European Research Infrastructure supporting Smart Grid Systems Technology Development, Validation and Roll Out

Technical Report TA User Project

CESEPS

Grant Agreement No:	**654113**
Funding Instrument:	**Research and Innovation Actions (RIA) – Integrating Activity (IA)**
Funded under:	**INFRAIA-1-2014/2015: Integrating and opening existing national and regional research infrastructures of European interest**
Starting date of project:	**01.11.2015**
Project Duration:	**54 month**

Contractual delivery date:	**18/10/2018**
Actual delivery date:	**18/10/2018**
Name of lead beneficiary for this deliverable:	**Alonzo Sierra, University of Twente**
Deliverable Type:	**Report (R)**
Security Class:	**Public (PU)**
Revision / Status:	**draft**

Project co-funded by the European Commission within the H2020 Programme (2014-2020)

Document Information

Document Version: 1

Revision / Status: draft

All Authors/Partners Alonzo Sierra / University of Twente

Distribution List ERIGrid consortium members

Document History

Revision	Content / Changes	Resp. Partner	Date
1	Draft	Alonzo Sierra	18.10.18
[Rev. No]	[Short description of document changes]	[Partner Short Name]	DD.MM.YY
[Rev. No]	[Short description of document changes]	[Partner Short Name]	DD.MM.YY

Document Approval

Final Approval	Name	Resp. Partner	Date
[Review Task Level]	[Given Name + Name]	[Partner Short Name]	DD.MM.YY
[Review WP Level]	[Given Name + Name]	[Partner Short Name]	DD.MM.YY
[Review Steering Com. Level]	[Given Name + Name]	[Partner Short Name]	DD.MM.YY

Disclaimer

Copyright Notice

Table of contents

Abbreviations

AIT	Austrian Institute of Technology
BD	Bodhi
CESEPS	Co-Evolution of Smart Energy Products and Services
CL	CrystalLight
DC	Direct Current
IDE	Integrated Development Environment
LED	Light-Emitting Diode
LI	LightInsight
MQTT	Message Queuing Telemetry Transport
PV	Photovoltaic(s)
RLC	Resistor-Inductor-Capacitor
SEPS	Smart Energy Products and Services
SmartEST	Smart Electricity Systems and Technology Services
SQL	Structured Query Language
TCP/IP	Transmission Control Protocol/Internet Protocol
UT	University of Twente

B	Energy Budget (Bodhi)
C_{MAX}	Maximum Storage Capacity (CrystalLight)
E_C	Energy Consumed
E_P	Energy Produced
R_B	Budget Ratio (Bodhi)
R_E	Energy Ratio (LightInsight)

Executive Summary

Smart energy product development has typically followed a top-down, technology-driven approach where there are significant differences between the products designers have in mind and the expectations and desires from the people that are intended to use them. A co-evolutionary, design-driven approach to the development of smart energy products and services (SEPS) where user insights and expectations are included in the early stages of the product development process may create a new perspective on how to ensure these technologies are successful in facilitating energy-efficient behaviour from end-users.

The main goal of this project is to find which sociotechnical factors can determine whether a SEPS design will be successfully accepted and implemented by end-users, and how these factors can be translated into clear guidelines for creating future SEPS designs. To this end, several SEPS concepts were first tested by end users in a real-life environment; the data gathered from these tests included energy measurements as well as qualitative data capturing user insights and experiences.

This technical report covers the subsequent testing of these prototypes that took place at the Austrian Institute of Technology (AIT), which sought to validate prototype operation using the available equipment from the Smart Electricity Systems and Technology Services (SmartEST) Laboratory, as well as extending the range of conditions where the prototypes' performance was evaluated by modelling situations which were not possible during real-life user testing.

The operation of all three SEPS prototypes was successfully validated using equipment from the SmartEST 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. The test sequences created for all three prototypes were translated into a clear lighting sequence which showed that the proposed user feedback algorithms operate as expected, further supporting the results previously obtained in end-user tests.

In addition to the prototype validation, four different use scenarios were modelled using existing household consumption and PV production datasets to visualise prototype performance in a wider range of testing conditions than those previously encountered during end-user testing. Despite the short time period analysed and the absence of user response to prototype performance, the modelled scenarios provide valuable insights into some of the issues these SEPS could encounter in these situations. A sensitivity analysis provided additional information into the impact some key parameters have on prototype feedback, revealing the importance of adequately estimating these variables for maximising the effectiveness of each prototype.

1 General Information of the User Project

USER PROJECT PROPOSAL	
User Project acronym	CESEPS
User Project title	Co-Evolution of Smart Energy Products and Services
Main scientific/ technical field	Smart grids
Keywords	Smart products, smart grids, product design, user interaction
Host Research Infrastructure	Austrian Institute of Technology (AIT)
Starting Date for the Access	21.09.2018

2 Research Motivation

While most of the technical knowledge for the development of smart energy systems exists already, one of the main challenges these systems face at present is the successful integration of their underlying products and services into households, ensuring that energy is efficiently used and achieving a better match between supply and demand. The Co-Evolution of Smart Energy Products and Services (CESEPS) project is a collaboration between Dutch and Austrian research teams which seeks to address this issue by proposing a co-evolutionary design-driven approach in which technologies, marketplaces and stakeholder adoption will be merged and developed concurrently.

2.1 Objectives

The main objective of CESEPS 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" [1]. Specific project objectives also include, among others:

1. Developing 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 the contextual barriers encountered.

2. Developing 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, constructing 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. Developing 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.

5. Implementing some of these newly developed energy products and services on test sites of the consortium.

6. Validating and scaling the smart energy products under various situations, including a co-simulation framework combining real and simulated components for scaling and replication.

2.2 Scope

The work in this project is done as part of Work Package 5 (Smart Energy Products and Services) of the CESEPS project, which is tasked with merging experiences, findings and results from other Work Packages into activities which aim to support improved SEPS development. Contribution to tasks 5.1 (Conceptual Product Design SEPS), 5.4 (Small Pilots on Campus) and 5.5 (Design Guidelines for SEPS) will be the main focus of this project. This work will also be part of the Master thesis "Guidelines for the Successful User-Centred Design of Smart Energy Products and Services" for the Sustainable Energy Technology programme at the University of Twente (UT).

The main goal of this thesis project is to find which sociotechnical factors can determine whether a SEPS design will be successfully accepted and implemented by end-users, and these factors can be translated into clear guidelines for creating future SEPS designs. To this end, several SEPS concepts developed by Industrial Design Engineering students at the UT were chosen for advanced prototyping in order to test these concepts with end users in a real-life environment. These tests took place in two different locations: two studio apartments in TU Delft's Green Village and a detached house in Enschede, The Netherlands. The data gathered from these tests includes technical measurements such as household energy production and consumption, as well as qualitative data capturing user insights and experiences.

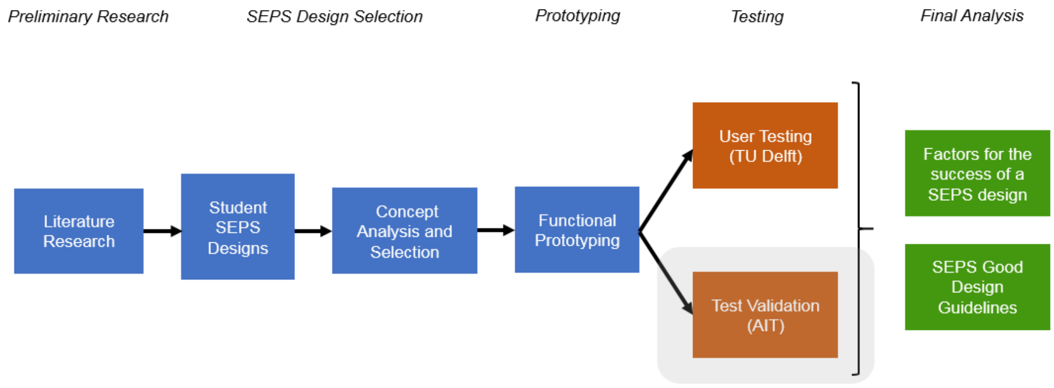

Figure 1. Thesis Flowchart with activities done at AIT highlighted in grey

3 State-of-the-Art

The main goal of smart energy products and services (SEPS) is to use energy more efficiently and increase the penetration of renewables in the residential sector. Different types of SEPS have been created in order to achieve this goal for each of the different applications of energy in households. Smart meters were the first smart energy products to be deployed during the late 90's, followed by connected (smart) thermostats in the early 00's. LED technology, switched plugs and other appliances became 'smart' later on, with the use of dedicated software becoming increasingly more important to manage information and to overcome compatibility issues between different technologies [2].

Although there seems to be little research on the development barriers SEPS themselves are facing at present, consulting literature on smart grids and smart energy systems in general [3] [4] [5] reveals a number of issues which currently limit their implementation at residential communities. SEPS are the building blocks of these systems, so understanding these issues and taking them into consideration during the design process is necessary to ensure the entire system is successfully adopted by users.

The first main issue is related to SEPS diffusion and the role of incentives in facilitating or hindering this process. Economic incentives are typically the most analysed type of incentive since they form the backbone of demand side management strategies, and several authors have looked into the effect of different pricing schemes on residential energy consumption. Other incentives include increasing awareness on energy consumption [6], increased comfort, increasing home security [2], increasing property value, forming part of a collective initiative and becoming independent of utility companies. The consequences of using incentives to induce a specific response from users are often hard to predict, and the adoption of SEPS can sometimes result in unforeseen, counterproductive side effects. One of the most common side effects found in the literature is the so-called "*rebound effect*" where a household's energy consumption increases after smart energy technologies are installed [4] [5].

The interaction between users and SEPS is another relevant issue which mainly focuses on how the user **controls** the SEPS and what kind of **feedback** is obtained in return. Regarding SEPS control, research suggests that more important than the control function itself is the user's *perception* of control over the product. If too little control is offered users 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 interfere or override this decision-making process and let the user decide manually; Verbong et al. compared this to the 'sport' and 'comfort' settings in a car [6].

On the other hand, users must rely on feedback to increase awareness on how they use energy and what changes may lead toward greater sustainability since energy use is rather invisible, and people have only a limited understanding of the impact of their actions. Information can be presented to the user in real-time or historically, and from these two real-time has been found to be the most effective type of feedback since it's more visible and direct to the user [4]. Furthermore, real-time data encourages active experimentation from the user [7], who can see what happens to energy consumption when certain appliances are turned on or off at any given moment or the ideal moment during the day for using them.

Furthermore, the data itself should be presented in a visual way rather than using numbers to facilitate its understanding by users. A user survey by Obinna [8], for example, indicated this as the most desired feature for smart thermostats. If visual feedback is not possible, it can 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 [5].

SEPS feedback can 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 can be in the form of meeting a daily or weekly consumption target or scoring ‘green’ appliance usage [7]. In addition to collaboration, competition can also be used to set goals for users. Comparing and/or ranking a user’s consumption within a group, for instance, can be an effective motivation for users to become more energy efficient [8].

Finally, as with any ‘smart’ solution SEPS are highly dependent on the collection and interpretation of data, and this data should be properly safeguarded. Data collected from a household is highly sensitive since it can reveal what kind of activities users do and when they do them. SEPS users thus need to be assured that their data is managed safely responsibly, with secure authentication and data encryption protocols being a basic requirement [5]. 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 also give them a higher sense of security.

4 Executed Tests and Experiments

4.1 Test Plan

As described in Section 2.2, several student-developed SEPS prototypes were tested by end-users in the Netherlands in order to evaluate user experience and identify the key factors for successful SEPS acceptance and implementation. Further testing of these prototypes took place at AIT, which sought to achieve the following goals:

- Validate prototype operation using the available 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 end-user testing.

- Extending the range of conditions where the prototypes' performance was evaluated by modelling situations which were not possible during real-life user testing. This can be achieved by using datasets from previous experiments to create several scenarios, each representing a particular set of conditions. These scenarios can provide a useful insight into how the prototypes would perform in situations which were not found during the user testing phase.

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

4.1.1 Use Scenario Simulation

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 average household load.

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.

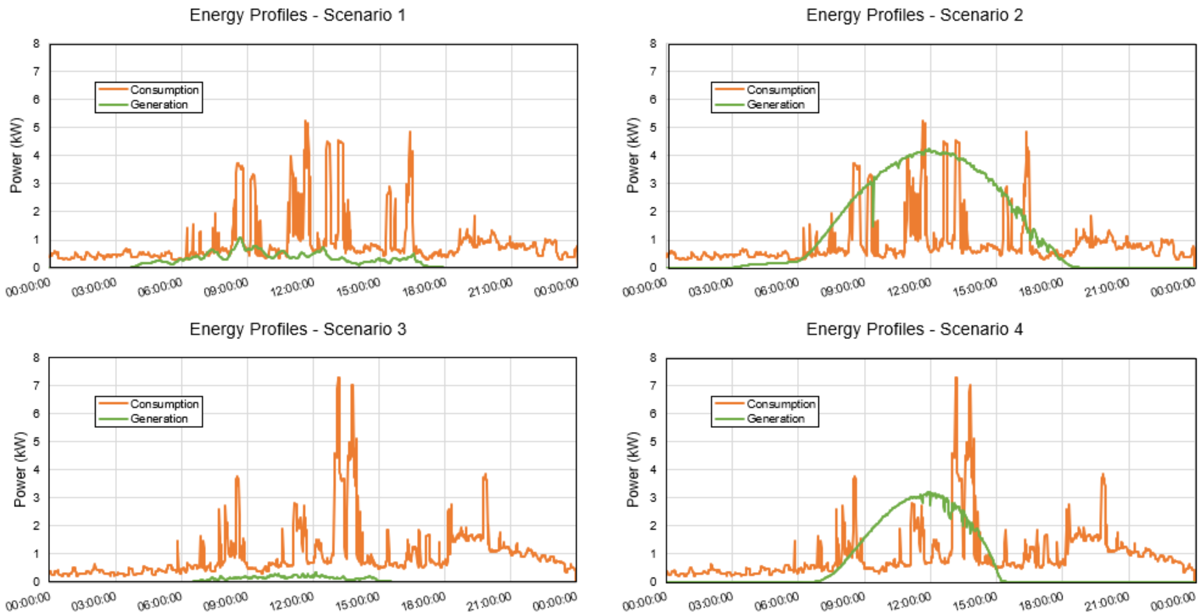

Figure 2. Energy profiles for the four modelled scenarios, showing consumption in orange and production in green. Clockwise from top left: Scenario 1 (Summer Load, Inadequate PV), Scenario 2 (Summer Load, Adequate PV), Scenario 4 (Winter Load, Adequate PV), Scenario 3 (Winter Load, Inadequate PV).

4.1.2 Prototype Laboratory Validation

A PV simulator and a controllable load were used as inputs to create a series of production-consumption datapoints which were interpreted by each prototype's feedback algorithm in order to simulate different system states and set LED properties accordingly. A different testing sequence was designed for each of the three prototypes so that all possible system states (each of which is associated with a particular LED colouring or intensity) take place at regulated intervals; this will make it possible to visually confirm if the feedback generated by the prototype is correct.

4.2 Description of Tested SEPS Prototypes

Three SEPS prototypes were considered for this project, all of which were originally designed by Industrial Design Engineering students for the 'Sources of Innovation' course at the University of Twente. These prototypes measure a household's energy consumption and production and provide simple feedback to users using LED lighting. This section presents a short description of each prototype and the algorithm it uses to determine feedback to users; the names used in this report are those given to the SEPS concepts by the students themselves.

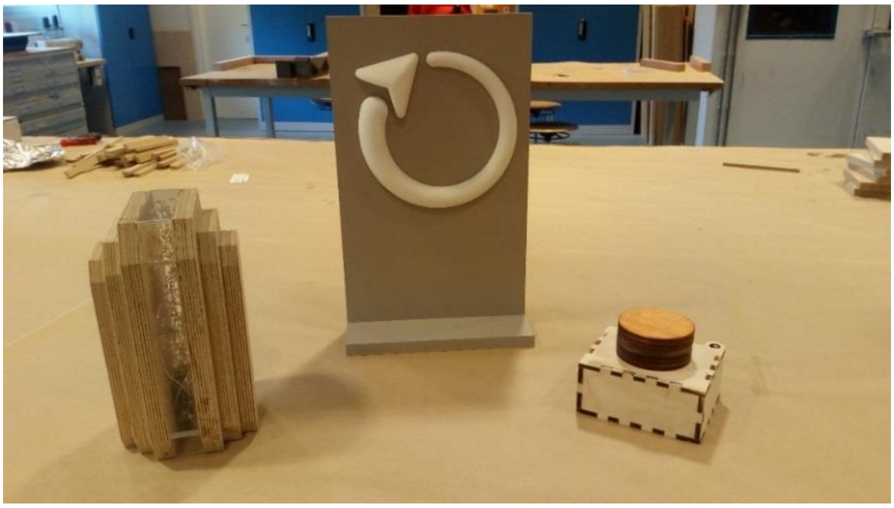

Figure 3. The three SEPS prototypes tested at AIT. From left to right: CrystalLight, Bodhi, LightInsight.

4.2.1 Bodhi (BD)

The Bodhi prototype operates as an '*energy budget'* indicator. Users can 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 (*B*) will be determined by a *budget ratio* (R_B), which indicates the relationship between actual and planned (cumulative) consumption during a given interval, as seen in Figure 4 below.

Unlike the two other prototypes, Bodhi does not depend on energy production since it only requires measuring energy consumption to provide feedback to users.

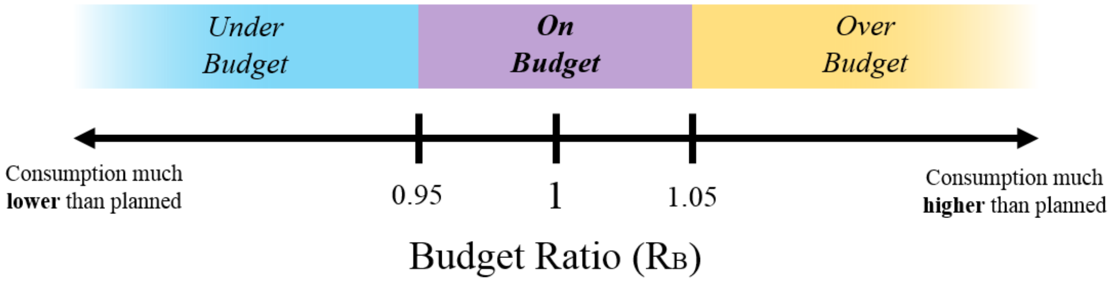

Figure 4. Bodhi LED feedback as a function of R_B

4.2.2 CrystalLight (CL)

CrystalLight works in a conceptually similar way to a battery: each day, surplus electricity from a household's PV array will make its light grow stronger ('charging' the product) while electricity consumption will gradually dim it, meaning that a light still on at the end of the day will indicate that overall production exceeded consumption while no light will indicate the opposite. To do this, the state of charge of the virtual 'battery' at each given interval will be converted into a brightness value between 0 and 100% for the prototype LEDs, following the algorithm shown in Figure 5 below.

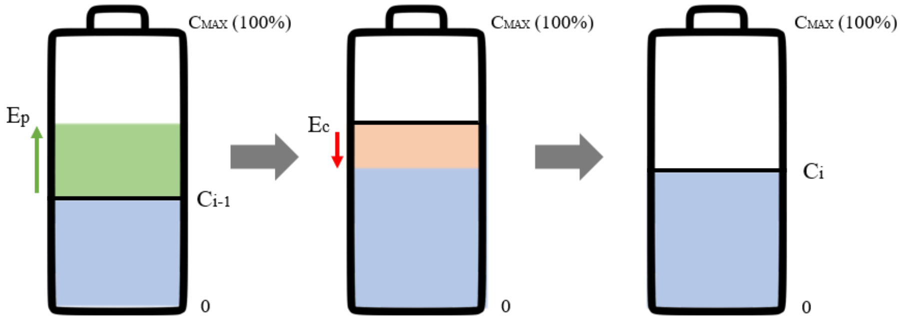

Figure 5. CrystalLight 'battery' charging algorithm; a new charge level is calculated by adding the energy produced (Ep) and subtracting the energy consumed (Ec) during a given interval. Charge must always be a value between 0 and C_{MAX}, where C_{MAX} denotes the battery's maximum storage capacity.

4.2.3 LightInsight (LI)

This prototype consists of a small dial which can give users information on the balance between their energy consumption and production. The dial will show one of four possible system states:

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

The relationship between these two variables will be expressed as an energy ratio (R_E). In addition to the value of R_E itself, the direction in which this indicator is changing can be used to provide a more detailed insight into how the system is performing. To this end, two different colour schemes will be used (see Figure 6 below).

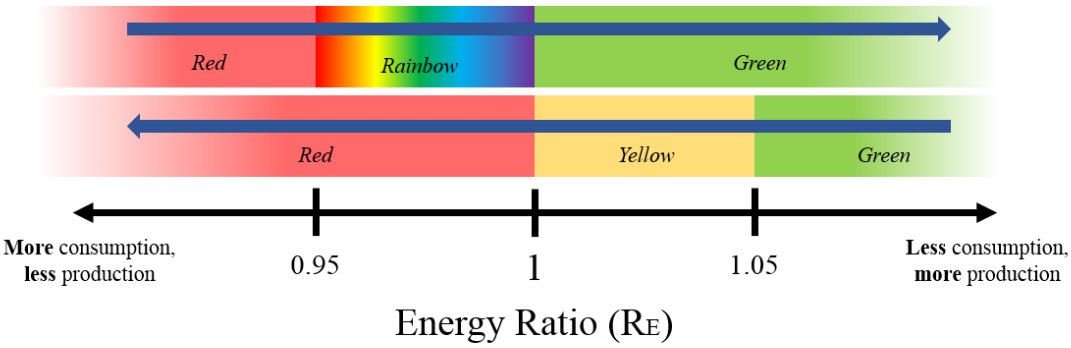

Figure 6. LightInsight LED feedback as a function of energy ratio, showing different colour schemes depending on whether R_E is increasing (top) or decreasing (bottom)

4.3 Test Set-up

4.3.1 Use Scenario Simulation

The algorithm used by each prototype to determine its LED output properties was tested by using production and consumption profiles to model four different use scenarios. Since the prototypes were designed to periodically read the required data from smart meters, a simple script was created which replicates 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 (*Ec*) and energy production (*Ep*) 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, as shown in Figure 7 below.

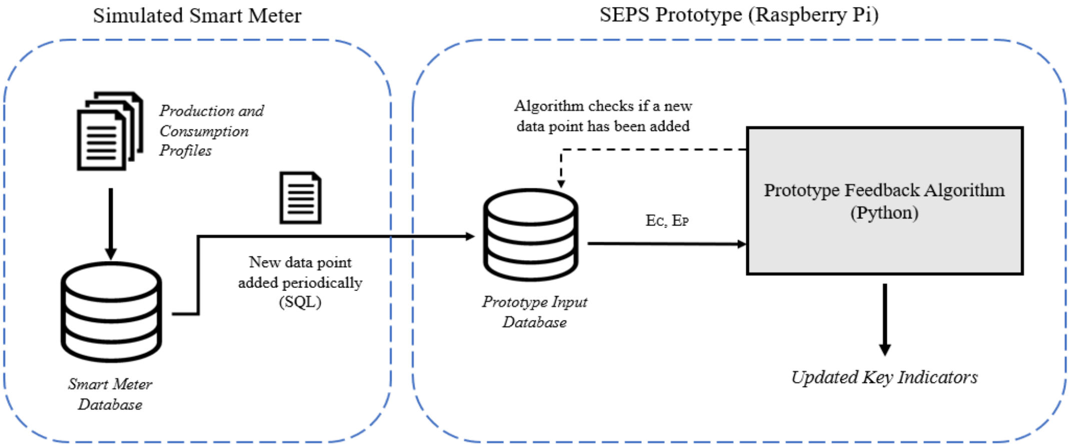

Figure 7. Test set-up for the Use Scenario Simulation phase

4.3.2 Prototype Laboratory Validation

Figure 8 shows the testing set-up for this phase, where 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. Finally, the prototype performed the necessary calculations to determine LED properties following the feedback algorithms described in Section 4.2.

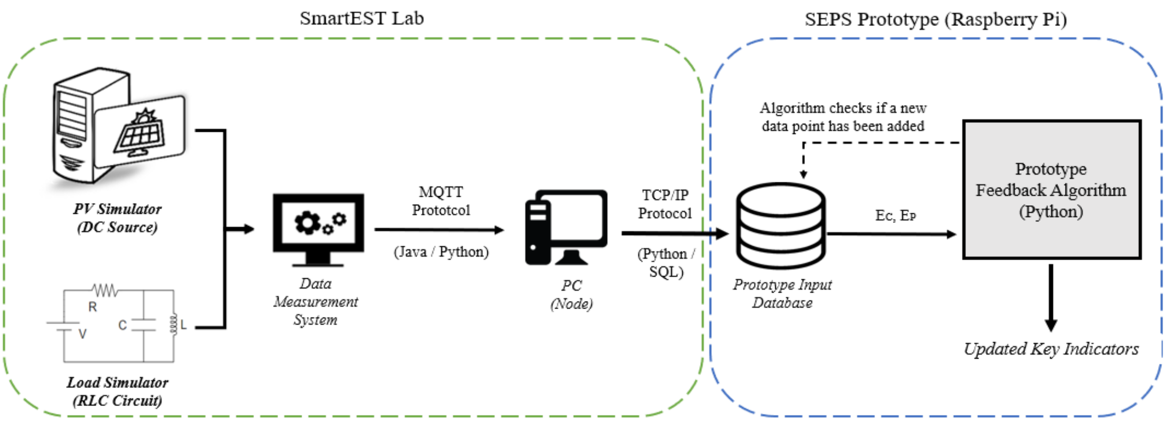

Figure 8.Test set-up for the Prototype Validation phase

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 presented in Figure X 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.

4.4 Data Management and Processing

The following software tools were used during both testing phases:

- **Python** – This programming language was chosen for writing the scripts containing each prototype's feedback algorithm because of its compatibility and ease of use with the Raspberry Pi microprocessors that serve as the prototypes' main electronic component. Commercially available IDEs such as Eclipse and Thonny were used as a workspace for script development.
- **SQLite** – This database engine was used to create and manage input and output databases. The queries required for storing, retrieving and selecting datapoints were embedded within the main Python scripts.
- **Communication Protocols** – Two protocols were used to transmit the data from the lab measuring system to the prototypes. First, the lab's custom-built communication middleware (based on the MQTT protocol) periodically sent the measured values to a PC which served as a node. These values were then passed on from the PC to the prototypes using a simple TCP/IP client-server module.

5 Results

5.1 Use Scenario Simulation

This subsection presents the results for the four modelled use scenarios, each covering all three prototypes. A sensibility analysis is also included for evaluating the impact key parameters such as *energy budget* (Bodhi), *battery capacity* (CrystalLight) and *transition range* (LightInsight) have on prototype feedback.

5.1.1 Scenario 1 – Summer Profile, Inadequate PV Production

Bodhi

The value of Bodhi's budget ratio throughout the day (see Figure 9 below) shows 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 detail later on.

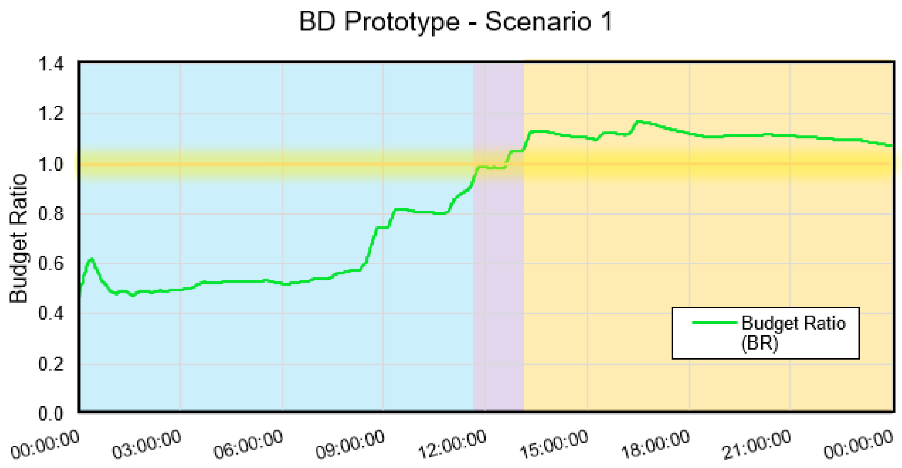

Figure 9. Bodhi (BD) prototype performance for Scenario 1. Background colour corresponds to the light colour shown by the prototype LEDs; the yellow line indicates the balance point between actual and planned consumption.

CrystalLight

Figure 10 shows that this prototype spends 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, is quickly reached and then consumed. This should not be surprising considering that energy consumption consistently outperforms production in this scenario (see Figure 2, top left).

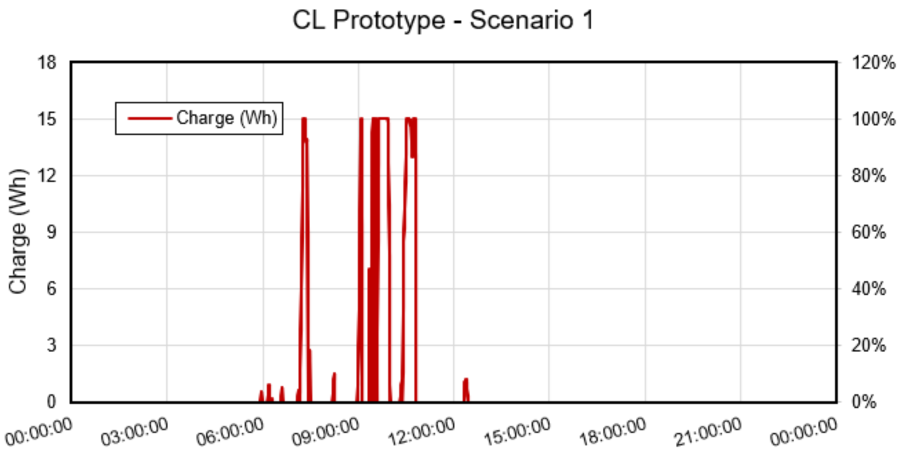

Figure 10. CrystalLight (CL) prototype performance for Scenario 1; LED intensity (corresponding to the prototype's state of charge) is shown on the right.

LightInsight

The 'red' light state (i.e. consumption overtaking production) takes place around 93% of the time, the only exception being several short periods in the morning as seen in Figure 11 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) are extremely rare, each occurring less than 1% of the time. This is due to the way R_E changes abruptly from one interval to the next, rarely falling within the transition range ($0.95 < R_E < 1.05$) which is caused by changes in consumption rather than production.

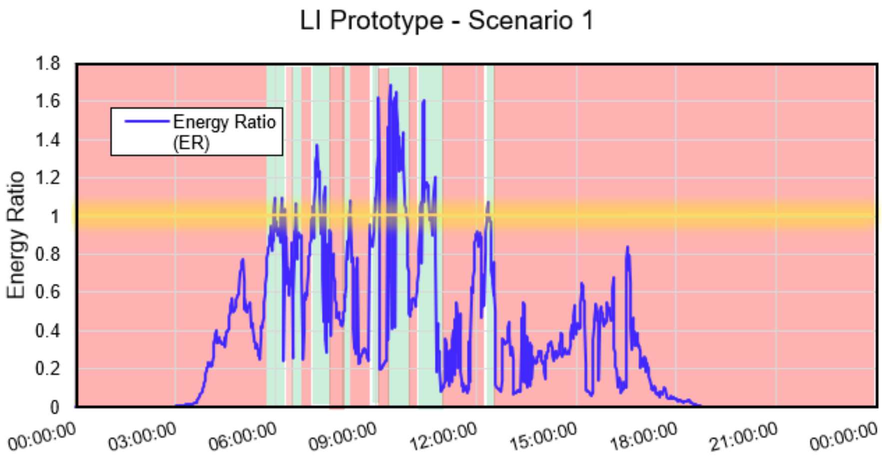

Figure 11. LightInsight (LI) prototype performance for Scenario 1. Background colour corresponds to the light colour shown by the prototype LEDs; the yellow line indicates the balance point between energy consumption and production.

5.1.2 Scenario 2 – Summer Profile, Adequate PV Production

Bodhi

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

CrystalLight

In this scenario, fast charging takes 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 is significantly better than in the previous scenario; the only times in which a full discharge occurs are the early morning hours where PV production has not yet started.

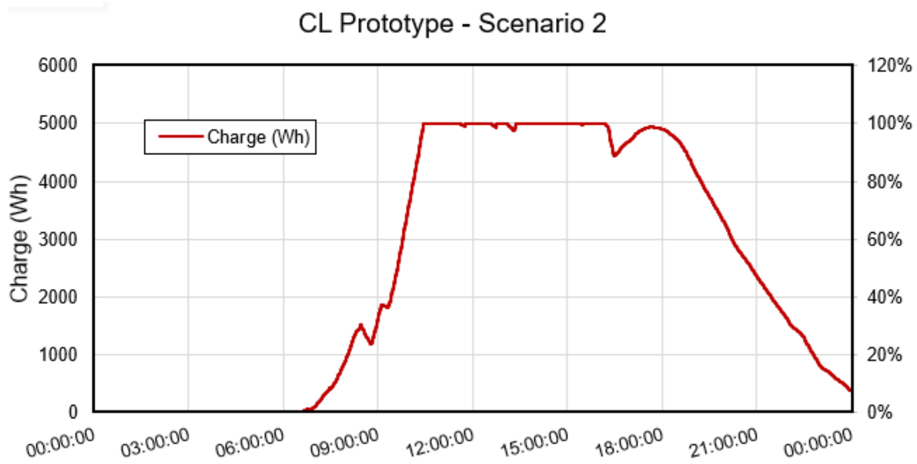

Figure 12. CrystalLight (CL) prototype performance for Scenario 2; LED intensity (corresponding to the prototype's state of charge) is shown on the right.

LightInsight

As expected from the increase in PV production, 'green' periods are much more frequent, now amounting to around 40% of the day, and they last longer on average as seen in Figure 13 below. The energy ratio is 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 occur even less frequently than on Scenario 1, both accounting for only 0.9% of the total intervals.

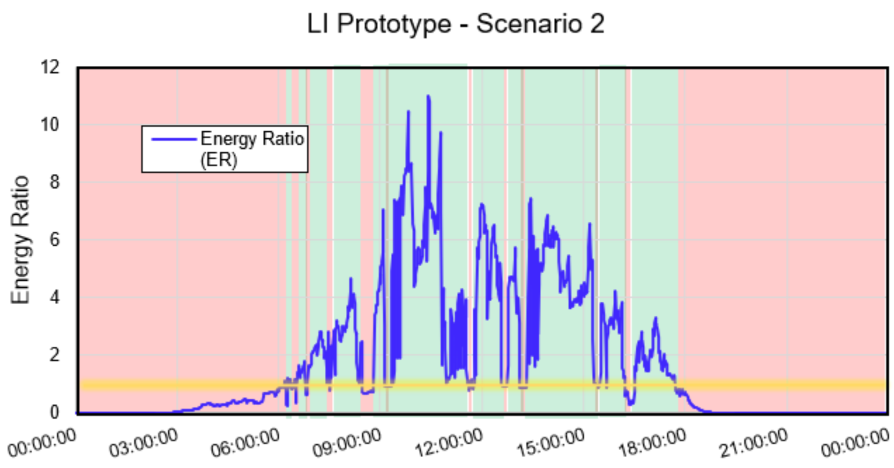

Figure 13. LightInsight (LI) prototype performance for Scenario 2. Background colour corresponds to the light colour shown by the prototype LEDs; the yellow line indicates the balance point between energy consumption and production.

5.1.3 Scenario 3 – Winter Profile, Inadequate PV Production

Bodhi

This scenario presents 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 is exceeded by the end of the day, although this occurs much later than during the summer; as was the case before, this greatly depends on the selected energy budget.

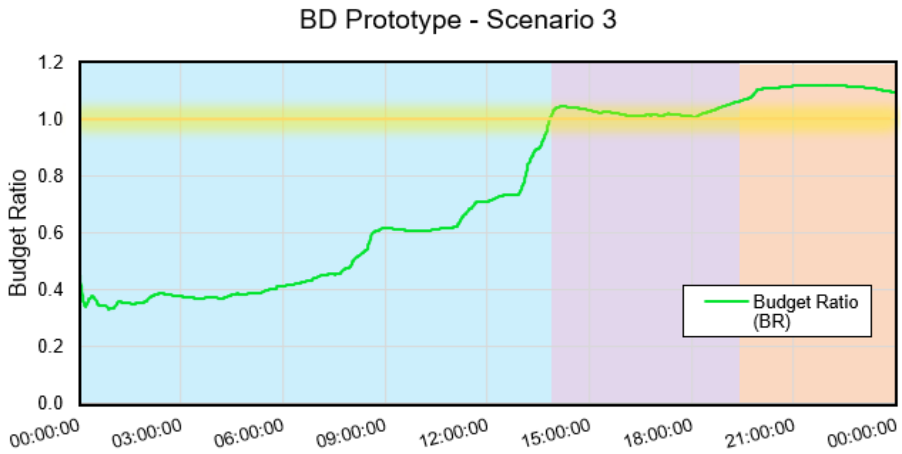

Figure 14. Bodhi (BD) prototype performance for Scenario 3. Background colour corresponds to the light colour shown by the prototype LEDs; the yellow line indicates the balance point between actual and planned consumption.

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 will be constantly off.

LightInsight

The performance of this prototype confirms the observations made for CrystalLight; 'red' lights are shown the entire day with R_E failing to approach the balance point; a maximum value of only 0.6 is reached.

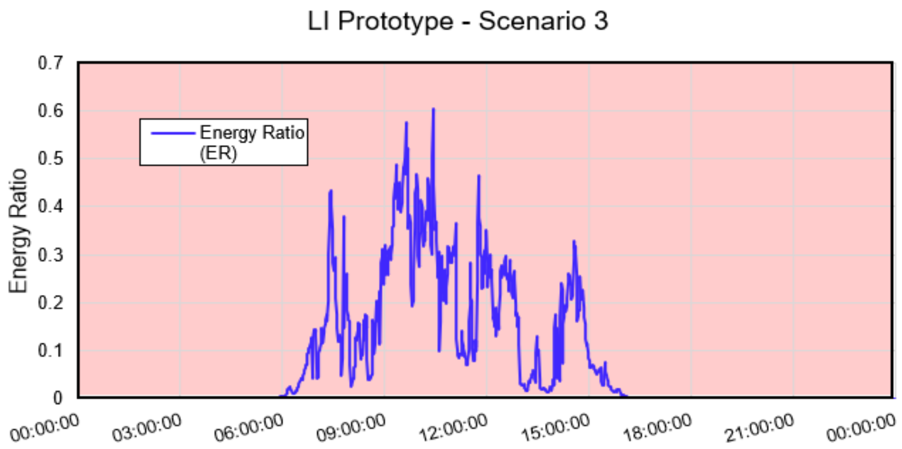

Figure 15. LightInsight (LI) prototype performance for Scenario 3. Background colour corresponds to the light colour shown by the prototype LEDs; the yellow line indicates the balance point between energy consumption and production.

5.1.4 Scenario 4 – Winter Profile, Adequate PV Production

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

CrystalLight
In a similar way to Scenario 2, the prototype undergoes a charge-discharge cycle during the daytime, with a second shorter charging phase in the early afternoon (see Figure 16 below). The discharge phases are 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 stops at around 11:00; the effects of setting different values for this parameter will be explored during the sensitivity analysis later on.

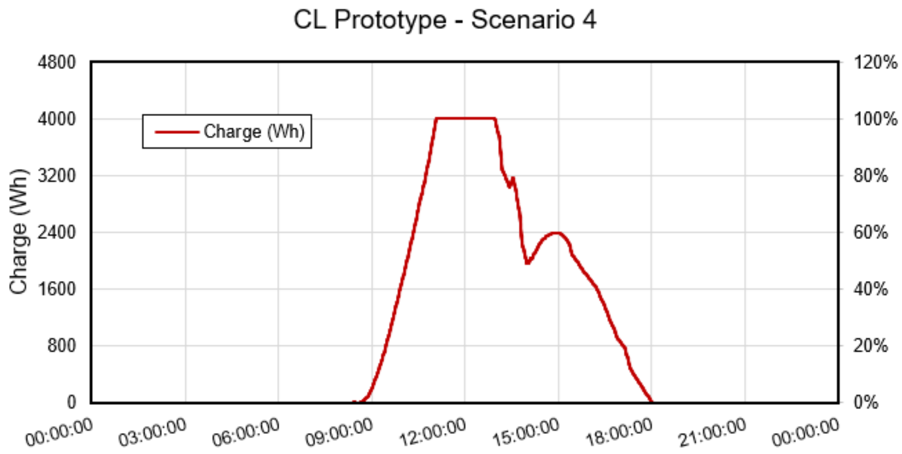

Figure 16. CrystalLight (CL) prototype performance for Scenario 4; LED intensity (corresponding to the prototype's state of charge) is shown on the right.

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

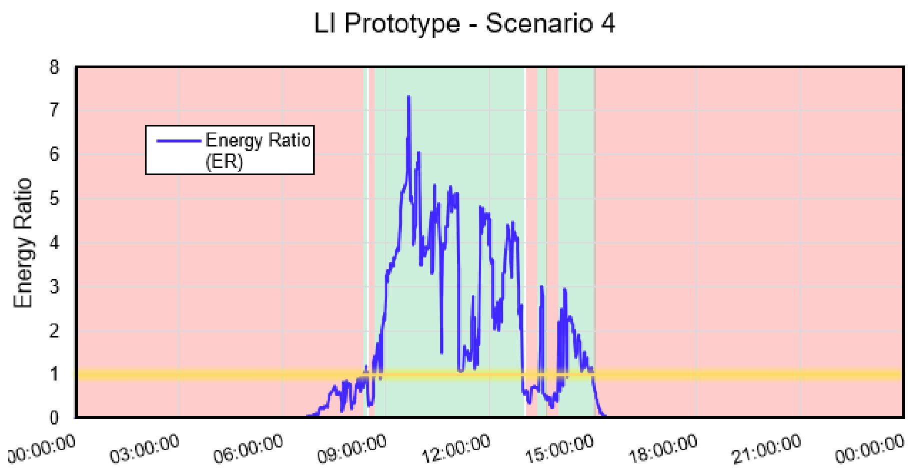

Figure 17. LightInsight (LI) prototype performance for Scenario 4. Background colour corresponds to the light colour shown by the prototype LEDs; the yellow line indicates the balance point between energy consumption and production.

5.1.5 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:

Bodhi – *Energy Budget (B)*
Figure 18 shows how increasing or decreasing the previously selected energy budget for the summer load profile (Scenarios 1 and 2) results in a significant variation in the LED colours shown by Bodhi throughout the day, either modifying the length of each system state (Figure 18, bottom right) or not reaching one of the system states altogether (Figure 18, 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.

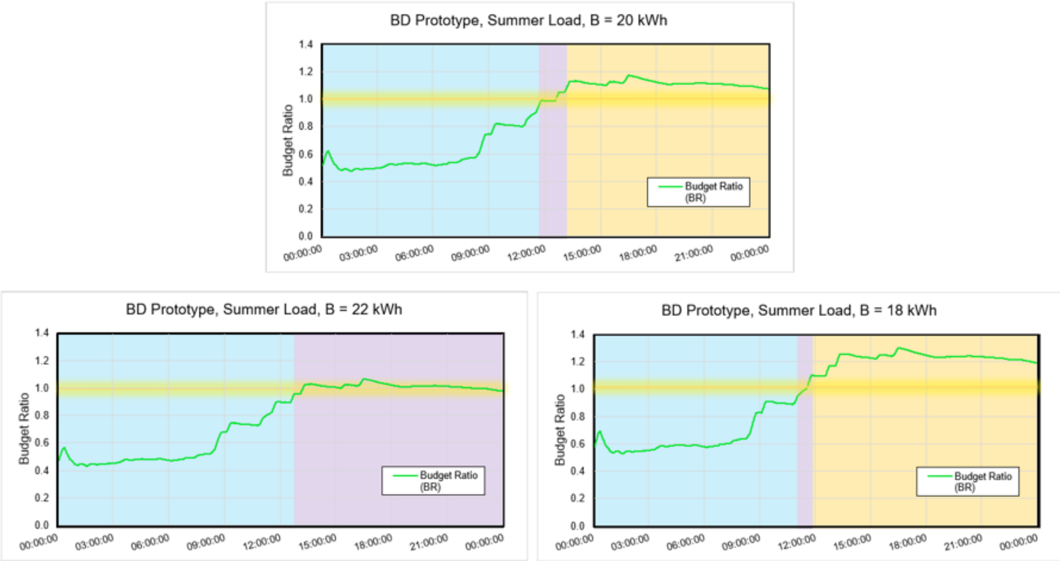

Figure 18. Bodhi sensitivity analysis using the summer use scenarios. Top: benchmark case (B = 20 kWh), bottom: 10% increase on B (left), 10% decrease on B (right).

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 19 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 is a clear variation between all four profiles, with a lower C_{MAX} value correlating to a more pronounced charge 'clipping' when the full charge is reached. In all profiles the charging phase starts exactly at the same time but discharging occurs at different intervals: the more energy stored, the later the discharging will take place.

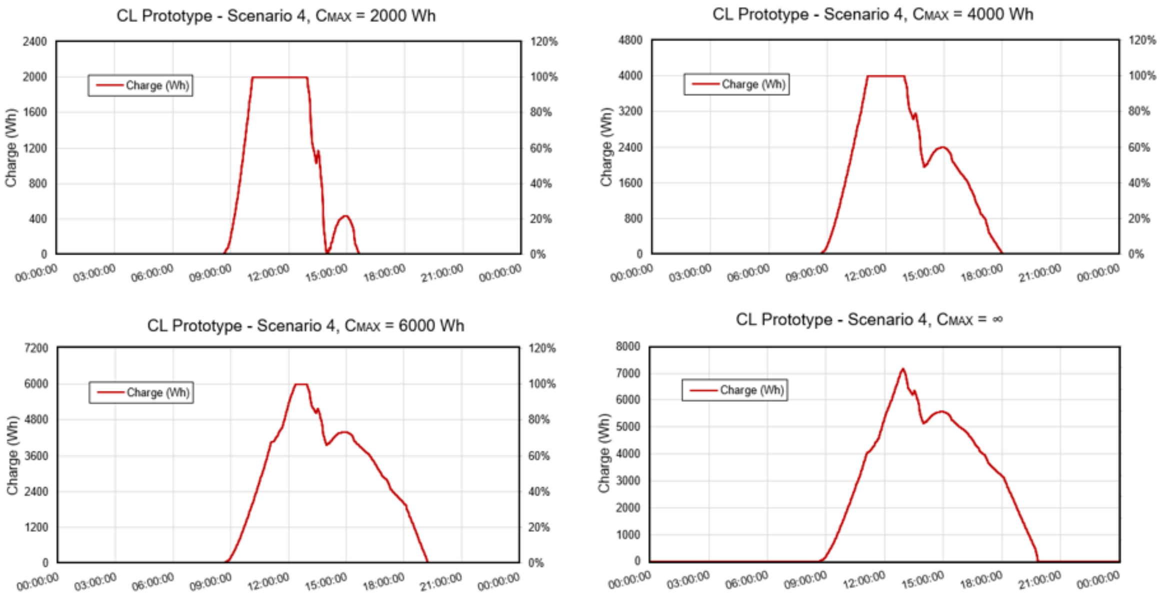

Figure 19. CrystalLight sensibility analysis in Scenario 4, showing increasing values for C_{MAX} and an "infinite capacity" case where all surplus energy is stored.

Since CrystalLight's 'battery' is not physical but conceptual, 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 lies around the highest point observed in the "infinite capacity" curve (Figure 19, bottom right), for values higher than this no additional energy will be stored and the average state of charge will only decrease.

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 1 below shows the frequency for each system state with four different transition ranges.

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%

Table 1.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 ($R_E = 1$).

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.

5.2 Lab Validation Testing

As described in Section 2, 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 20 below shows the laboratory infrastructure and some of the user interfaces used during this phase.

Figure 20. 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 21 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 21. Time-lapse showing Bodhi’s lighting transitions through all three system states

CrystalLight: Figure 22 below shows different stages of the modelled charge/discharge cycle, where the prototype’s LED brightness gradually increases before reaching its maximum intensity level, then becoming dimmer until the ‘full discharge’ state is attained.

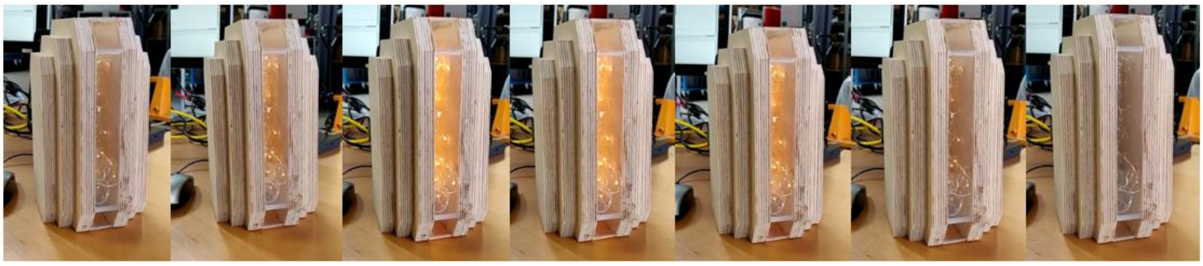

Figure 22. Time-lapse showing CrystalLight at different stages of a charge-discharge cycle

LightInsight: Both colour schemes previously shown in Figure 23 were evaluated, first increasing the value of R_E from 0.9 to 1.1 (Figure 23, pictures 1-3) and later decreasing it (Figure 23, pictures 3-5) back to its initial value.

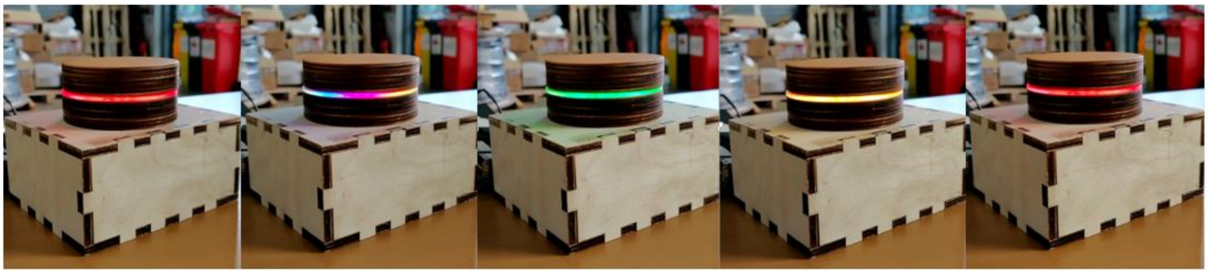

Figure 23. Time-lapse showing each of LightInsight's system states

6 Conclusions

The operation of all three SEPS prototypes was successfully validated using equipment from the SmartEST 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.

Regarding the *simulation of use scenarios*, some prototypes' behaviour matched the patterns observed during end-user testing (e.g. LightInsight), while others showed significant variations (e.g. Bodhi). In either case, the operation period analysed 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 times.

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 behaviour 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.

Regarding the *lab validation tests*, the test sequences for all three prototypes were successfully translated into a clear lighting sequence which confirms that their feedback algorithms are operating correctly and further supports the results previously obtained in end-user tests. It is worth noting that the tests 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.

Finally, it is important to point out that one of the main challenges encountered during the lab testing 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.

7 Open Issues and Suggestions for Improvements

This section briefly introduces some of the open issues and areas for further research found during the testing, along with suggestions for how they could be tackled in the future:

- Use scenarios covered a relatively short timescale where some of the patterns typical of residential consumption are difficult to identify. Using more extensive datasets covering at least one week will result in a more accurate picture of the way energy is consumed in households.

- The sensitivity analysis revealed the importance of adequately estimating key parameters for maximising the effectiveness of each prototype; this could be used as the starting point for developing a more complex algorithm which adapts to use patterns by periodically recalculating these parameters.

- The laboratory validation omitted the use of smart meters, instead providing data directly from the measurement system to the prototypes. Further research should consider the impact of smart meter reliability in prototype performance, as well as improving their resilience to incomplete or intermittent smart meter measurements.

- Testing prototype response to unusual grid conditions (power outages, voltage spikes, etc.) was not possible since only one copy of each prototype was created and there was a high risk of permanent hardware damage. Conducting these tests in the future could greatly improve the safety features of these SEPS and help identify their main failure mechanisms.

8 Dissemination Planning

As a part of CESEPS, the obtained results will be disseminated through the project’s communication channels. Additionally, the results will be an essential part for the CESEPS deliverables D5.1 Co-Simulation Analysis of SEPS and T5.5 Design Guidelines of SEPS. Based on the results and findings, papers are aspired to be published on suitable conferences like Cired 2019, Solar/Wind/EV Integration Workshop, SmartGreens 2019 or CCTA 2019.

Furthermore, this work is part of a Master thesis project titled “Guidelines for the Successful User-Centred Design and Implementation of Smart Energy Products” and the final results will be made public as an extensive report by the University of Twente.

9 References

[1] CESEPS, „Project Objectives," [Online]. Available: http://www.ceseps.eu/the-project/objectives/. [Accessed 18 10 2018].

[2] R. Ford et al., „Categories and functionality of smart home technology for energy management," *Building and Environment,* Nr. 123, pp. 543-554, 2017.

[3] N. Balta-Ozkan et al., „Social barriers to the adoption of smart homes," *Energy Policy,* Nr. 63, pp. 363-374, 2013.

[4] D. Geelen et al., „Empowering the end-user in smart grids: Recommendations for the design of products and services.," *Energy Policy.,* Nr. 61, pp. 151-161, 2013.

[5] T. Christensen et al., „Recommendations and criteria for the design of smart grid solutions for hoseholds: Lessons learned for designers and policy makers from the IHSMAG project.," 2016.

[6] G. Verbong et al., „Smart grids or smart users? Involving users in developing a low carbon electricity economy.," *Energy Policy,* Nr. 52, pp. 117-125, 2013.

[7] D. Geelen et al., „Smart Energy households' pilot projects in The Netherlands with a design-driven approach.," in *4th IEEE PES Innovative Smart Grid Technologies Europe (ISGT Europe).*, 6-9 October, Copenhagen, Denmark, 2013.

[8] U. Obinna, „Assessing Residential Smart Grids Pilot Projects, Products and Services: Insights from Stakeholders, End-users from a Design Perspective," Doctoral Thesis, Delft University of Technology, Delft, The Netherlands, 2017.

10 Annex

10.1 List of Figures

10.2 List of Tables