PhD in electrochemistry from the University of Cordoba in Argentina. Her research interest lie on sustainable energy carriers, such as hydrogen and lithium-ion batteries. She is a fellow researcher at the Future Energy Systems group at Process & Energy Department in TU Delft. Her current research focuses on experimental evaluation of hydrogen fuel cell electric vehicles connected to the grid, via vehicle-to-grid (V2G) technology and system modelling of smart grids incorporating these vehicles in V2G.

Barbara van Mierlo is associate professor, working as a sociologist at the Knowledge, Technology and Innovation Group of Wageningen University. She studies processes of transformative, systemic change towards sustainability and their intersection with everyday social practices. Being actively engaged in these processes, special interests include the significance and features of interactive learning and discursive strategies, the value of change-oriented evaluation, emergence of reflexivity, responsible innovation, and transdisciplinary collaboration. This research takes place in diverse domains, such as energy, health care and agriculture. She has developed the methodology of Reflexive Monitoring in Action (RMA), which has a wide international uptake in among others sustainable agriculture, natural resource management, renewable energy and health.

Hilde Brouwers graduated in Development and Rural Innovation in 2018 at Wageningen University. After enjoying her Master thesis, which focused on niche activities and changing practices in the pharmaceutical sector, she stayed at Wageningen University to continue conducting research for the CESEPS project. Key focus areas of her are: relations between stakeholders, users' interaction with technology and group processes that play a role in technology acceptance or interventions.

Esin Gültekin received her degrees in Industrial Engineering and Management Sciences (BSc) and Innovation Sciences (MSc) both from the Eindhoven University of Technology. She graduated with a MSc thesis about Innovation Ecosystems and the predicate 'with great appreciation'. In CESEPS she worked in the work package of Stakeholders and Users.

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Wouter Schram is PhD candidate of Copernicus Institute of Sustainable Development of Utrecht University. In his research he investigates the implementation of photovoltaics (PV) in the Low-voltage grid. Battery storage on household and community level are assessed from a technical, economic and environmental perspective. For example, they determined the optimal battery size for various PV households in the Dutch city Amersfoort, and quantified the peak shaving potential of these batteries. Also, they perform multi-objective optimization of Community Energy Storage, thereby determining the trade-offs between economics and the environment when operating a battery.

Ad van Wijk is sustainable energy entrepreneur and part-time Professor Future Energy Systems at TU Delft, the Netherlands. He also works for KWR Waterresearch Institute to develop and implement the research program Energy and Water. And he is appointed at the 'New Energy Coalition' to realize the green hydrogen economy in the Northern Netherlands. In 1984, van Wijk founded the company Ecofys, which eventually grew into Econcern. Econcern developed many new sustainable energy products, services and projects. Examples include the 120 MW offshore wind farm Princess Amalia in the North Sea, several multi-MW solar farms in Spain and a bio-methanol plant in the Netherlands, which is the largest second-generation biomass plant in the world. Van Wijk achieved many important prizes for excellent entrepreneurship. Amongst others he was Dutch entrepreneur of the year in 2007 and Dutch top-executive in 2008. At TU Delft van Wijk focuses on the energy systems of the future. His research is mainly on techno-economic analysis of hydrogen and fuel cell cars in smart cities and smart grids. He has founded The Green Village as the living campus of the TU Delft. Van Wijk has published a very readable book 'How to boil an egg' and he has written the books 'Welcome to the Green Village', 'Our Car as Power Plant' and '3D printing with biomaterials', 'The Green Hydrogen Economy in the Northern Netherlands and 'Solar Power to the People'.

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9 APPENDIX

Appendix A: List of the Dutch residential smart grid projects (Brouwers & van Mierlo, 2018a)

Name project	*Location*	*Start date*	*End date*	*# households*	*Subsidized or paid by*	*Features smart grid system*
Smart Grids Brabant	Den Bosch (Maarspoort)	2008	2011	34	Consortium partners	A renewable energy source (unspecified), smart meters and smart EV charging poles.
PowerMatching City	Hoogkerk	2009	2010	22	European Commission (no. FP6-038576)	Domestic solar panels and batteries, electric scooters, smart heat pumps, smart washing machines and a PowerMatcher (software system that matches energy supply and demand). Smart meters, feedback via tablet.
Smart Grids Brabant	Den Bosch (Geerpark)	2010	2013	NI (aim: 400)	Costs are part of building plan	Households are able to choose sources of renewable energy, smart meters are installed and smart charging poles.
Profit for all - Amersfoort	Amersfoort	2011	2015	100	Utrecht Economic Board	Domestic solar panels, with households being able to choose 4 smart appliances. Smart meters were provided and demand was shifted by flexible tariffs.
Profit for all - Utrecht	Utrecht (Lombok)	2011	2015	NI	Utrecht Economic Board	Domestic solar panels, with households being able to choose 5 smart appliances. Households made use of electric cars. Smart meters were provided and demand was shifted by flexible tariffs.
Hoog Dalem: all electric	Gorinchem	2011	2017	42	Consortium partners	Domestic solar panels (owned by residents), with household batteries. Semi-automated smart washing machines, dish washers and automatic heat pumps.
PowerMatching City 2	Hoogkerk	Jan. 2012	Jan. 2015	40	Agentschap NL (IPIN)	Domestic solar panels, batteries, electric scooters, smart heat pumps, smart washing machines, a PowerMatcher (software system that regulates energy supply and demand). Smart meters and feedback via tablet.
Heijplaat Energie-neutraal	Rotterdam	Jan. 2012	Jan. 2015	180	Agentschap NL (IPIN)	Domestic solar panels via housing corporation. No smart appliances, only use of a smart meter.
Couperus Smart Grid	Den Haag	Jan. 2012	Jun. 2015	288	Agentschap NL (IPIN)	Wind energy via an energy company. Makes use of automated smart heat pumps.
Smart Grid	Lochem	Jan. 2012	Sept. 2015	170	Agentschap NL (IPIN)	Domestic solar panels and invested in a collective solar park. No smart appliances, use of smart meters and feedback on energy levels via an app.
Intelligent Network & Energy transition	Zeewolde	Jan. 2012	2016	NI (aim: 4000)	Agentschap NL (IPIN)	Collective solar panels, wind energy and use of biogas. All smart appliances are used, are automated via an energy management system and controlled on the basis of flexible tariffs.
Cloud Power Texel	Texel	Apr. 2012	Jan. 2015	300	Agentschap NL (IPIN)	Collective solar panels and wind energy. No smart appliances, users get a message when energy levels are high and are motivated by flexible tariffs.
i-Balance	Hooghalen	Sept. 2012	Sept. 2015	50	**Ministry Economic Affairs-RVO**	Domestic solar panels and collective wind energy. Fuel cells and electric vehicles act as storage technologies.

Name project	*Location*	*Start date*	*End date*	*# households*	*Subsidized or paid by*	*Features smart grid system*
Your Energy Moment	Zwolle	Dec. 2012	Dec. 2015	212	Agentschap NL (IPIN)	Domestic solar panels, semi-automated smart washing machines and tumble dryers. Also feedback via smart meters and an app, and flexible tariffs.
MeppelEnergy	Meppel	Jan. 2013	2033	NI (aim: 3 400)	Ministry Economic Affairs-RVO, TKISG01005	Biogas that generates electricity when supply is low. Automated smart heat pumps.
Your Energy Moment	Breda	Mrt. 2013	Aug. 2015	150	Agentschap NL (IPIN)	Domestic solar panels, semi-automated smart washing machines and tumble dryers, and automated heat pumps. Also feedback via smart meters and an app, and flexible tariffs.
EnergySense	Netherlands	2014	2024	NI (aim:10 000)	European Regional Development Fund	Initiated by Groningen University and Energy Academy Europe, who conduct research on energy usage in several areas in the Netherlands. Households can participate if they have a smart meter.
Samen Slim met Energie	Haaren	2015	2016	104	Consortium partners	Collective solar panels, no smart appliances or storage technologies. Only use of smart meters, an online platform with advice and a game app that makes people aware of energy.
Autonomous Energy District 2	NI	2015	2020	NI	Consortium partners	Renewable energy is not required. Households have a battery and fuel cells. Demand management features are unknown.
Your Energy Moment 2.0	Breda	2016	2018	90	Consortium partners	Domestic solar panels, semi-automated smart washing machines and tumble dryers, and automated heat pumps. Also feedback via smart meters and an app, and flexible tariffs. In this version of the project, 39 households were provided a storage battery.
Bothoven	Enschede	2016	2040	NI (aim: 2000)	Municipality Enschede & two local housing corporations	Renewable energy is not required and no use of storage technologies or smart appliances. Users can decide this themselves. Demand is only managed by smart meters.
City-Zen	Amsterdam	2016	n.d.	25 (aim: 50)	Consortium partners	City-Zen makes use of a virtual power plant. Households can trade energy with prices based on supply and demand. Households are able to generate electricity via domestic solar panels and store their own energy in batteries when electricity is cheap.
Schoonschip	Amsterdam	2016	n.d.	46	Residents	Schoonschip is a starting project with a citizen initiative concerned with building its own district with one connection to the central power grid. Many renewable energy sources, storage technologies and smart appliances are expected to be used.
Your Energy Moment 2.0	Etten-Leur	Jan. 2017	2018	17	Consortium partners	Wind energy via an energy company, which can be stored in a collective battery. No smart appliances, use of feedback via smart meters and an app, and flexible tariffs.
Energiekoplopers	Heerhugowaard	2015	2016	203	Agentschap NL (IPIN)	Domestic solar panels and makes use of electrical boilers, fuel cells (for 5 households) and virtual fuel cells (for 9 households, this is combined with a virtual power plant). Automatic smart heat

Name project	*Location*	*Start date*	*End date*	*# households*	*Subsidized or paid by*	*Features smart grid system*
						pumps and solar panel switches match supply and demand.
Collective Battery Rijsenhout	Rijsenhout	2017	2018	35 (aim: 585)	Alliander	Solar panels and a collective battery for all households. An energy management system matches supply and demand, feedback via meters and an app.
Energiekoplopers 2	Heerhugowaard	Dec. 2017	2019	100+	Consortium partners	Domestic solar panels and makes use of electrical boilers, fuel cells (for 5 households) and virtual fuel cells (for 9 households, this is combined with a virtual power plant). Automatic smart heat pumps and solar panel switches match supply and demand. In this edition of the project batteries are provided.
Gridflex Heeten	Heeten	2017	2020	47	Consortium partners	No smart appliances, but flexibility is combined via an aggregator. Users are involved via an energy cooperative.
Enercons (1)	Enschede	2017	n.d.	NI	Consortium partners	Renewable energy, storage technologies and smart appliances can be different for each household. Enercons makes use of the Lyv Smart Lyving home energy management system in which the end user can connect all devices.
Enercons (2)	Haarlemmermeer	2017	n.d.	35	Consortium partners	Renewable energy, storage technologies and smart appliances can be different for each household. Enercons makes use of the Lyv Smart Lyving home energy management system in which the end user can connect all devices. In this location, if users want to make use of a collective battery, data about energy usage in the energy management system must be shared with a central operator.
Lyv Smart Lyving	Rotterdam	2017	n.d.	NI	Consortium partners	Renewable energy, storage technologies and smart appliances can be different for each household. Enercons makes use of the Lyv Smart Lyving home energy management system in which the end user can connect all devices. In this location, if users want to make use of a collective battery, data about energy usage in the energy management system must be shared with a central operator.

Appendix B. User Questionnaire

Questionnaire on SEPS User Testing

A) Basic Information

Age Group:
O < 20 years
O 20 – 35 years
O 35 – 50 years
O 50+ years

Highest education level:
O High school diploma
O Bachelors in applied sciences
O University and higher
O Other: ________________________

Number of household members:
O 1
O 2
O 3
O 4
O 5 or more

Type of house:
O Town House
O Detached House
O Flat or apartment (including student dorm)
O Other: _______________________

Ownership status:
O Home owner
O Renter/Tenant
O Family member
O Other: _______________________

B) Perceptions on energy use

Do you know how much electricity and/or gas you normally consume?
O Yes
O No

How would you rate your energy use at home?
O Very low
O Low
O Average

O High
O Very High

Which appliance(s) do you think consume the most energy? *(please select 3)*
[ ] Washer
[ ] Dryer
[ ] Dishwasher
[ ] Water Heater
[ ] Heating
[ ] Refrigerator
[ ] Oven
[ ] Other: ____________________

When do you think you use energy the most?
O Morning (6:00 – 12:00)
O Afternoon (12:00 – 20:00)
O Night (20:00 – 6:00)

What would be your main motivation for using smart energy products and services (SEPS)?
(rank the following options with 1 being the highest priority)
[ ] Efficient energy use and renewables are a great way to save some money on my electricity bill
[ ] They use the latest technologies to make life at home more comfortable
[ ] I am concerned about our impact on the environment and I want to do more to help reduce it
[ ] Other people are increasingly interested in them so I should check them out as well

Have you previously owned or used any smart energy products?
O Yes
O No

If so, which ones?
____

If not, why not?
O They are expensive
O They are hard to use
O There is not enough information on these products and what they do
O I am not interested in using them / I don't see their usefulness
O Other: ____

C) First Impressions on SEPS

On a scale from 1 to 5, how attractive do you find the following smart energy products?

	1 *Not Attractive*	2 *Barely Attractive*	3 *Neutral*	4 *Attractive*	5 *Very Attractive*
Bodhi	*O*	*O*	*O*	*O*	*O*
CrystalLight	*O*	*O*	*O*	*O*	*O*
LightInsight	*O*	*O*	*O*	*O*	*O*

Which product would you choose to have at home?
O Bodhi
O CrystalLight
O LightInsight

Which features made you select this smart energy product? *(multiple answers possible)*
[ ] Appearance (shape, colour, materials)
[ ] Size
[ ] Expected ease of use
[ ] Feedback mechanism (i.e. the way the lights change)
[ ] Other: _ ______________________

D) Impression after use

Where did you place the product?
O Living Room
O Kitchen
O Dining Room
O Bedroom
O Other: ________________________

How often did you interact with the product? ***(interact = pay attention to the lights, possibly performing an action in response to this observation)***
O More than once each day
O Once each day
O Once every few days
O Once a week
O Less than once a week / Never

How often was there a reaction to the product's feedback?
(react = perform an action in response to the interaction)
O Always
O Often
O Rarely
O Never

How did you usually react to this feedback, e.g. when colours or light intensity changed?
(multiple answers possible)
[ ] I tried to reduce my energy use in that moment
[ ] I tried to reduce my energy use later on

[ ] I tried to use appliances at a different time of the day
[ ] No action / I was already satisfied with my energy use
*[ ] Other:*____

Were you able to quickly understand the meaning of the light feedback?
O Yes, it was very intuitive
O Yes, but it took some time to get used to it
O No, I did not understand how it worked

Would you like to keep this SEPS at home?
O Yes, I think it will make me use energy in a smarter way
O Yes, because I like the way it looks
O No, I don't think it's useful to have around

How often did you check the *PowerTracker* user interface that was provided during the first phase of the tests?
O More than once each day
O Once each day
O Once every few days
O Once a week
O Less than once a week / Never

How difficult was it to understand the information displayed on this interface?
O Very Easy – I understood the information almost immediately
O Easy – It took some time to learn how to use it but afterwards I encountered no problems
O Hard – I did not understand some of the information
O Very Hard – I was completely unable to interpret what the information in the HEMS meant

Which functions or features would you add to the SEPS?
____
____

E) Conclusion

After this experiment, how would you rate your energy use at home?
O Very low
O Low
O Average
O High
O Very High

What are your reasons for using smart energy products and services (SEPS) now?
(rank the following options with 1 being the highest priority)
[ ] Efficient energy use and renewables are a great way to save some money on my electricity bill
[ ] They use the latest technologies to make life at home more comfortable

[ ] I am concerned about our impact on the environment and I want to do more to help reduce it
[ ] Other people are increasingly interested in them so I should check them out as well

Did your perception on energy use at home change? How?
(most used appliances, time of energy use, etc.)

____
____
____

If any of your habits changed, could you describe how this change happened?

____
____
____

Further remarks:

____
____
____
____

Appendix C. Complete End User Testing Profiles

- Phase 1 - Reference Measurements and User Interface Feedback

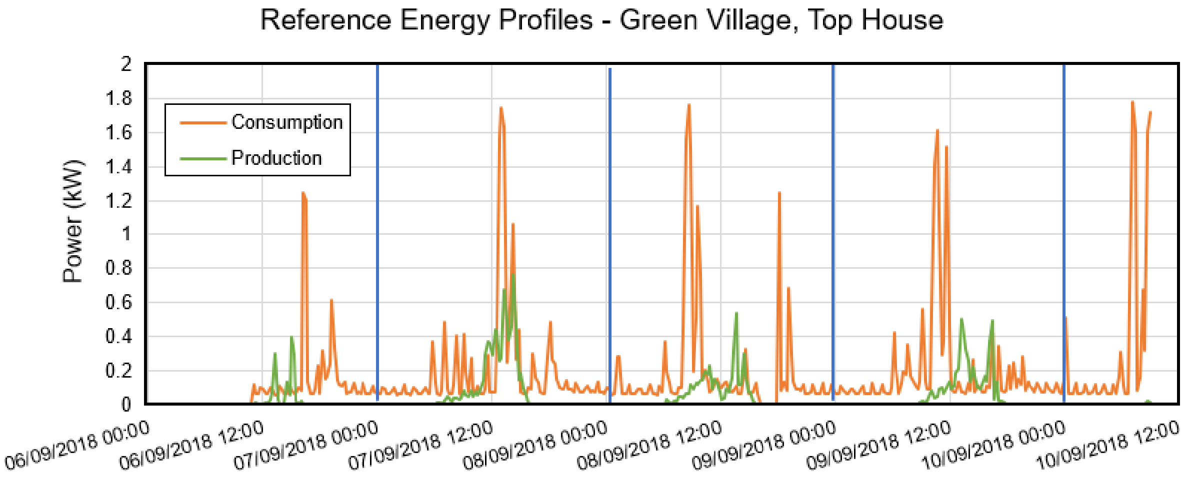

Figure A.1 Reference phase complete energy profiles for the top Sustainer Home, showing consumption in orange and production in green

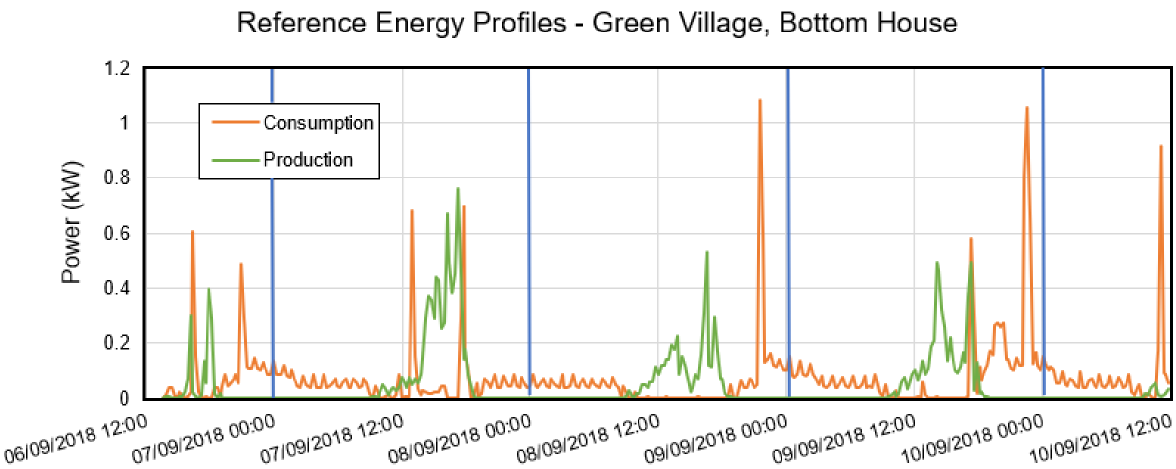

Figure A.2 Reference phase complete energy profiles for the top Sustainer Home, showing consumption in orange and production in green

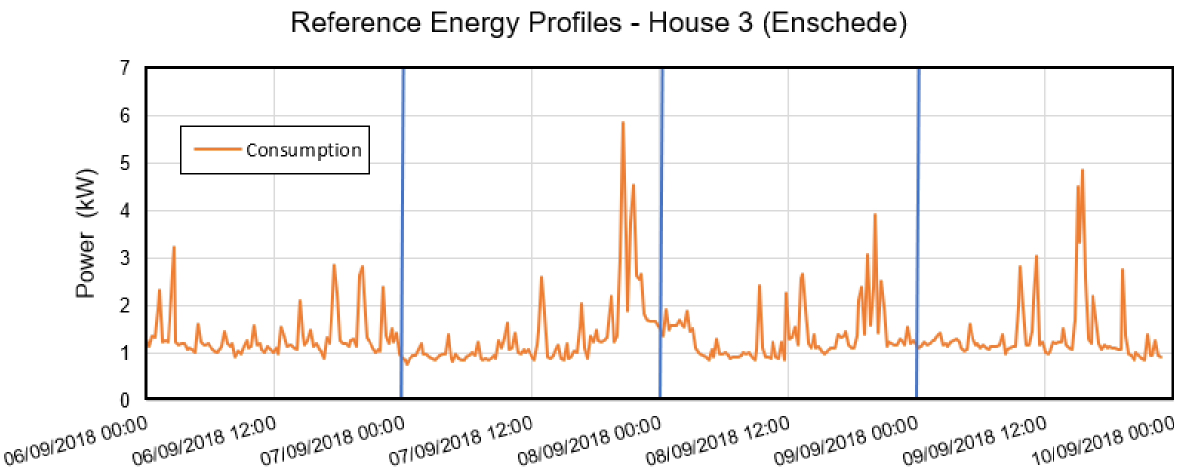

Figure A.3 Reference phase complete energy profiles for the stand-alone house

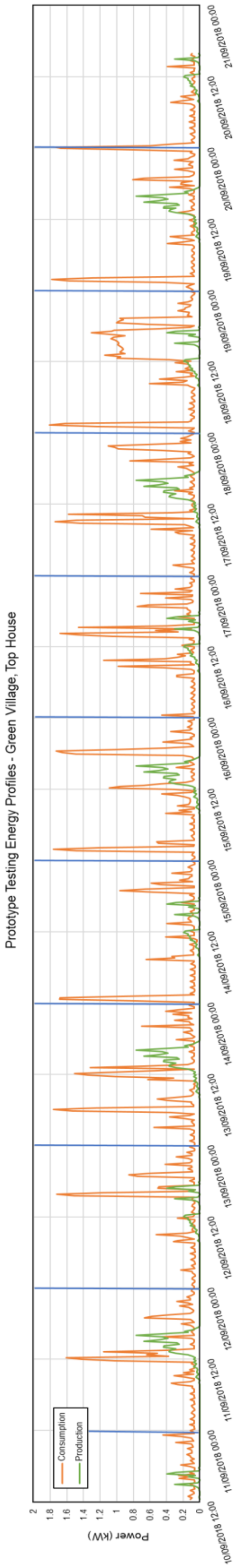

Figure A.7. Testing phase complete energy profiles for the top Sustainer Home, showing consumption in orange and production in green

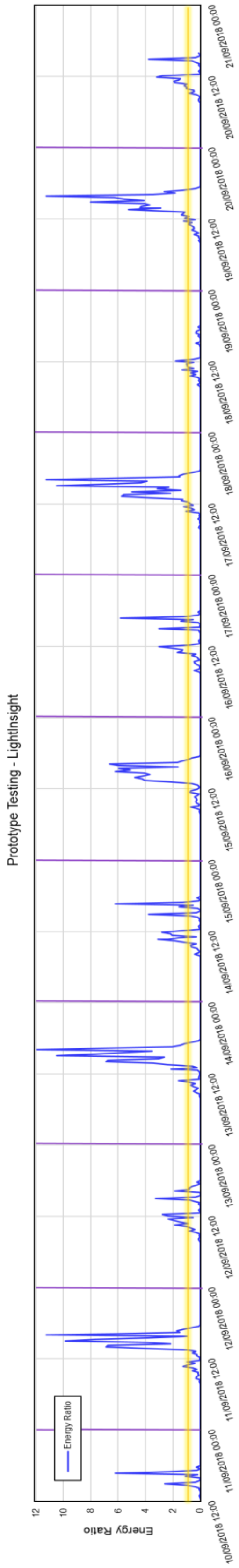

Figure A.8. LightInsight performance during testing phase. The yellow line indicates the balance point between energy consumption and production.

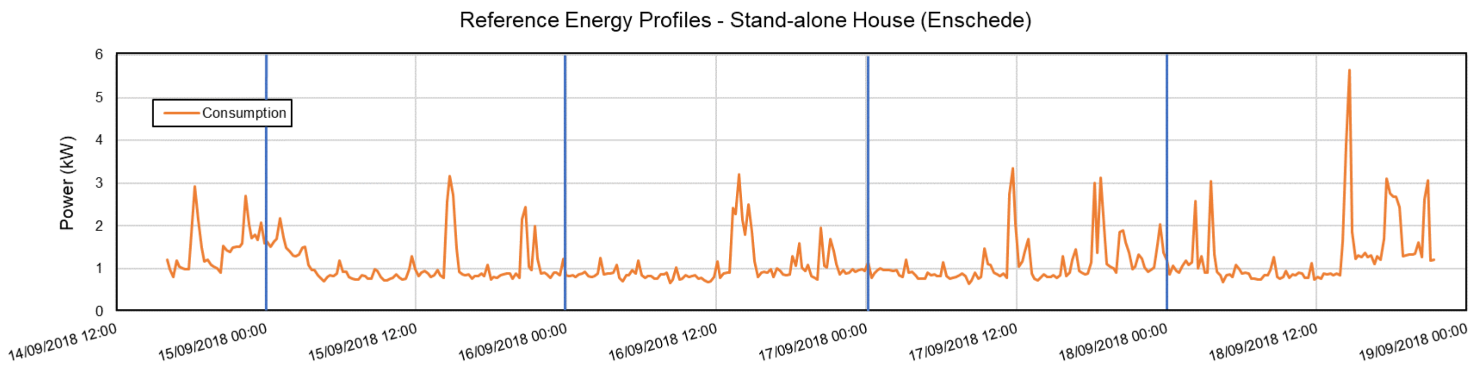

Figure A.9. Testing phase complete energy profiles for the stand-alone house

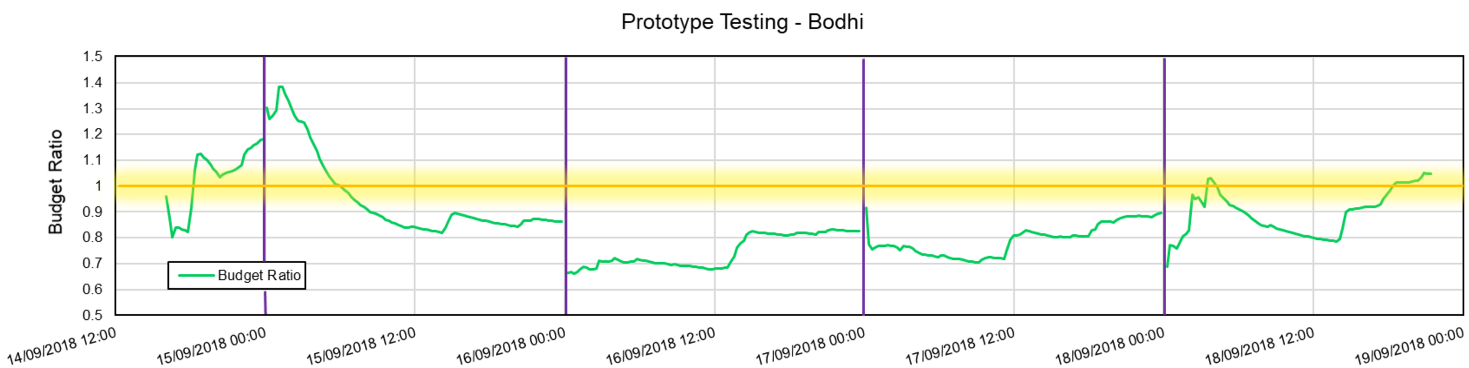

Figure A.10. Bodhi performance during testing phase. The yellow line indicates the balance point between actual and planned energy consumption.

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