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Electricity Supply and Demand Control in a Car as Power Plant Neighborhood

An Agent Based Model

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Executive Summary

Limiting global warming to less than 2°C is an ambitious target 196 countries declared to pursue at the Paris climate conference in December 2015 (COP21). The impact of atmospheric CO_2 concentrations on the absolute global warming creates a significant uncertainty. According to common published scenarios by the Massachusetts Institute of Technology (MIT), the Potsdam Institute for Climate Impact Research (PIK) and the International Institute of Applied System Analysis (IIASSA), it roughly means that net-zero emissions need to be realized by 2070. On the other side, there is the increasing global energy demand as the result of a growing world population and economy. Achieving net-zero emissions with an increasing energy demand would imply radical transformations of the global and local energy systems.

A Car as Power Plant (CaPP) system is an innovative concept that integrates the foundational areas of the energy system (power, buildings, transport and industry) with emission-free technologies. Renewable electricity, rainwater and fuel cell electric vehicles (FCEVs) supply the electricity, heat, mobility and water demand of a system. Such a system solves one of the key issues of energy systems with a high renewable penetration: the need for overcapacity due to rarely synchronized energy supply and demand. CaPP systems store excess energy in the form of hydrogen. FCEVs, consequently, consume the hydrogen to produce electricity for either mobility or the CaPP system. Such systems can be completely independent of fossil fuels and are therefore potentially one of the key ingredients for achieving net-zero emissions by 2070.

A prerequisite for the implementation of CaPP systems in a society or neighborhood, is to have a significant share of FCEVs in the vehicle fleet. FCEVs, howerver, currently have very limited availability and no such neighborhoods exist yet. CaPP systems, therefore, still require proof of concept. This proof of concept will focus around the small scale neighborhood case of CaPP systems. A CaPP neighborhood would have a small scale, self-sufficient microgrid. In conventional energy systems, electricity is supplied by centralized power plants and the prime use of passenger vehicles is mobility. In a CaPP neighborhood these concepts are fundamentally different. Besides being consumers, residents become the electricity producers, and passenger vehicles produce electricity on top of providing mobility. To assure electricity balance in such systems, an electricity supply and demand control structure is required. Scheduling schemes FCEV power production, demand response mechanisms and supply response mechanisms are the elements of the very control structure studied in this research.

This master thesis aims to contribute to the proof of concept of CaPP systems by developing a model that allows studying the effects of different control structure scenarios on the electricity balance of a CaPP neighborhood. This requires a model of the socio-technical system of a CaPP neighborhood. Socio-technical systems relate to connections between human behavior and complex infrastructures. In a socio-technical CaPP system, mobility needs and electricity demand correspond to human behavior, while the energy system corresponds to the complex infrastructure. Quantitative insights about the behavior of this socio-technical system with respect to the control structure allow stakeholders and future project developers to make substantiated decisions about projects and related policies.

The CaPP model is developed with an agent based approach. Agent-based modeling (ABM) is a common method to model complex socio-technical systems, as it is a bottom-up approach and allows for structural changes. A bottom-up approach implies that individual behavior of entities of the system is described, instead of the behavior of the aggregate system. This is convenient because the emerging behavior of complex systems is often hard to grasp. Complex systems are often adaptive; structural changes in the model allow for entities to change decision-making and adapting to circumstances.

The model is used to answer the following research question: *What are the influences of the electricity supply and demand control structure on the electricity balance of a Dutch 200 household CaPP neighborhood?* A Dutch neighborhood is defined by adequately configuring the characteristics of the system, the behavior of the residents (mobility patterns and demand profiles), and the renewable energy (RE) resources (wind and solar). Seven specific elements of the control structure are studied:

1. a minimum number of two hour timeframes per week each FCEV should be available for power production scheduling,
2. the maximum number of two hour timeframes per day each FCEV can be scheduled for power production,
3. the default FCEV output when producing electricity,
4. the maximum FCEV output when producing electricity,
5. the number of FCEVs required for power production backup
6. home side demand control for shifting peak demand to hours with PV production,
7. price level control to increase supply and decrease demand when there is a supply deficit.

The effects of the control structure are depended on the number of FCEVs, the degree of social cohesion and RE resources (i.e. the season). Therefore, the performance of the CaPP system with respect to these concepts is also studied.

Three performance levels are defined to quantify the performance of the CaPP system with respect to the electricity balance. The first and most important performance level is the amount of hours per four weeks in which an electricity deficit occurs. A criterion of one hour per four weeks is used in order to have an acceptable performing system. This criterion allows for a simple conclusion per scenario, acceptable or unacceptable. However, the method is debatable, as it does not provide information about the impact of the power deficits. The second and third performance levels provide additional information about the electricity balance. The second performance level sketches a profile of which and how many demand and supply response mechanisms are used to balance the electricity. The focus is on three main response mechanisms:

1. the use of backup FCEVs (supply response),
2. increasing the FCEV output (supply response) and
3. price level control (demand and supply response).

The third performance level provides information about the quality of the electricity system. It contains two measures, the efficiency of the system as well as the share of hours that are produced by FCEVs of owners that enjoy producing electricity.

In the performed experiments the control structure is varied between two extremes, a strict and a loose control structure. In the strict control structure FCEVs are obliged to be available for scheduling seven times per week, the FCEV output is 40 kW and the price level control is strong (reducing demand about 50%). In the loose control structure FCEVs are obliged to be available for scheduling just once per week, the FCEV output is 20 kW and the price level control is weak (reducing demand about 20%). The base and sub-strict control structure have values of the control elements in between these extremes. The base scenario is used in most of the experiments and contains the default values of the control structure.

The analysis with the model identified significant differences in the system's performance in summer and in winter. In summer, 80 FCEVs are required for an acceptable performance with the base control structure and 100 FCEVs with the loose control structure. In winter 200 FCEVs are insufficient to obtain less than one hour of power deficit per four weeks with the base control structure. 100 FCEVs and the sub-strict control structure lead to an average of 1,08 hours of power deficit per four weeks, 200 FCEVs reduce this value to 0,52.

The willingness of residents to produce electricity with their FCEV and their reaction to supply and demand response mechanisms are the two main factors of social cohesion incorporated in the CaPP model. The model behavior shows the importance of these elements. In a reference scenario, which includes 100 FCEVs, the base control structure, RE resources of May, 50% of residents reacting to response mechanisms and 50% of residents always available for production when parked at home, 0,38 hours of power deficit occurred during four weeks. If residents do not react to response mechanisms and if their FCEVs are available for the minimum required timeframes per week for power production (as opposed to always available when parked at home), a total of 172 hours of power deficit occurred per four weeks. Having residents reacting to control mechanisms and only available for power production for the minimum number of required timeframes per week, has a large impact on the second performance level. In that case 126 hours of additional response mechanisms are required to balance the electricity compared to the base scenario.

More detailed analysis of the influences per performance level, season, control element and number of FCEVs can be found in the model behavior section of this thesis. The results of this research provide project developers with preliminary insights on suitable types of control structures for planned CaPP systems. It provides expectations about the system's electricity balance, which can support setting out strategies for successful implementation of the first CaPP projects. The model is flexible, such that it can also be applied in different cases and more specified cases. Information about the degree of social cohesion as well as mobility and demand profiles have been shown to be valuable, as they are highly influential factors in the performance of a CaPP system. It is recommended that CaPP project developers perform market research on these aspects in early stages of the project. Stakeholders related to policy making in CaPP systems are recommended to apply different policies in different seasons. Loosening scheduling rules when possible results in a higher degree of freedom for FCEVs (i.e. their owners). Adequate response mechanisms allow for the local energy market to find electricity balance by itself.

During the model development phase of this master thesis project a variety of model simplifications of the complex CaPP system is made. The model is freely available and all interested modelers, engineers and programmers are invited to adjust it for their own purposes in any way possible. Specific suggestions to improve the model are: developing alternative power production scheduling procedure, implementing an extensive solar yield scheme, expanding the model by implementing full electric vehicles and researching FCEV decision making.

Preface

The master program 'Engineering and Policy Analysis' at the TU Delft educates its students to deal with complex problems with a multi-perspective approach. Students with technical backgrounds are taught skills in fields as economics, statistics, modeling and policy analysis. I particularly enjoyed the modeling courses such as system dynamics modeling and discrete system modeling. This caused me to become fiercely interested in agent-based modeling (ABM) the moment I discovered my faculty had a large group of ABM experts. I decided to learn agent-based modeling by myself and to find a master thesis topic to which I could apply this method. As an engineering and policy analysis student, my modeling graduation topic would naturally involve a complex socio-technical system. A final prerequisite for my thesis was related to my personal interest: something related sustainablility. All these topics have come together perfecly in the development of an ABM for a Car as Power Plant neighborhood. If I were to tell myself of eigth years ago: 'you will graduate on developing a model that explores an innovative sustainable energy system', my enthusiasm would probably have caused me to study much harder.

I practically performed the complete research at the office of EV consult in Amsterdam, where I was doing an internship as well. This resulted in some worthwhile delay in the whole process. Besides spending months of modeling behind my laptop, I have gained experience in being a consultant in an overlapping topic: sustainable mobility. The downside of this process with respect to my thesis was that I worked on the project as a 'lone wolf'. Despite several attemps from Esther, my direct supervisor, to get more involved with the CaPP team from the university. Nevertheless, I believe I can be very pleased with the results of this thesis in which both my strengths and weaknesses have dominated the workflow from time to time.

Foremost, I would like to express deep gratitude to Esther Park Lee who, as my direct supervisor, performed very helpful, professional and insightful throughout the whole project. Whenever needed, I could count on her and she would provide very constructive feedback. I have experienced a very pleasant, open working relation with the whole committee. I believe steep learning curves in such big individual projects can be achieved only if students have the freedom to define their own trajectory, even though this occasionally means to make mistakes. The structure and freedom that the committee and the TPM faculty allowed during my master thesis (and complete master's program for that matter) has been extremely pleasant. I would like to thank the whole committee for their time and effort they have put in me and my project.

Finally, I would like to thank: Martijn Warnier for his guidance, Auke Hoekstra for taking the time to validate the CaPP model, Marleen Wijnands, for her invaluable support, and Suzanne van de Kooij, whose energetic enouragements kept me going during long and stressful days.

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List of Abbreviations

CaPP – Car as Power Plant

RE – Renewable energy

EV – Electric vehicle

FCEV – Fuel cell electric vehcile

FEV – Full electric vehicle

PHEV – Plug-in hybrid electric vehicle

ICEV – Internal combustion engine vehicle

H_2 – Hydrogen

ABM – Agent based modeling or agent based model

PV – Photo voltaics

V2G – Vehicle to grid

Avg – Average

Sd – Standard deviation

Min – Minimum

Max – Maximum

1 Introduction

1.1 Towards a Net-Zero Emission Society

Anthropogenic emissions have raised atmospheric CO_2 concentrations to levels unprecedented in at least the last 800,000 years (IPCC, 2013). Even though the greenhouse effect of CO_2 molecules is unequivocal, the exact impact of atmospheric CO_2 concentrations on the global warming creates a significant uncertainty. Global leaders try to set out sustainable pathways during the yearly climate conference. At the Paris climate conference (COP21) in December 2015 this successfully resulted in a declaration, signed by 196 countries, to pursue limiting global warming to less than 2°C (UNFCCC, 2015). According to common published scenarios by the Massachusetts Institute of Technology (Reilly et al., 2015) and the International Institute of Applied System Analysis (IIASA, 2012), this roughly means that net-zero emissions need to be realized by 2070.

The global primary energy use has shown a steady increase from 25 EJ in 1850 to about 500 EJ nowadays (IIASA, 2012). Due to the expected growing global economy and the growing world population, this trend is not likely to turn around in the next few decades (World Energy Council, 2013), even with large scale adoption of renewable energy technology. The MIT energy outlook predicts an increase in demand of about 60% by 2050 compared to 2010 (Reilly et al., 2015). The increase in energy demand and the ambition to achieve net-zero emissions by 2070 imply radical transformations of the global and local energy systems. Central to these transformations is the switch from carbon-based fuels to renewable technologies.

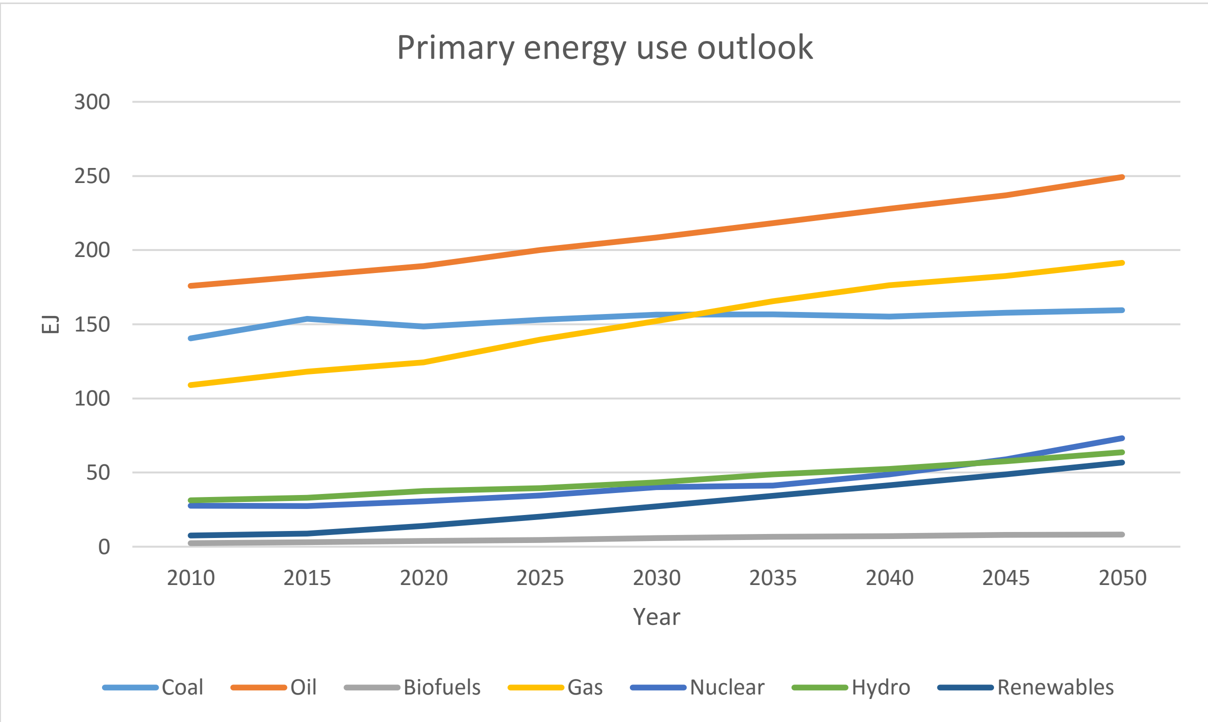

Figure 1: Primary energy use outlook, 2050

(adapted from Reilly et al. (2015))

1.2 Fuel Cell Electric Vehicles and Car as Power Plant Systems

By 2016, around 1.2 billion passenger cars are on the road worldwide (Navigant Research, 2015). 99.9% of these provide mobility with the incumbent internal combustion technology (IEA, 2015a), completely running on carbon-based fuels. The transport sector emits altogether 14% of the global CO_2 emissions (IPCC, 2014). The remaining 0.1% of the vehicle fleet is comprised of a variety of electric vehicles (EVs), among which full electric vehicles (FEVs), plug-in hybrid electric vehicles (PHEVs) and fuel cell electric vehicles (FCEVs). Although still small in numbers, EVs are likely to be the future of the mobility sector (Trigg, Telleen, Boyd, & Cuenot, 2013). Both the market entrance and the market adoption of EVs have been, and will be, fostered by demand for sustainable products and technological innovations in fields such as electrical engineering, battery technology (Haddadian, Khodayar, & Shahidehpour, 2015; Rezvanizaniani, Liu, Chen, & Lee, 2014), and fuel cell technology (Alaswad, Baroutaji, et al., 2016). Cost and performances of the different types of EVs challenge those of ICEVs more and more every year (Newbery & Strbac, 2014).

With only two models available on the market (the Hyundai ix35 and the Toyota Mirai), FCEVs are in the earliest phases of adoption. Governmental roadmaps and market prognoses often foresee significant FCEV market penetration by the year 2030 (IEA, 2015b). Prof. Ad van Wijk from the TU Delft is a firm believer of the FCEV technology. His research focuses on the use of FCEVs for electricity production as well as mobility. This concept is named ‘Car as Power Plant’ (CaPP), and potentially holds the key to the required radical transformations of our energy systems (Wijk & Verhoef, 2014). In a CaPP neighborhood renewable energy is produced locally. The energy is either used directly in the neighborhood or stored, via electrolysis with rainwater, in hydrogen. FCEVs are fueled with the hydrogen and produce electricity for either mobility or for the community. CaPP is an hollistic approach that integrates the water, energy and mobility systems into one connected utility system. This allows achieving net-zero emissions not only in the transport sector, but also the building sector, the electricity sector and, potentially, the industry sector.

The idea of a CaPP system originated from the notion of efficient use of resources. FCEVs are essentially small hydrogen fueled power plants and the average passenger car is only in use for about 10% of the time (Wijk & Verhoef, 2014). The production potential of a FCEV fleet is huge, considering the number of passenger cars in the world and the global energy demand: see Table 1.

Table 1: The potential of CaPP systems

Component	***2015***	***2030***
Passenger vehicles in the world (cars)	1.200.000.000[1]	2.000.000.000[1]
FCEV output (kW)	100[2]	100[2]
Potential global production from FCEVs (TWh/year)	1.051.200	1.752.000
Global energy demand (TWh/year)	25.000[3]	35.000[3]
%-time a FCEV is needed for power production	2,48%	1,99%
%-time passenger vehicles are available	90%[2]	90%[2]

[1](Navigant Research, 2015), [2](Wijk & Verhoef, 2014), [3] (Bayram, Michailidis, & Devetsikiotis, 2014)

1.3 Technology status

The ideological satisfaction of a sustainable interrelated and interconnected society might sketch a futuristic image of the CaPP concept. CaPP systems, however, require nothing more fancy than current day technologies of FCEVs, smart meters, renewable energy (RE), and hydrogen production. RE production from wind and hydro are seen as mature technologies. Solar energy from photo-voltaics (PV) has become cost-efficient in many scenarios during the last decade (Badawy, 2015). However, a common issue with high penetration of RE is the need for overcapacity due to rarely synchronized energy supply and demand. Hydrogen production through electrolysis has been used for non-commercial purposes for more than fifty years now (Bertuccioli et al., 2014), but the high energy cost of electrolysis result in a polluting and inefficient process when fueled by fossil fuels. Those issues are not transferable to CaPP systems, because CaPP systems store excess electricity and all energy is renewable. Additionally, the CaPP concept is based on the performances of current FCEV technologies such as power output, efficiencies, capacity, lifetime and cost. Innovation is likely to improve these performances (IEA, 2015b), increasing the potential and attractiveness of CaPP systems.

CaPP is a relative new approach for our energy systems that still requires proof of concept. Providing that proof is one of the aims of the 'Green Village' project from the TU Delft. In the Green Village a FCEV will power several buildings with local renewable energy. It will be the first CaPP pilot project, hoping to gather experience on operational barriers and performances. Research in fields related to FCEVs and vehicle to grid (V2G) can also contribute towards the proliferation of the CaPP concept. Such fields include:

1. Fuel cell technology, treating fields as nanotechnology, fuel cell chemistry (Alaswad, Palumbo, Dassisti, & Olabi, 2016), hydrogen production (IEA, 2006), and platinum mining (IEA, 2006)
2. FCEV innovation, on which car manufacturers spend billions of dollars to develop competitive FC automobiles
3. Research on microgrids (Lidula & Rajapakse, 2011)
4. Research on electrical power engineering (Haidar, Muttaqi, & Sutanto, 2014)
5. Research on vehicle to grid (V2G) (Guille & Gross, 2009; Mwasilu, Justo, Kim, Do, & Jung, 2014) .

1.4 The knowledge gap

Sufficient electricity supply is an important factor when integrating the mobility and the energy systems of a neighborhood or society. A particular crucial role in the electricity supply of a CaPP system is played by the availability of FCEVs for power production. The availability of FCEVs depends on unpredictable mobility patterns and social attitudes of the participants. To assure the electricity balance in a CaPP system, some form of control structure is required. In this thesis the control structure of a CaPP system is defined as *'a set of rules and incentives that influence the electricity supply and demand'*. Pilot testing control structures without the existence of neighborhoods with FCEVs would be difficult and costly. However, knowledge about the impact of different scenarios for the control structure is valuable for the proof of concept of CaPP systems.

KNOWLEDGE GAP

The impact of different CaPP control structures on electricity supply and demand is required for the proof of concept of CaPP systems, but, partly due to the current FCEV market status, such control structures have not yet been explored.

Main Research Goal

Obtaining quantitative knowledge about the influences of electricity supply and demand control structures in a Dutch 200 household CaPP system by coupling individual behavior of residents of a neighborhood to current available CaPP technologies on the operational scale.

The primary reason to focus on a Dutch 200 household neighborhood is to limit the research scope to a specific case. The focus means to assess a typical Dutch case, i.e. a CaPP neighborhood with Dutch mobility patterns, Dutch electricity demands and Dutch RE resources. The quantitatve insights this research aims to achieve have great societal value. Any step towards realizing the first CaPP neighborhoods bring zero-emission societies closer. Accelerating this process means to achieve sustainable environments sooner.

Stakeholders in CaPP pilot projects could use the results for a variety of purposes. This is not limited to providing quantitative insights for defining adequate policy frameworks and system configurations. Potential residents of a CaPP neighborhood would be helped to form expectations about the usage of their FCEV and the circumstances related to electricity supply. This clarifies the impact of the CaPP system on their lifes, promoting participation pilot projects. If the results are applicable beyond the specific case study, the societal value of this research would be significantly increased. Therefore, a secondary goal is to develop a research methodology that allows for simple adjustments to study other cases or future scenarios.

The main research question is constructed in line with the main research goal:

Main Research Question

What are the influences of the electricity supply and demand control structure on the electricity balance of a Dutch 200 household CaPP neighborhood?

Seven specific elements of a control structure that are suitable in a CaPP neighborhood are studied. Each element belongs to one of the three following categories: 1) scheduling rules, rules for scheduling FCEVs for power production, 2) demand response, incentives that influence the household demand, and 3) supply response, incentives that influence the electricity supply by FCEVs. The seven elements, a description and their categories are shown in Table 2

Table 2: Elements of the control structure

Control structure element	*Description*	*Control category*
Minimum production timeframes per week	The amount of times FCEVs should be available for scheduling per week	Scheduling
Maximum production timeframes per day	The amount of times FCEVs can be scheduled per day	Scheduling
Default FCEV production output	The amount of FCEVs that will be scheduled to supply the expected demand	Scheduling
Maximum FCEV production output	The potential FCEV output increase for power production	Supply response

#FCEVs for backup scheduled	The amount of FCEVs that will be scheduled for back up	Scheduling
Home side demand control	An incentive to shift evening peak demand to daytime hours	Demand response
Price level control	A financial incentive that reduce the demand and increases the supply by increasing the kWh price of electricity	Supply response & demand response

The social attitudes of CaPP system's participants influence how they react to supply and demand response and how frequently they are willing to produce electricity with their FCEV. A CaPP neighborhood with a large share of active and responsive participants can be said to have a high degree of social cohesion. This degree of social cohesion influences the electricity balance of the neighborhood, and, thus, also the effects of the control structure. Other factors that play important roles in the effects of the control structure are the RE resources and the number of FCEVs. The above leads to the following division of the main research question:

Subquestions

1. *What are the implications of seasonal differences for the control structure of the CaPP neighborhood?*
2. *What is the impact of scheduling rules on the electricity balance of the system?*
3. *What are the influences of home-side demand control on the electricity balance of the system?*
4. *How do supply response mechanisms influence the electricity balance of the system?*
5. *How do the number of FCEVs and the degree of social cohesion affect the control structure?*

These sub questions are not independent. For example, the effects of supply response depend on the number of FCECs that are scheduled, which is dependent on the scheduling rules.

1.5 Research Scope

The electricity supply and demand control structure of a CaPP system is part of the system's management. The management of a CaPP system can be identified as 'community energy management' (see section 2.2). Community energy management includes aspects such as financial risk or technical and organizational management. The specific scope of this research with respect to community energy management is illustrated in Figure 2. It should be noted that controlling the electricity supply and demand could contain more aspects than the seven elements studied in this research.

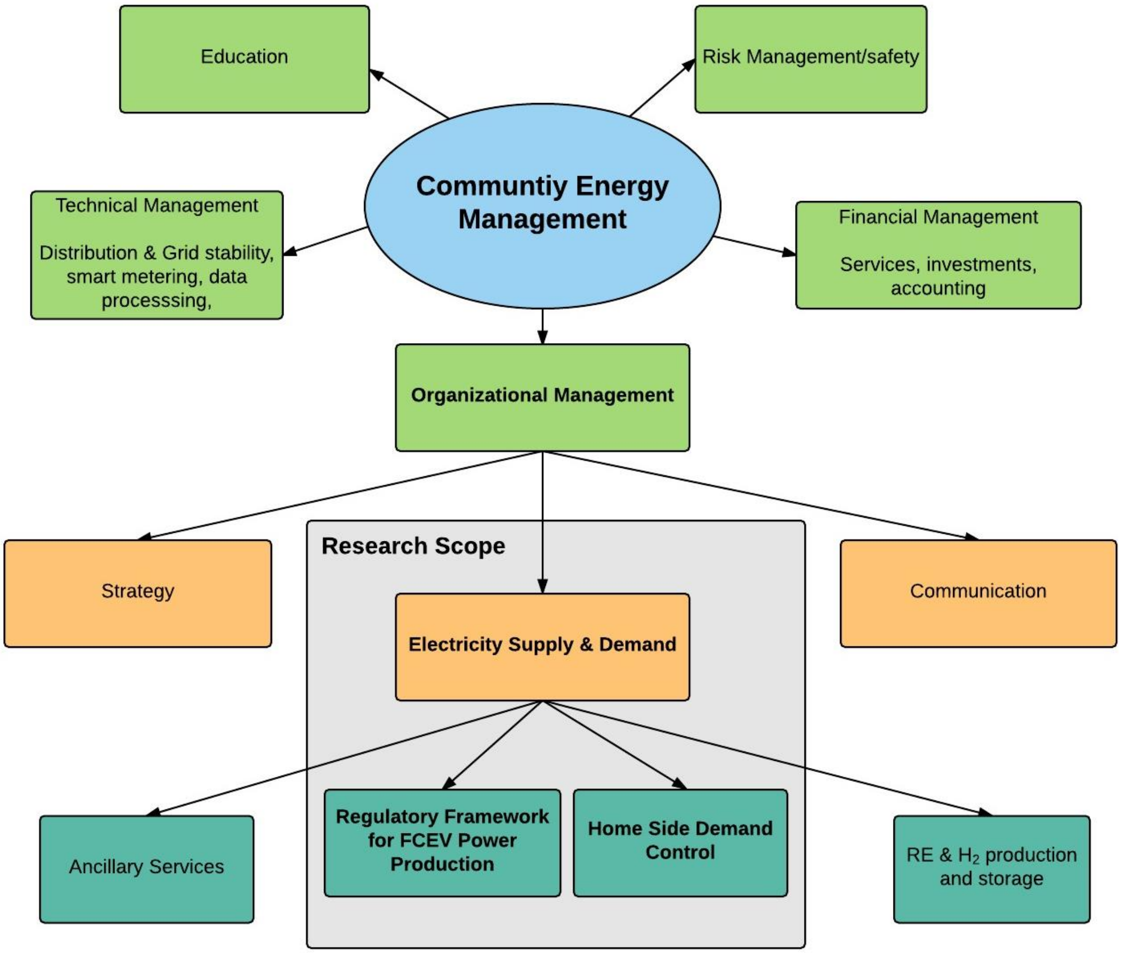

Figure 2: Research scope

Varying the seven control elements can lead to many possible forms of the control structure. To focus on specific attitudes, four scenarios for the control structure are defined. The scenarios vary from a 'loose' control structure, applicable in situations with abundant electricity supply, to a strict control structure, applicable in situations with limited electricity supply. The specific value ranges are chosen to be reasonable and practical for real CaPP systems:

- Only in the strict and sub-strict control structure more than one maximum production timeframe per day (with at most three), as one production timeframe corresponds to two production hours.
- FCEVs are obliged to be available for power production scheduling at most seven timeframes per week.
- An output range of 15kW to 40 kW, corresponding to 8 and 3 potential production hours with a full tank (which contains around 118 kWh, see calculation below).
- Home side demand control is used in all control structure scenarios. Its effects are studied in separate scenarios.
- Strict price control is assumed to lead to a 50% reduced demand and loose price control to a 20% reduced demand. Note, price control only affects the demand of active participants.

Table 3: Control structure scenarios

Control component	*Loose control structure*	*Base control structure*	*Sub-strict control structure*	*Strict control structure*
Minimum production timeframes per week	3	5	6	7
Maximum production timeframes per day	1	1	2	3
Default FCEV output	15	15	25	30
Maximum FCEV output	30	30	40	40
#FCEVs for backup scheduled	2	2	1	1
Home side demand control	on	on	on	on
Price level control reduction factor	0.8	0.7	0.6	0.5

$$kWh\ production\ from\ a\ full\ FCEV\ tank =$$

$$\frac{tank\ capacity * FC\ efficiency * energy\ density\ of\ hydrogen}{\#\ seconds/hour} =$$

$$\frac{5000\ g^1 * 60\ \%^1 * 142\ MJ^2}{3600} = 118{,}33\ kWh$$

[1](Wijk & Verhoef, 2014), [2](IEA, 2006)

To obtain the quantitative knowledge that answers the research questions an Agent-Based Model (ABM) is developed. Chapter three elaborates on the reasoning behind the choice of agent based modeling. With the research goal in mind the focus of the model is defined as:

Focus of the Agent-Based Model

Capturing the emergent electricity supply and demand balance of a CaPP system as a result of the dynamics of individual mobility patterns, individual electricity demand subject to the control structure.

1.6 Thesis Outline

The core of this thesis document entails the developed ABM and the resulting model behavior. In chapter 2, FCEV technology is briefly explained and several theories are applied to CaPP systems. Chapter 3 explains the methodology of this research. From that point onward the thesis focuses on the model development, experimentation and interpretation in the sections: system identification, system formalization, model functionality, model verification and validation, model behavior, conclusion, discussion and reflection. All figures, tables and graphs in this work are original unless denoted differently.

2 Theoretical framework

This chapter discusses several theories related to CaPP system. Firstly, fuel cells and the market status of FCEVs are shortly discussed. Secondly, CaPP systems are identified as community energy systems, micro grid systems and smart grid systems. Lastly, CaPP systems are related to the theory of disruptive innovations.

2.1 Fuel Cell Electric Vehicles

Vehicles with a fuel cell drivetrain are called fuel cell electric vehicles. Their fuel cell stock converts chemical energy from hydrogen and oxygen into electrical energy and water. Several types of fuel cells exist, the most common, and the one used in FCEVs, is the Proton Exchange Membrane Fuel Cell (PEMFC). The basic chemistry of a hydrogen PEMFC is fairly simple (Alaswad, Palumbo, et al., 2016):

- A catalytic oxidation reaction of H_2 occurs at the anode side of a fuel cell, splitting hydrogen into two protons (H^+) and two electrons (e^-).
- The two protons permeate through a non-conductive polymer electrolyte membrane to the cathode side.
- The two electrons are conducted via an external circuit to the cathode side.
- A catalytic reduction reaction of protons, electrons and oxygen molecules occurs at the cathode side.
- The electron flow via the external circuit is the electrical produced by the fuel cell.

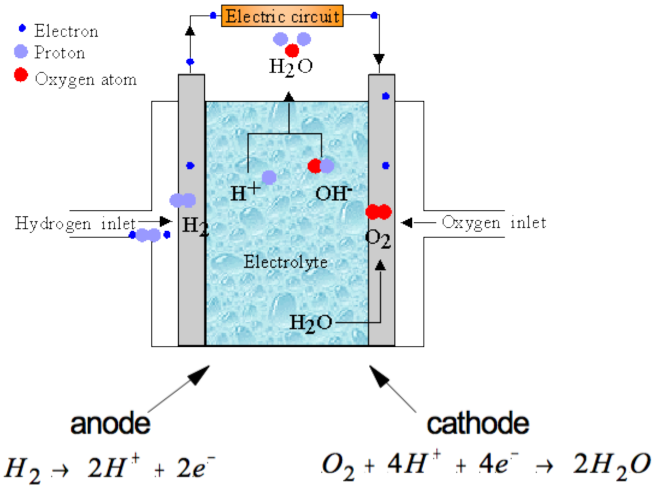

Figure 3: PEMFC functionality

(source: University of Cambridge, http://www.ceb.cam.ac.uk/research/groups/rg-eme/teaching-notes/fuelcells)

The performance of such a PEMFC is dependent on a variety of factors. The following three aspects are fields on which current FCEV research hopes to improve FC technology (Alaswad, Palumbo, et al., 2016):

1. The cathode catalyst
2. The non-conductive polymer membrane
3. Methods to reduce carbon monoxide poisoning of the fuel cell

Fuel cell technology itself is not novel. The concept was already demonstrated in 1801, and has been extensively developed for the purpose of space missions during the cold war. However, the relative high costs of this technology made it unattractive for passenger cars (Fuel Cell Today, 2012). Driven by sustainability considerations, several car manufactures started to develop FCEV prototypes in the '90s (Fuel Cell Today, 2012). This resulted in the launch of the first commercial passenger FCEV in 2008, the Honda FCX clarity. Just around 80 of these models have been leased until the announcement of the phasing out of the model in 2014 (CEPI, 2014). In 2014 and 2015, respectively, two newer models joined the market, the Toyota Mirai and the Hyundai ix35. Hyundai announced the production of 10.000 ix35 models, making it the first mass-produced FCEV (Lucas, 2012). The sales target for the Toyota Mirai (marketed late 2015) is set at 1.000 for 2016. Adding up these figures lead to a current global FCEV deployment of a mere 1.000 units.

The slow market adoption of FCEVs was not unexpected. The lack of hydrogen refueling stations limit the practibility of FCEVs as passenger cars to very specific regions and purposes (CEPI, 2014). A collective of automakers, hydrogen providers and policy makers in California set out to install the first hydrogen station network. Their aim was to roll out a network of 68 stations between 2013 and 2015 to commercialize FCEVs in California (Kang, Brown, Recker, & Samuelsen, 2014). Denmark recently finished world's first national hydrogen fueling station network by constructuing its ninth hydrogen station, as shown in Figure .

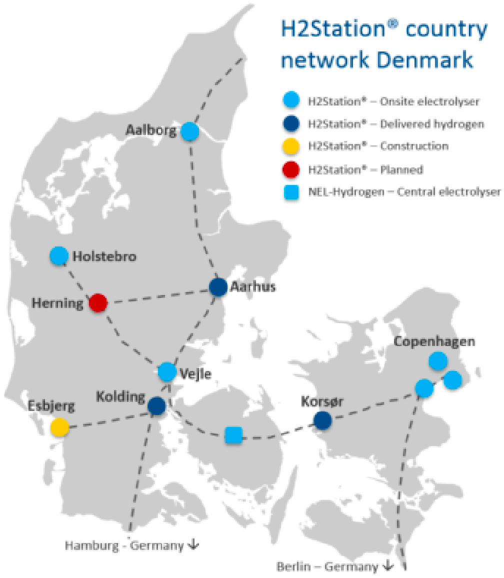

Figure 4: Hydrogen charging network in Denmark

(source: Insideevs.com)

2.2 Energy systems of the future

Current electricity grids are part of a basic, inefficient and inflexible energy system. They convert about two thirds of its energy into waste heat, are unidirectional, lose about 8% on transmission, have 20% of its generation capacity only in use for 5% of the time and are hierarchical, making them prone to large-scale failures (Farhangi, 2010). Such characteristics are not suitable to adress the core challenges utilities face with respect to energy systems (Tuohy, Milligan, Silva, & Müller, 2013):

- Generation diversification
- Optimal deployment of expensive assets
- Demand response
- Energy conservation
- Reducing the carbon footprint

Three innovative approaches to energy systems with an alternative grid structure aim to adress these issues: community energy systems, microgrids, and smartgrids. All three approaches utilize distributed generation, i.e. localized, (partly) sustainable electricity generation, shifting from large-scale electricity production with a central grid to local-scale production and distribution (Chicco & Mancarella, 2009). The approaches differ in their focus (see Table 4: Focus of different energy system approachesTable 4), making them non-mutual exclusive. In other words, an energy system can be classified as a community energy system, a microgrid and a smartgrid at the same time, or any combination of those.

Table 4: Focus of different energy system approaches

Energy system approach	***Focus***
Community energy systems	Community participation and benefits[1]
Microgrids	Localized power system engineering and grid optimization[2]
Smart grids	Integration of information and communication technologies[2]

[1](Gordon Walker & Devine-Wright, 2008), [2] (Lidula & Rajapakse, 2011), [3](Ipakchi & Albuyeh, 2009)

2.2.1 Community energy systems

A community energy system integrates decentralized sustainable energy generation with the local communtiy. They are often seen as testing fields for radically different energy systems because the social acceptance of it plays an important role. A clear definition of community energy systems has proven hard to find due to diversity in methods, purposes and social arrangements. Walter & Simcock analyzed a variety of community energy projects and identified two key dimensions (Walker & Simcock, 2012):

1. A process dimension, concerned with who is involved and who has influence in the system.
2. An outcome dimension, concerned with the distribution of social and econmic benefits.

The upfront benefits from most community energy systems are generated energy and avoided carbon emissions. In addition is a wide variety of other benefits possible, such as locally generated income, a cheap and reliable energy supply, participatory and locally accepted project development, community cohesion and improved local social capital. Depending on one's viewpoint a particular dimension can be prioritized (A and B in the figure below) or a wider perspective can be taken (C in the figure below).

The electricity equilibrium of a CaPP system is balanced by the collective demand, the power production behavior, and power production scheme. All residents are directly involved in the system and they can be characterized as the main participants. Their behavior is the prime influential factor. A distinction can be made between residents with and without FCEVs, but regardless, a CaPP neighborhood scores very open and participatory on this dimension. A policy related party with roles such as regulation, monitoring and feedback, might pull this dimension slightly in the direction of the closed institutional side. It is also possible to keep these activities within the community itself.

Key to a CaPP community energy system is to be energy self-sufficient in a sustainable manner (Wijk & Verhoef, 2014). With that in mind, benefits of the CaPP energy system are green and reliable energy and fuel supply. These benefits are distributed among the community, marking the outcome dimension entirely local and collective. The other benefits described above (financial benefits, community cohesion and improved social capital, and acceptance) are conceivable for a CaPP neighborhood as well. In addition, a a CaPP system provides participants control of one's own energy/fuel profiles and bills by (financial or social) incentives the participants can respond to.

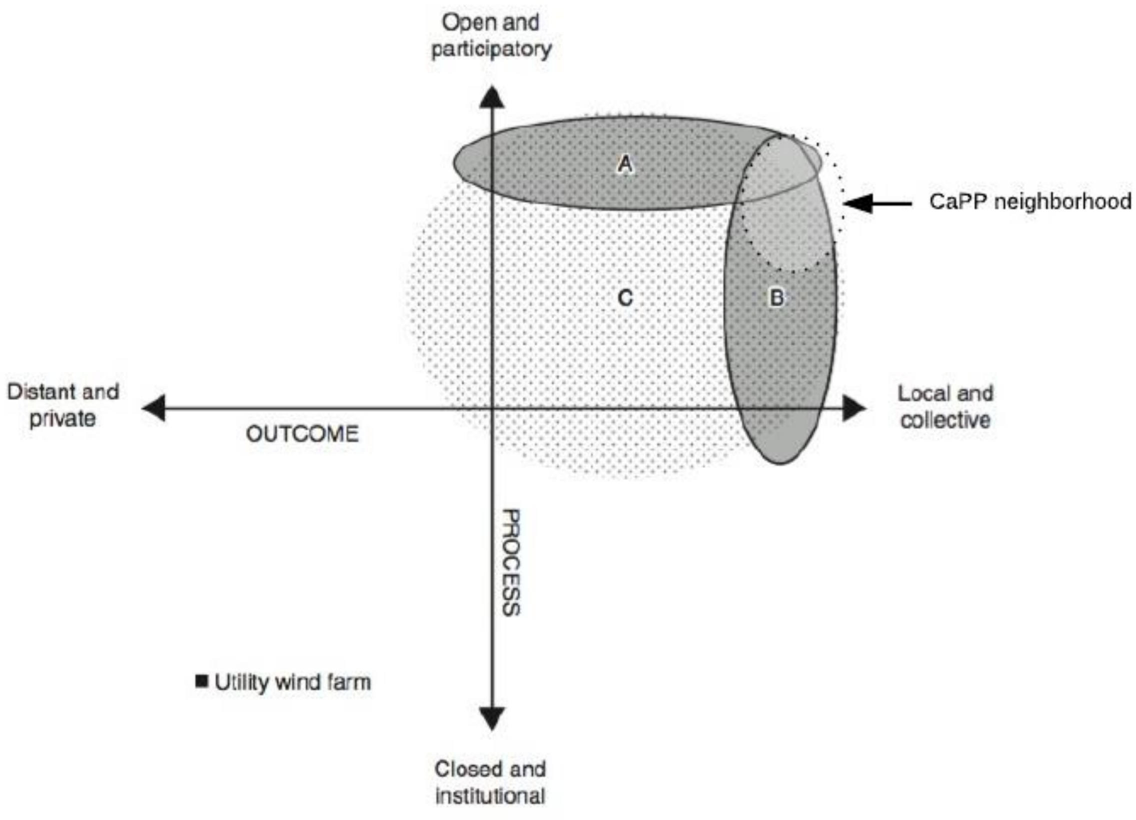

Figure 4: Dimensions of community energy systems and the CaPP position

(adapted from Walker and Simckock (2012))

2.2.2 Microgrids

A microgrid is a local electricity grid that comprises distributed generation, local energy storage and customer loads (Chicco & Mancarella, 2009). They provide varying degrees of electricity autonomy by operating either grid-connected, grid-isolated or in some transition between those. Distributed generation technologies used in microgrids may include any form of local generation, from emergent renewables to incumbent IC engines. Lately, has the focus been on low-carbon methods, such as hydro, wind and cogeneration (Lidula & Rajapakse, 2011). Fuel cells are seen as promising future alternatives due to their potential extremely high electrical efficiency and integration with hybrid settings. Energy storage is essential to successful operation of the autonomous microgrid, it balances the power demand and supply in three ways: 1) response to high frequency load fluctuations, 2) allows the DGs to operate as dispatchable units and 3) provides the initial energy demands (Lidula & Rajapakse, 2011).

2.2.3 Smart grids

Smart grids are the next-generation, intelligent electricity grids. In essence, they provide stakeholders full transparancy and control over the electricity balance through two-way communication and smart metering (controls and sensors). Enabling utilities to make use of demand response, peak shaving, and service quality control (Farhangi, 2010). Smart grids empower stakeholders to realize energy transitions, because their intelligence allows for decentralized generation to be incorporated effectively. The characteristics of a smart grid and those of the traditional grid are shown in the table below.

Table 5: Characteristics of smart grids (Farhangi, 2010)

Traditional grid	***Smartgrid***
Electromechanical	Digital
Unidirectional	Bidirectional
Centralized generation	Distributed generation
Hierarchical	Network
Few sensors	Many sensors
Blind	Self-monitoring
Manual restoration	Self-restoration
Failures and blackouts	Adaptive and islanding
Limited control	Pervasive control
Few costumer choices	Many costumer choices

2.2.4 Conclusion with respect to CaPP Neighborhood

In the previous sections, three energy system approaches that can adress future grid challenges have shortly been introduced. An energy system can be catergorized as one or more of these approaches at the same time. The conceptual structure of an energy system that is both a smart and a microgrid is shown in Figure 5. Depending on the process and outcome dimension of such a system (i.e. who participates and who benefits), it can additionaly be categorized as a community energy system, as is the case with a CaPP neighborhood. The concuptual structure of a CaPP neighborhood is designed in Figure 6.

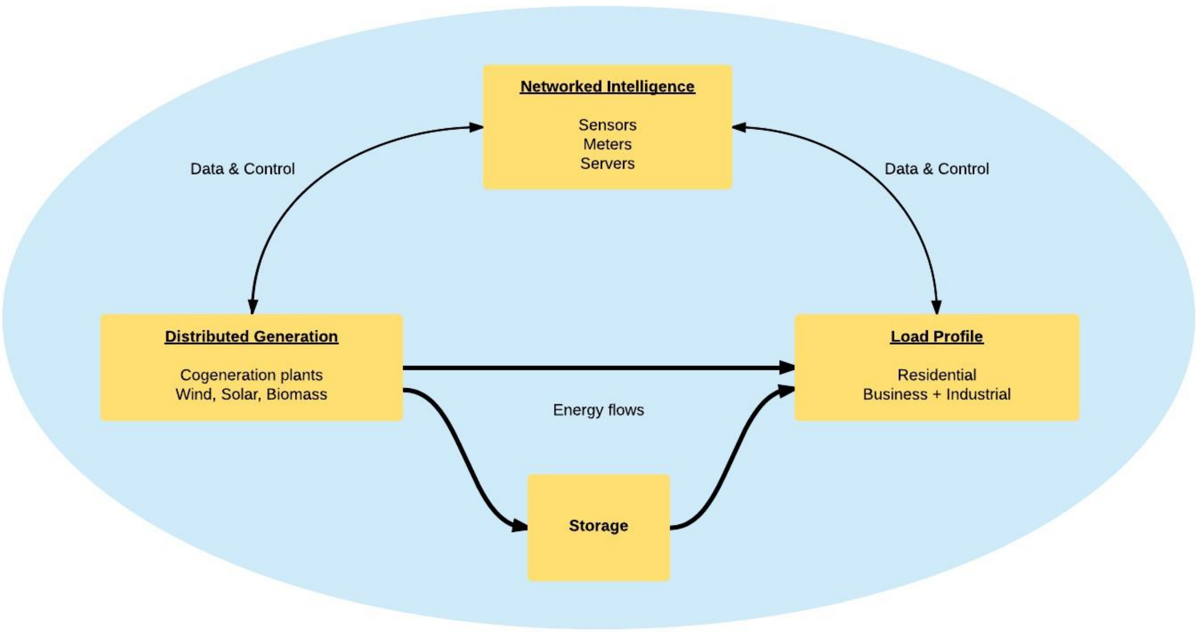

Figure 5: Smart micro grid system

(source: original)

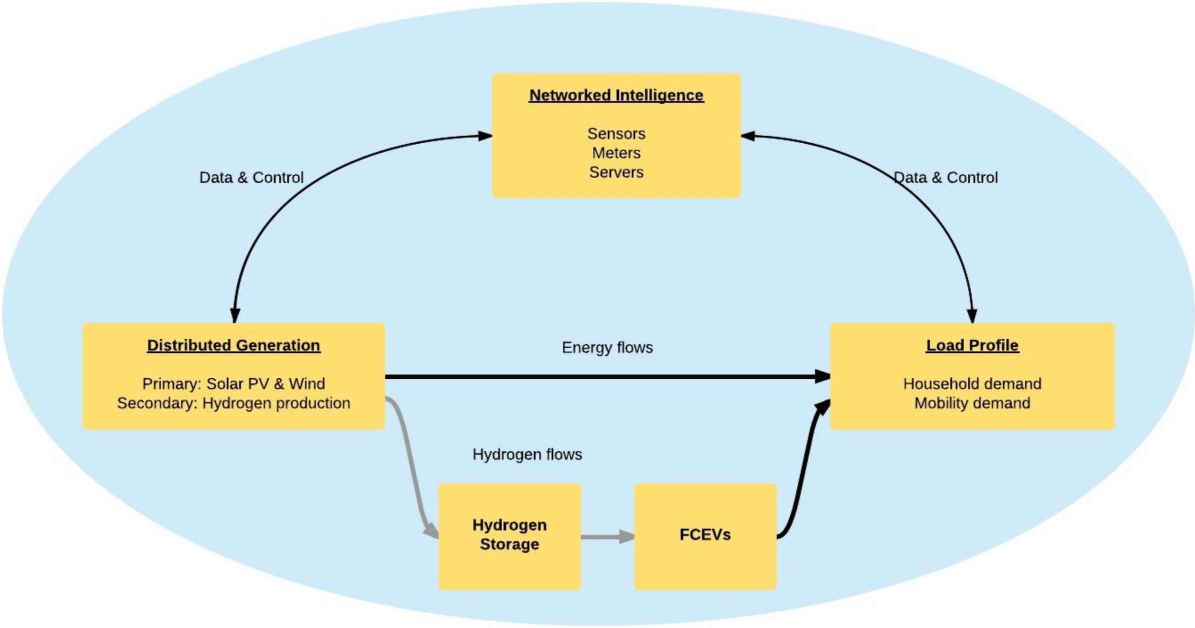

Figure 6: The CaPP system as a smart micro grid system

(source: original)

2.3 Disruptive Innovation

In the theory of innovation as defined by M. Christensen (2015) two main types of innovation can be distinguished: sustaining innovation, one that does not affect the existing markets, and disruptive innovation, one that brings a new performance set that, if successful, ends up overtaking the existing market (Klenner, Huesig, & Dowling, 2013). Disruptive innovations initially underperform compared to incumbent technologies on dimensions that appeal to the mass market. But their new performance set includes higher values along other dimensions that are desired by small consumer groups. Initially the theory was described with the term 'technology', but to include services, the term 'innovation' was chosen. In literature these terms are often interchangeable (Klenner et al., 2013).

With that framework of innovations, CaPP systems can be defined as a disruptive innovation. They provide a wide set of new values (local participation, environmental benefits, consumer choices, autonomy, etc) compared to the current mobility and utility sector. They do not yet appeal to the mass market, because the mass market is satisfied with the current energy supply systems and FCEV deployment remains extremely low. Exclusive niche markets for the disruptive CaPP systems may be progressive neighborhoods with environmental oriented residents.

If CaPP systems end up being a successful disruptive innovation, Ad van Wijk's vision of a CaPP society will be the result. However, the theory of disruptive innovation has little predictive value, it is hard to determine without hindsight what disruptive technologies will be successful (Klenner et al., 2013). Hardman et all. researched common characteristics of successful disruptive innovations (Hardman, Steinberger-Wilckens, & Van Der Horst, 2013). Their results and the correspondence to CaPP systems are listed in the table below. The table shows that most characteristics of a successful disruptive innocation are potentially present in CaPP systems.

Table 6: Characteristics of disruptive innovations with respect to CaPP systems

Disruptive Innovation Characteristic (Hardman et al., 2013)	***Correspondence to CaPP systems***
The threat of the new technology is not often recognised by existing market leaders	Applicability of CaPP is currently very limited
Disruptive technologies are initially more expensive than the incumbent technologies.	FCEVs and RE production are currently relative expensive
The quality is initially worse then the quality of the technologies that will be replaced.	Quality is yet unproven
The technologies have some form of 'added value' to the consumer.	Environmental benefits and social capital
The disruptive technologies will fill niches markets first, then spread out to the macro level.	Likely the focus on progressive neighborhoods
The incumbent technology in turn becomes the technology for niche market applications.	Centralized power plants and ICEVs are likely to remain used in specific cases

3 Methodology

Besides modelling, there are many other ways to obtain insights in the behavior of CaPP systems. Market exploration, pilot projects and technical analyses are some examples. This methodology chapter elaborates on the choice of agent-based modeling and defines a performance framework for the model to structurally draw conclusions from the model behavior.

3.1 A Model of a CaPP system

A model is a simplified representation of a system with the goal of understanding the system's behavior. The socio-technical system of a CaPP neighborhood is the system whose behavior this research aims to understand. Socio-technical systems refer to the interaction between infrastructure, technology and human behavior (Righi & Saurin, 2015). In the socio-technical CaPP system, mobility patterns, household electricity demand and attitudes of participants are the factors of human behavior. FCEVs, RE production and the microgrid distribution system are the technologies and infrastructure.

A model is a simplification by definition. The modeler makes the simplification based on his or her perception, knowledge and available data. Understanding the model limitations that result from these simplifications is crucial for correct interpretation of the results. The following two chapters (Chapter 4 'System Identification' and Chapter Formalizing the CaPP Neighborhood Model') are devoted to clarify the model boundaries and the simplifications made for the CaPP model of this research.

3.2 The choice of Agent-Based Modelling

Computer simulations provide tools for modelers to asses a wide variety of scenarios and parameters of simplified systems. Basic reasoning leads to the conclusion that a model of the socio-technical system of a CaPP neighborhood requires at least 50-100 parameters. There are parameters describing the characteristics of households; such as, the number of residents, an amount of PV modules, parameters concerning energy demand, parameters concerning mobility needs and parameters household interaction with other entities and the environment. The same line of argumentation applies to FCEVs and to some extend also to the other system's components. This results in a very large number of possible input and output states of the system, making computer simulation a useful method for this research.

The focus of the model (as defined in section 1.5) is to capture the emergent system behavior as the result of individual decision making by households and FCEVs. This requires a bottom-up approach that describes the behavior micro-level entities. Complex socio-technical systems are flexible and adapt to different circumstances. Examples of this in a CaPP system are; demand-response, reaction to regulations and changing individual behavior through experience. To capture these characteristics, the modeling method should allow for changes in model structure, adaptability of entities, and memory of entities. A final desired characteristic of the modelling method is discrete-time simulation. Discrete timesteps allow developing a practical structure for power production scheduling and mobility patterns, for example timeframes of 15 minutes or 1 hour. Table 7 shows how agent based modelling fits these desired characteristics of the modeling method.

Table 7: Characteristics of modelling approaches (adapted from: (Kisjes, 2014))

Characteristic	*System dynamics*	*Discrete systems*	*Agent-Based*

Model approach	Top-down	Top-down	Bottom-up
Micro-level entities	None	Passive	Active
Dynamic behavior	Feedback loops	Events occurrence	Decisions and interactions of agents
Mathematical formulation	Stocks and flows	Events, activities and processes	Agents and environment
Timesteps	Continuous	Discrete	Discrete
System structure	Fixed	Fixed	Dynamic

The CaPP model is largely developed according to the methodology described by van Dam, Nikolic and Lukszo in 'Agent-Based Modeling of Socio-Technical Systems (van Dam, Koen. Nikolic, Igor. Lukszo, 2013). Their approach follows the steps shown in Figure 7.

Figure 7: Steps in developing an ABM of a socio-technical system

3.3 Performance of the CaPP System

Drawing conclusions about the effects of the control structure on the electricity supply and demand requires performance indicators for the model. Three levels of performances, each of less priority, are defined. The first performance level looks at the occurrence of electricity deficits. From a general perspective, it deals with the question: 'is there sufficient electricity supply in the system?'. Acceptable performance of the CaPP system is in this research defined as:

Acceptable performance

The CaPP system has an acceptable performance if less than 1 hour with a power deficit occurs per four weeks.

The value of one hour of power deficit is not a literature value nor is suggested that CaPP neighborhood should adopt this value. In practice, policy makers and the system's participants should agree upon a value suitable for their case. This might be completely different from one, such as zero or fifty, but only at night. The value of one is used in this research because Dutch people are used to have zero power deficits impacting their electricity demand (personal experience). However, in a CaPP system, sporadic power deficits might be acceptable as residents themselves have influence on the supply and demand of electricity.

The second performance level is about the response mechanisms required to balance the electrcity. The overall question is: 'What response mechanisms are needed to achieve sufficient electricity supply?'. It is an overview of how often backup FCEVs, output increase of FCEVs, and price control is needed and how often those are sufficient response mechanisms. This second performance level provides the insights to make distinctions between the performance of scenarios with similar hours of power deficit. In general, the less response mechanisms are used, the better the second level performance.

The third performance level deals with the question: 'what is the quality of the supplied electricity?'. This is performance level is divided into two facors: 1) the system efficiency, depending on the share of electricity directly provided by the PV farm, and 2) the share of production hours performed by FCEVs that are willing to produce power. The latter is a result from social attitudes of the residents. Some might voluntarily produce electricity for the neighborhood while others do so only to comply with the rules of the control structure. A summary of the performance levels is shown in Table 8.

Table 8: Description of performance levels

Performance level	*Performance description*	*Central question of performance level*
1	Occurrence of electricity deficits	Is there sufficient electricity supply?
2	Supply and demand response profile	What response is needed to get sufficient supply?
3	System efficiency	What is the quality of the supplied electricity?
3	Share of voluntary produced hours	What is the quality of the supplied electricity?

The ABM model should at least provide the following information of each timestep to assess these performance levels of the configured system:

- Energy/hydrogen flows and stocks
- When and why demand and supply response mechanisms are used
- Required and available FCEVs for power production scheduling
- Activities of FCEVs

The stricter the control structure the more FCEVs are available for power production and the more effective the control mechanisms are (see section 1.5). That means that strict control structures perform better than loose control structures. However, loose control structures are socially more desirable, as FCEVs and households are less constraint by control measures. Different domains of control structures versus system performances are conceptually shown in Figure 8. High performances and loose control structures are desired, but these may not both be achievable in all scenarios. In such cases a stricter control structure would be used, hence the performance is prioritized. This means that a loose control structure and a low performance is not a plausible scenario. After all, stricer control would increase the systems performance. Note, the boundaries between the sections are in fact blurry and the performance axis has a non-specified relation to the performance levels (but the first performance level is dominant).

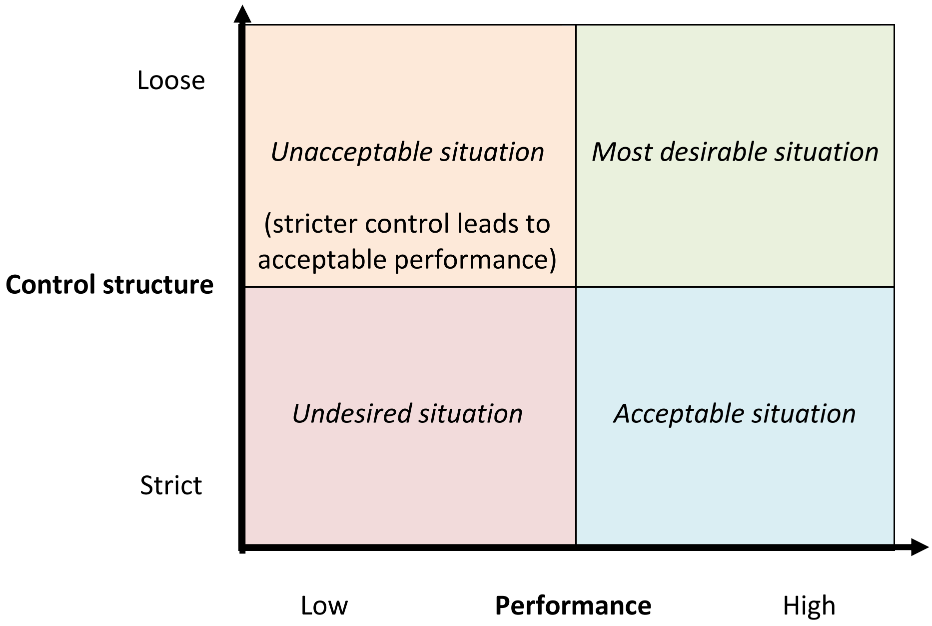

Figure 8: control structure and system performance domains (source: original)

4 System Identification

One of the first steps in the development of an agent based model is the identification of the key elements and interactions that play a role in the dynamics of a system. The system in this research is defined as the socio-technical system of a Dutch 200 household CaPP neighborhood. This chapter defines that system in more detail by providing a system overiew, setting the system boundaries and describing the Dutch case.

4.1 System Overview

Only residential electricity demand of the small scale CaPP neighborhood is considered, disregarding the demand of commercial and industrial buildings. The energy used in the neighborhood is provided by a wind farm and solar PV panels on the rooftops of the houses. The electricity produced by the wind farm is used in an electrolyser for the production of hydrogen. The PV panels provide electricity for the households. However, the remaining PV electricity is send to the electrolyser when the household demand is larger than the PV production. All FCEVs of the neighborhood refuel the locally produced hydrogen and, accordingly, use the hydrogen to produce electricity for either mobility or the households. **Error! Not a valid bookmark self-reference.** is a representation of the key elements and the energy flows of the CaPP nieghborhood.

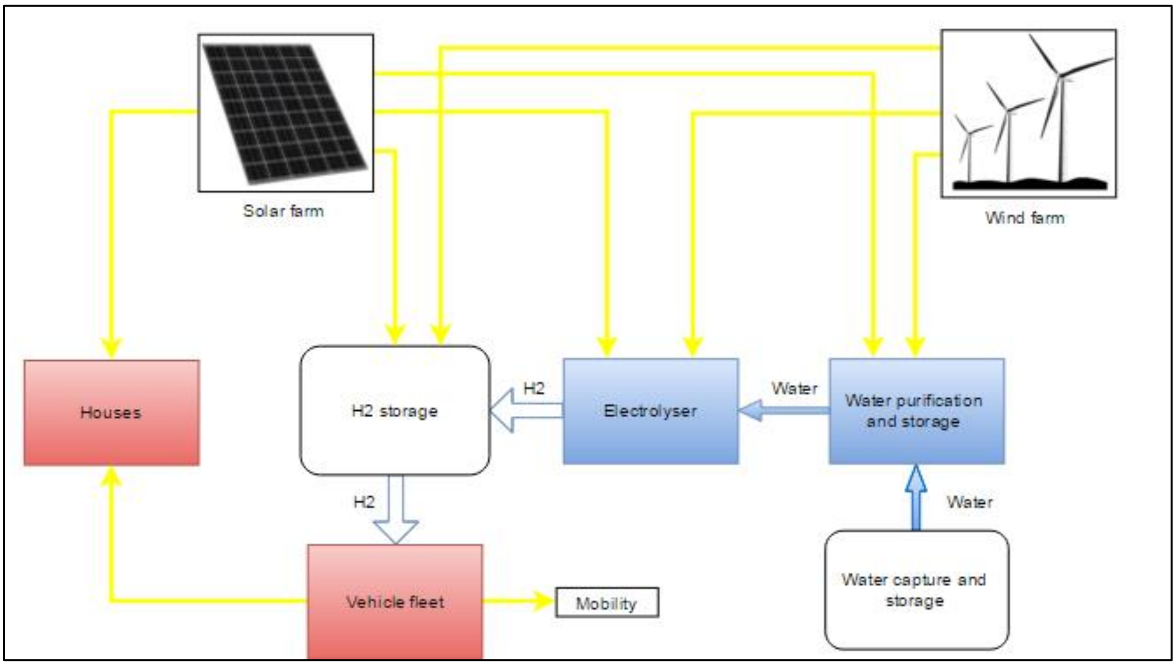

Figure 9: System overview

The key elements of the model that determine the system's performance are identified as the key model concepts. These model concepts result in the dynamic emergent patterns of the model.

The key model concepts

- *The individual, non-deterministic electricity demand of households*
- *The individual, non-deterministic mobility patterns of FCEVs*
- *Attitudes and behavior of households and FCEVs with respect to production, demand and response mechanisms*

- *The electricity supply and demand control structure*
- *PV production*
- *Wind production*

4.2 Model boundaries

Each model is a simplification of the physical system it represents. Table 9 lists the most important simplifications made that set the boundaries of the CaPP model.

Table 9: List of simplifications made

Number	*Simplification*
1	The behavior of all agents are defined in timesteps of 1 hour. This implies that FCEV activities and household demand profiles are represented by 1-hour activity 'blocks'
2	Residents own either zero or one FCEVs
3	Only FCEVs of the residents participate in CaPP activities
4	FCEVs of the neighborhood always refuel from the local hydrogen storage
5	Technical aspects of the hydrogen system are not considered, only the hydrogen flows and stock are monitored
6	If the hydrogen storage is almost full/empty a certain amount of hydrogen is exported/imported (simply added to or reduced from the system
7	The individual PV panels of the households are seen as a collective PV farm with the same performance factor and yield
8	The PV yield is equal to the global irradiance times the performance factor of the solar panels times the efficiency of the solar panels.
9	Technical failures and maintenance are not considered
10	Transmission and storage losses are not considered
11	Sufficient water is assumed to be available from rainwater collection. H_2 production, its storage, production and management are not considered.
12	The effects of response mechanisms are modeled but their methodologies are not considered (for example, price-level control increses the supply and demand based on the social attitudes of the residents, but the price-level control mechanism is not considered)
13	Households are all-electric (heat demand translates into electricity demand)
14	Household demand profiles attain the average demand profile with varying random factors (between 0,5 and 1,5)
15	Power production and scheduling happens in 2hr timeframes
16	There is no connection between household electricity demand and mobility patterns

4.3 Case Description and Assumptions

The 200 household Dutch CaPP system is not based on a physical neighborhood case in the Netherlands. The case study is meant to represent a typical Dutch neighborhood to which CaPP systems might be applicable in the future. The general assumptions made for the case are listed below. The idea is that the system represents a mid-class suburban area with mostly detached houses. The next sections elaborate on the general assumptions.

- 40 appartments, 40 semi-detached houses and 120 detached houses
- an average of 12 m2 PV panels per household
- One wind turbine of 3 MW
- Solar and wind data from a central location in the Netherlands (source: KNMI, 2015)
- Average Dutch mobility profiles
- Average Dutch household demand profiles for detached houses.

- An electricity demand reduction factor of 0.5 for appartments, and 0.75 for semi-detached houses.

4.3.1 Mobility profiles

The mobility profiles of the neighborhood should ideally resemble typical Dutch neighborhood patterns. However, this implies some controversy. In reality each neighborhood is unique and typical Dutch neighborhoods do not exist. The non-existence of such a neighborhood allows for some freedom of choice for the values that define case study. Regardless, Dutch mobility patterns are studied and some conlcusions are drawn for a plausible Dutch CaPP neighborhood. Table 10 shows Dutch mobility data from 2014 (CBS, 2014).

Table 10: Average Mobility Patterns in the Netherlands (CBS, 2014)

Age and Motive	*Trips*	*Distance*	*Minutes*
	times/day	km/day	min/day
Age: 25-45			
Total	3	39,98	69,25
Commuting	0,77	16,12	22,94
Other	2,23	23,86	46,31
Age: 45-65			
Total	2,75	35,06	65,75
Commuting	0,69	12,79	19,12
Other	2,06	22,27	46,63

From the table can be deducted that adults in the age group of 25-65 years make around 0.73 commuting trips per day. That means that the change a random 25 to 65 year old Dutch citizen is a commuter, is around 36%. The following assumptions for the Dutch CaPP case are made:

- in 80% of the households live at least two adults of the 25-65 age group,
- in 10% of the households lives one adult of that age group,
- the remaining 10% of the households have a 25% a commuter lives there.

Based on these assumptions and the 36% change an adult is a commuter can be calculated that around 107 of the 200 households in the CaPP neighborhood have at least one commuter in the household (see the Table 11).

Table 11: Commuters and household compositions in the CaPP neighborhood

Household composition	*Share of total*	*Amount of households*
Neighborhood	100%	200
Households with two adults between 25-65	80%	160
of which at least 1 commuter	*59% = (1 - 0.64*0.64)*100%*	*94*
Households with one adult between 25-65	10%	20
which is a commuter	*36%*	*7*
Households with no adults between 25-65	10%	20

which have a commuter	*25%*	*5*
Total households with commuters		107

Furthermore, let’s assume that a few of those 107 households with commuters do not travel by private vehicles. This results in a neighborhood in which around half of the households (100) commute with their private vehicle. For the daily mileage 40 km, the highest average of the two age groups in Table 10, is assumed. This slightly higher value than the average is used because commuting trips from a suburban area are likely to be further than the average of the Netherlands, which contains the bulk of people living in urban areas.

An additional conclusion from Table 10 is that Dutch adults make around 1.1 non-commuting trips per day (2.06 to 2.23 displacements per day for the two denoted age groups). A part of those trips is likely to be facilitated by other means of transport (such as bikes). Therefore, the following average trip probabilities are assumed:

- Weekday trip probability for non-commuteres: 65%
- Weekend trip probability: 65%
- Evening trip probability: 65%

Figure 10 is used to define departure and arrival times for the FCEVs of the neighborhood. It plots average Dutch last arrival times and traveled distances. A commuter arrival peak between 17:00 and 20:00 and a non-commuter arrival peak between 11:00 and 14:00 can be identified. Similar characteristics are assumed for the CaPP neighborhood. Commuter departure times are assumed to be random between 7:00 and 9:00. Evening trips are assumed to end before midnight because Figure 10 shows little arrivals after 24:00. Weekend trips can be initiated all day long and have potential longer durations than evening trips. Section 5.5.1 explains for the parametrization of the described mechanics.

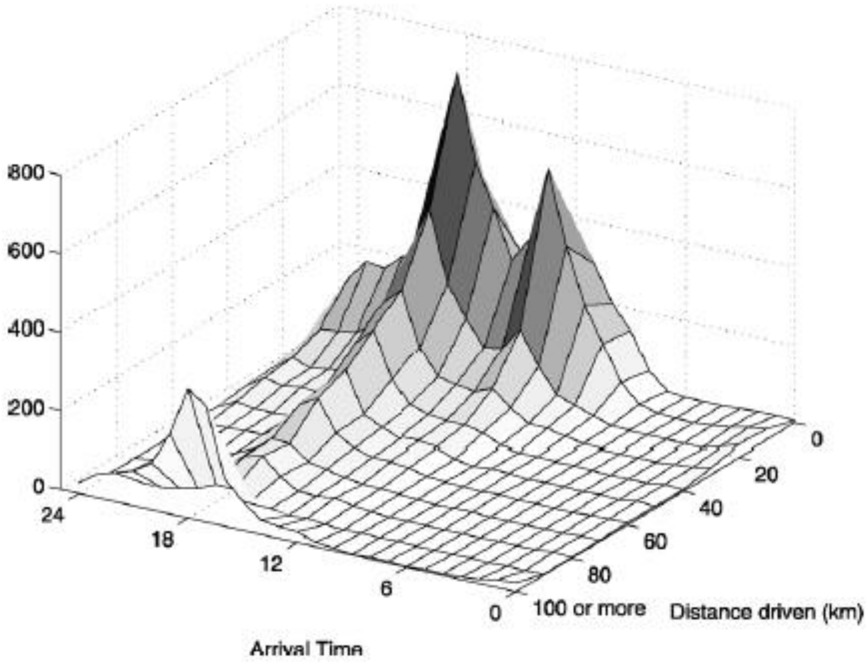

Figure 10: distribution of Dutch arrival times

(Verzijlbergh, Lukszo, Veldman, Slootweg, & Ilic, 2011)

4.3.2 Technologies

The system makes use of several fast developing technologies such as PV panels and FCEVs. Their characteristic at this point may differ significantly the situation in a few years. The table below shortly discusses the technologies and their values used for the case study.

Table 12: Technologies and their values

Technology	*Characteristics*	*Motivation*	*Source*
Solar Panels	Efficiency: 21%	Case assumption. Current market mainly multi- and mono-SI with efficiencies 12%-24%.	(Badawy, 2015)
	Performance ratio: 90%	Case assumption. A factor that takes the solar irradiance on non-horizontal planes *and* voltage conversion losses into account.	(SMA Solar Technology, 2015)
Wind turbines	Roughness length: 0,25	Case assumption. The typical roughness length of suburban terrain	(Moore & Bailey, 2004)
	Height of hub: 80m	Hub heights of 60-105m are available for the models used in this thesis	https://www.vestas.com/
	Powercurves	Power curves of the Vesta V90 3MW and 2MW[2]	https://www.vestas.com/
Electrolyser	Production: 50 kWh/kg H_2	Current Alkaline and PEM electrolysis efficiencies range from: 47-73 kWh/kg H_2	(Bertuccioli et al., 2014)
Compression	Energy consumption: 5% of energy that goes into the hydrogen system	As in the CaPP energy flow diagram from Green Village	Ir. V Oldenbroek
Water purification	Energy consumption: 7,7% of energy that goes into hydrogen system	As in the CaPP energy flow diagram from Green Village	Ir. V Oldenbroek

5 Formalizing the CaPP Neighborhood Model

The previous chapter defined the CaPP system of this research. This chapter deals with how that system is formalized into an agent-based model. An agent based models is comprised of interaction between agents, objects, links, the environment and the observer. Figure 11 is a conceptual overview of the interactions in the CaPP model. Agents in an agent based model are heterogeneous, autonomous entities that behave (or make decisions) according to pre-programmed rules (Getchell, 2008). Two types of agents occur in the CaPP model: FCEVs and households. Section 5.2 elaborates on these agents. The subsequent sections treat the objects, the obsever and the environment. Links are not further discussed as do not play a role in the CaPP model besides in the visualisation of the model world. Instead of providing a model narrative, section 5.5 explains the mechanisms of the CaPP model with a variety of figures and diagrams. Readers who want to understand the underlying principles in more detail are referred to Appendix C: Model Code.

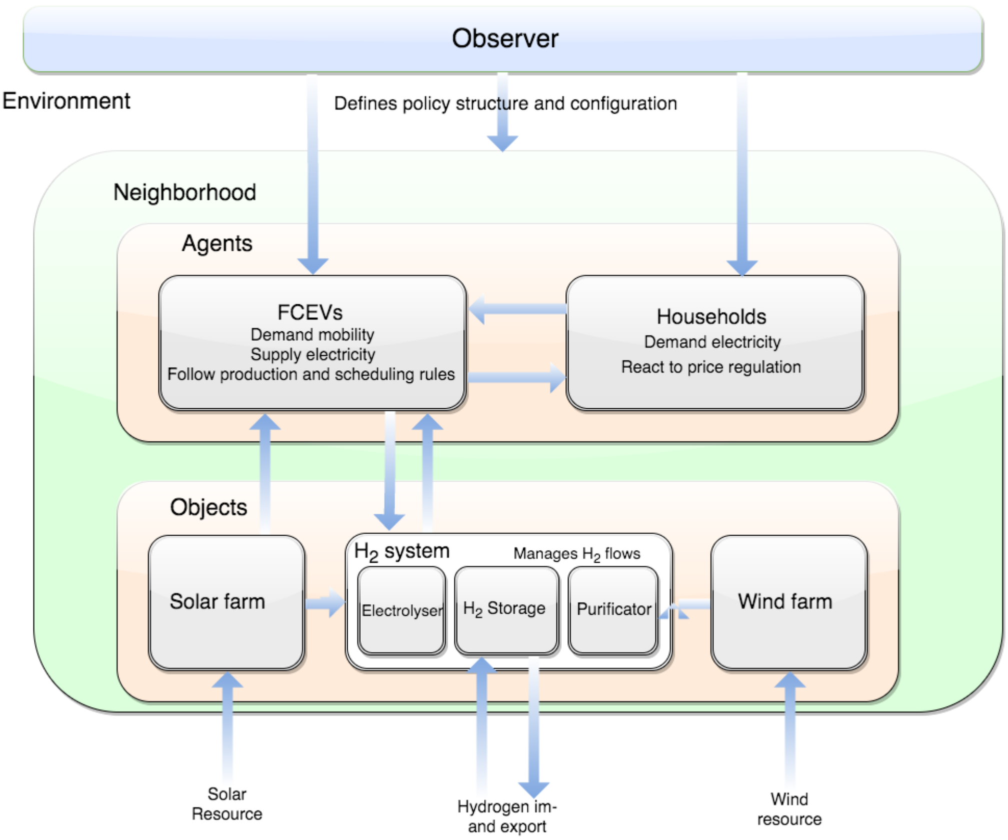

Figure 11: Model relations

5.1 Concept Formalisation

This section elaborates on the parameterization of the CaPP model. The input parameters, or concepts, used in the model are divided into two categories: concepts that determine a scenario within the case study and concepts that define the case study. The former, shown in Table 13, are the concepts that are varied in the experiments of this research. The latter, shown in Table 14, remain constant throughout the experiments.

Table 13: Formalisation of scenario concepts

Model Parameter	*Default Value*	*Unit*	*Description*
Wind and solar data selection	Bilt May 2015	NA	The period of the RE resource input data
#weeks	4	weeks	Number weeks the simulation runs
#FCEVs	100	FCEVs	Number of FCEVs in the neighborhood
Maximum minimum distribution	0,5	1	The share of residents that always available for power production scheduling when home vs the share that follows the control structure
Work home distirbution	0,5	1	The share of residents with a commuting profile
Active participant distribution	0,3	1	The share of residents that are an active participant
FCEV output	15	kW	The default FCEV production output
Max FCEV output	30	kW	The maximum FCEV production output
#FCEVs backup	1	FCEVs	The number of backup FCEVs that will be scheduled
Demand side management	FALSE	NA	The use of home side demand control
Min weekly production timeframes	7	timeframes/wee k	Minimum weekly number of timeframes FCEVs should be available for scheduling
Max production timeframesper day	1	timeframes/day	Maximum times per day a FCEV can be scheduled
Price level reduction factor	0,7	1	The factor with which individual demand is reduced when price control response

Table 14: Formalisation of case concepts

Model Parameter	*Default Value*	*Unit*	*Description*
Wind Farm			
Turbine type	Vesta-V90 3MW	NA	The power curve that is used to calculate the windfarm output
#turbines	1	turbines	The number of windturbines in the neighborhood
Height wind data	15	m	The height at which the wind input data represents the windspeed
Heigt turbines	90	m	The height at which the wind turbines in the neighborhood are placed
Roughnesslength	0,25	m	The roughness length of the wind turbine locations
Solar Farm			
Solar surface	12	m2	The average solar panel surface per household
PVPerformanceFacto r	0,7	1	The performance factor of the solar farm
Pvefficiency	20,6	%	The efficiency of the PV panels
H2 System			
H2 storage capacity	800	kg H2	The size of the local hydrogen storage
Electrolyser efficiency	20	g H2/kWh	The efficiency of the electrolyser
Share to electrolyser	0,873	%	The share the hydrogen system inbound electricity consumed by the electrolyser
Share to compression	0,05	%	The share the hydrogen system inbound electricity consumed by compression of hydrogen
Share to storage	0,077	%	The share the hydrogen system inbound electricity consumed by the storage

H2 export amount	40	% of storage	The amount of hydrogen that is expoerted when the storage is full
H2 import amount	200	kg H2	The amount of hydrogen that is imported whan the storage is empty
Variation Parameters			
Max probability weekend trip	0,9	1	The maximum probability of FCEVs to take weekend trips (random between 0 and this value)
Max probability evening trip	0,9	1	The maximum probability of FCEVs to take evening trips (random between 0 and this value)
Randomness electricity demand	0,8	1	A factor that determines the maximum randomness of the cumulative electricity demand (0,8 results in a factor between 0,6 and 1,4)
Household daily variation	1,5	1	A factor with which individual household demand varies daily
Participant swich prob	0,03	1	The probability that residents switch during electricity deficits
FCEV Characteristics			
FCEV tank capacity	5000	gram H2	
FCEV fuel economy	8,3	gram H2/km	The efficiency at which FCEVs travel
Trip average distance	40	km	The average distance of non-commuting
Trip variance	600	-	The non-commuting trip variance of the gamma distribution
Work average distance	30	km	The average distance to work
Work variance	250	-	The commuting trip variance of the gamma distribution
Recharge level	500	gram H2	The amount of hydrogen in a FCEV tank when it refuels
Production h2 consumption	50	gram H2/kWh	The efficiency at which FCEVs produce electricity for the neighborhood
Max prob not show up	0,07	1	The maximum probability a FCEV does not show op for power production
FCEV production efficiency	34,9	%	The overal efficiency of the electricity production via FCEVs
Additional control structure			
Solar forecasting	FALSE	NA	Allowing the system to precisely forecast the PV production, used in the scheduling procedure
Min fuel in tank	2000	gram H2	Minimum fuel in tank before power production
Obliged charging at night	FALSE	NA	All FCEVs must be available for scheduling at night
Parameters in script			
Share appartment	20	%	The share of appartments in the neighborhood
Share semi-detached houses	20	%	The share of semi-detached houses in the neighborhood
Share detached houses	60	%	The share of detached houses in the neighborhood
Share 2 residents	33	%	The share of households with 2 residents
Share 3 residents	33	%	The share of households with 3 residents
Share 4 residents	33	%	The share of households with 4 residents
Max Sustainability	1,4		The sustainability attitude

5.2 Agents and their Ontology

Part of the model formalisation as described in the book of agent-based modeling of socio-technical systems (van Dam, Koen. Nikolic, Igor. Lukszo, 2013) is the development of an ontology for the agents. An ontology is a way of structuring identified concepts by making relationships clear in a hierarchical way. It shows how the agent characteristics are formalized. The ontology of the two agent types in the CaPP model (FCEVs and households) are shown in

Household — Owns a → FCEV

FCEV	has a	active_participant*	is a	attitude	is a	string	yes, no	sensitive to certain policies
		production_preference*	is a	attidude	is a	string	maximum, minimum	attitude towards power production
		current_activity*	is a	status	is a	string	See activies FCEVs	the activity of the FCEV
		mobilityprofile	is a	characteristic	is a	string	work, home	commuter or non-commuter
		returntime	is a	time	17:00-20:00	commuter return time		
		startingtime	is a	time	07:00-08:00	commuter departure time		
		tripstarttime*	is a	time	07:00-22:00	start time of a trip		
		trip_duration*	is a	duration	is a	value	0-10 hr	the duration of a trip
		weekday_trip_probability	is a	probability	0.5-0.8	change of taking a day trip during the week		
		evening_trip_probability	is a	probability	0-0.9	change of taking an evening trip during the week		
		weekend_trip_probability	is a	probability	0-0.9	change of taking a trip during the weekend		
		distance_to_work	is a	distance	is a	value	ℝ+ (gamma-distributed)	the commuting distance
		avg_distance_trip	is a	distance	is a	value	10-40 km	avg distance of weekday trips
		avg_distance_weekend_trip	is a	distance	is a	value	30-50 km	avg distance of weekend
		distance_traveled*	is a	distance	is a	value	=>0 km	total distance traveled
		fuel_in_tank*	is a	amount of H2	is a	value	0-5500 g H2	H2 in fuel tank
		probability_not_show_up	is a	probability	0-0.07	change of not showing for scheduled power production		
Household	has a	active_participant*	is a	attitude	is a	string	yes, no	sensitive to certain policies
		residents	is a	value	2-4 residents	the amount of residents in the household		
		house_type	is a	characteristic	is a	sting	detached, semi-detchd., apt.	represents the house type
		current_demand*	is a	electricity demand	is a	value	0-1.5 kWh	represents the electricity demand
		demand_factor	is a	value	0-1	a factor that influences the diference with the avg electricity demand		
		sustainability	is a	attitude	is a	value	0.6-1.4	a factor that influences the demand
		dailyvariation*	is a	value	0.25-1.75	a daily factor that influences a households electricity demand		

Instance
Ontology relation
Value Range
short description

Figure 12. In the model the agents contain much more characteristics, but those correspond to the model funcionality rather than the conceptual relations. Examples of such characteristics are lists that keep track of previous activities and temporary values required for calculations.

One of the FCEV characteristics shown in the ontoloty is the 'current_activity'. The current_activity of FCEVs represent the activity a FCEV during a simulation. There are seven activities FCEVs can attain:

1. *Parked at home* – the FCEV is parked in the neighborhood
2. *Away* – the FCEV is currently not in the neighborhood
3. *Producing power* – the FCEV produces power and was scheduled to produce power
4. *Missing power production* – the FCEV was scheduled to produce power but did not show up
5. Producing back up power – the FCEV produces power and was scheduled as back up
6. *Idle back up* – the FCEV was scheduled as backup but the back up is not required
7. *Producing additional power* – the FCEV produces power because additional power production was required and this FCEV responded to that demand

When and how FCEVs decide which activity they have is explained in section 5.5

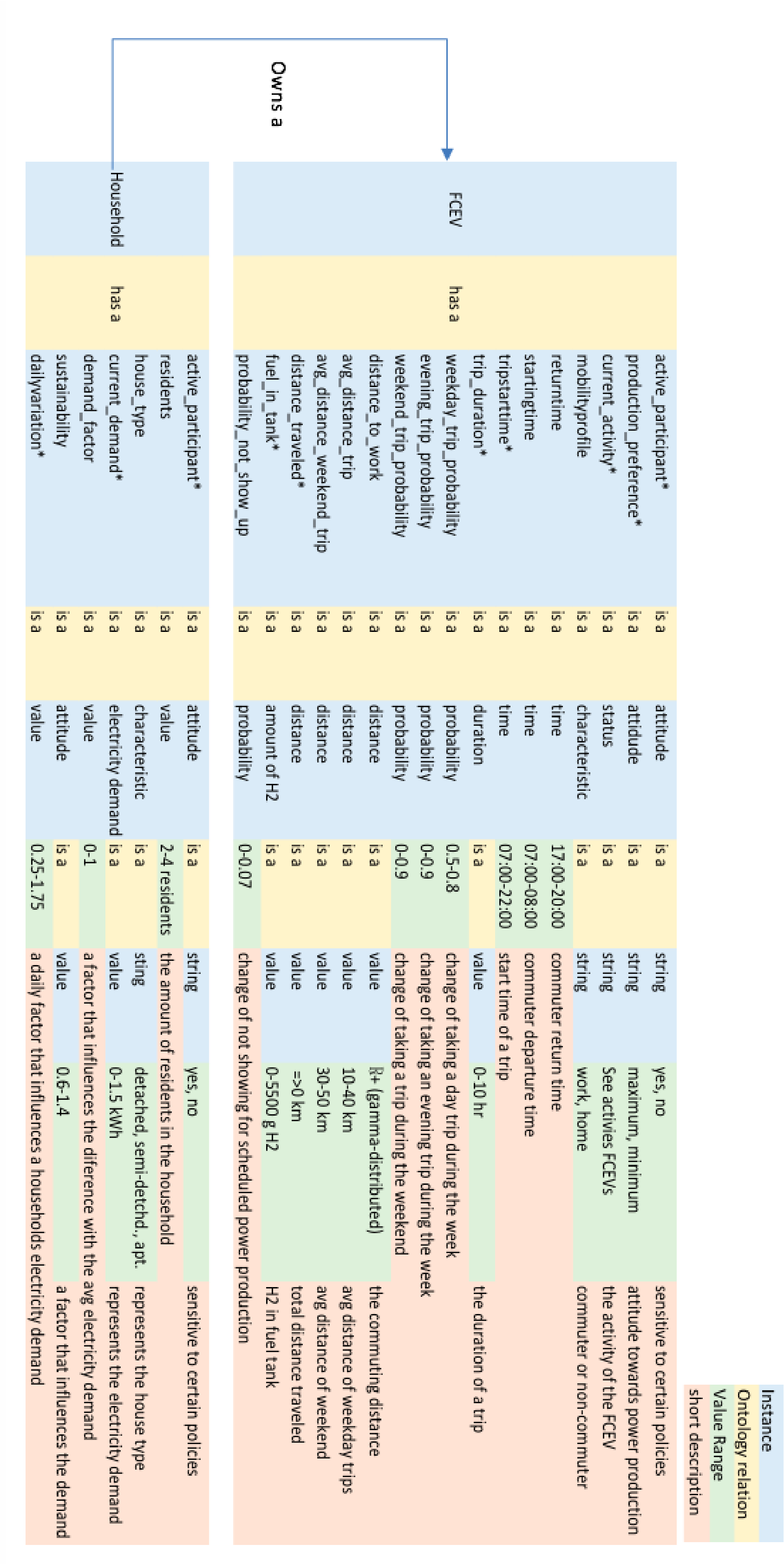

Figure 12: Agent ontology

5.3 Objects

Besides the previously defined households and FCEVs, the system overview in section 4.1 showed several more components of the socio-technical CaPP system: the collective PV farm, a wind farm, and the hydrogen system (with an electrolyser, purificator and storage). These components are intangible agents, i.e. they do not make decisions based on the state of the system, and therefore are identified as objects. The activities of these objects are modelled via global variables (see section 5.4). A summary of what these objects conceptually do in the model and the method of doing so is shown in the table below.

Table 15: Objects and their function in the model

Object	*Activity*	*Method*
Solar farm	Convert solar input data into electricity output	Calculates windspeed at hubheigt and couples that to the windfarm capacity and the power curves of the turbine type
Wind farm	Convert wind input data into electricity output	Couples the capacity, performance factor and efficiency of the PV farm to the solar irradiance
Electrolyser	Consumes power for hydrogen production	Consumes 87,7* percent of all electricity send into the hydrogen system
Hydrogen storage	Consumes power for hydrogen storage Keeps track of the hydrogen available	Consumes 5* percent of all electricity send into the hydrogen system Reduces the H_2 when a FCEV refuels, and manages H_2 import and export when below/above a certain level
Purificator	Consumes power for water purification	Consumes 7,3* percent of all electricity send into the hydrogen system

*values are defined in the case description, see Table 12.

5.4 The Environment & the Observer

The environment of an agent-based model should be seen the dynamic playing field in which the agents interact and which provides information for the agent's decision making. The information of the environment is embedded in global variables which are accessible to all agents. Each global variable belongs to one of the catergories or sub-categories of Table 16.

Table 16: Categories of global variables

Global (sub-)category	*Description of catergory*	*Example globals*
System configuration globals	Are set by the observer and maintain fixed during a simulation. They describe the system and fall in one of the sub-catergories below.	n.a.
Control structure	Describe the control structure	demand_side_management, max_production_timeframes/day
System set up	Describe the general simulation settings	#weeks, #FCEVs
FCEV	Describe the FCEV characteristics	tank_capacity, trip_variance
Household	Describe household characteristics	Max_sustainbability, share_detached_houses
Wind farm	Describe the wind farn characteristics	#turbines, roughnesslength
Solar Farm	Describe the solar farm characteristics	solar_surface, Pvefficiency
H_2 system	Describe the H_2 system characteristics	electrolyser_efficiency, share_to_storage
Output globals	Contain information about the simulation output	cumulative_electricity_demand_list, times_price_level_increased
Calculation globals	Required for modelling purposes	-

Observers in agent-basesd models can be interpreted as an external perspective that can influence the system before and during simulations. In the CaPP model, the observer configures the scenario and control structure before the simulation. It does not influence the system as the model runs.

5.5 Model Mechanisms

This section elaborates on five key model mechanisms: mobility patterns, FCEV scheduling and power production, household demand, supply response and electricity flows.

5.5.1 Mobility Patterns

Mobility patterns of FCEVs are important dynamics that influence the electricity supply because FCEVs can only be available for power production scheduling if it is 'parked at home'. This section explains how mobility patterns are formalized and when FCEVs are available for power production.

FCEVs in the model have either a work profile, representing the FCEV of a commuter, or a home profile, representing the FCEV of a non-commuter. The type of mobility profile FCEVs have partly determine the type of trips they make. Table 17 indicates the types of trips for both mobility profiles. Each trip type can occur once per day per FCEV. This means that during weekdays two trips per day can be taken, while on weekend days FCEVs make at most one trip per day. The realization of a trip depends on that specific trip-type-probability of that specific FCEV. The trip probabilities FCEVs may attain are shown in the table as well. Trip distances are generated via gamma distributions (see Figure 13 for an example). The averages of these gamma distributions vary per FCEV (except for commuting trips) and per trip type. The variance of gamma distributions is 250 for commuting and 600 for non-commuting trips. All values are determined via the case study in the system identification (see section 4.3.1).

Table 17: Mobility pattern formalization

Trip characteristic	*FCEV with work profile*	*FCEV with home profile*
Commuting trip	Yes	No
Probability	every workday	0
Distance	gamma distributed (shape: 3.5, scale: 8.6)	n.a.
Departure	random (7:00 or 8:00)	n.a.
Return	random (18:00 to 20:00)	n.a.
Week day trip	No	Yes
Probability	0	random (0.5 to 0.8)
Distance	n.a.	Gamma distr. f(avg trip distance of that FCEV)
departure	n.a.	random (8:00 to 11:00)
duration	n.a.	random (2 to 7 hrs)
Week evening trip	Yes	Yes
Probability	random (0 to 0.9)	random (0 to 0.9)
Distance	Gamma distr. f(avg evening trip distance of that FCEV)	Gamma distr. f(avg evening trip distance of that FCEV)
departure	random (19:00 to 20:00)	random (19:00 to 20:00)
duration	random (1 to 3 hrs)	random (1 to 3 hrs)
Weekend trip	Yes	Yes
Probability	random (0.5 to 0.8)	random (0.5 to 0.8)

Distance	Gamma distr. f(avg weekend trip distance of that FCEV)	Gamma distr. f(avg weekend trip distance of that FCEV)
departure	random (7:00 to 15:00)	random (7:00 to 15:00)
duration	random (3 to 8 hrs)	random (3 to 8 hrs)

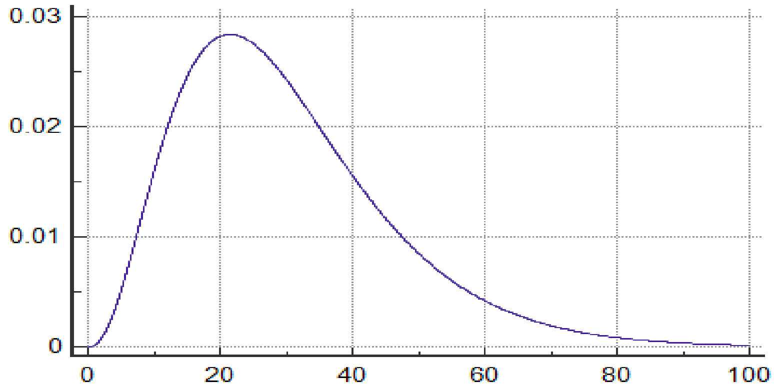

Figure 13: Gamma distribution used for the distance to work

The result of the defined method for tripprobabilities is that FCEVs may have different mobility patterns each day while still showing a certain structure. For example, a FCEV with a work profile and a high evening trip probability, resembles a commuter that frequently attends evening sessions (such as sports). To illustrate the differences between commuter and non-commuters as well as the difference between week an weekend days three examples are shown in Figure 14.

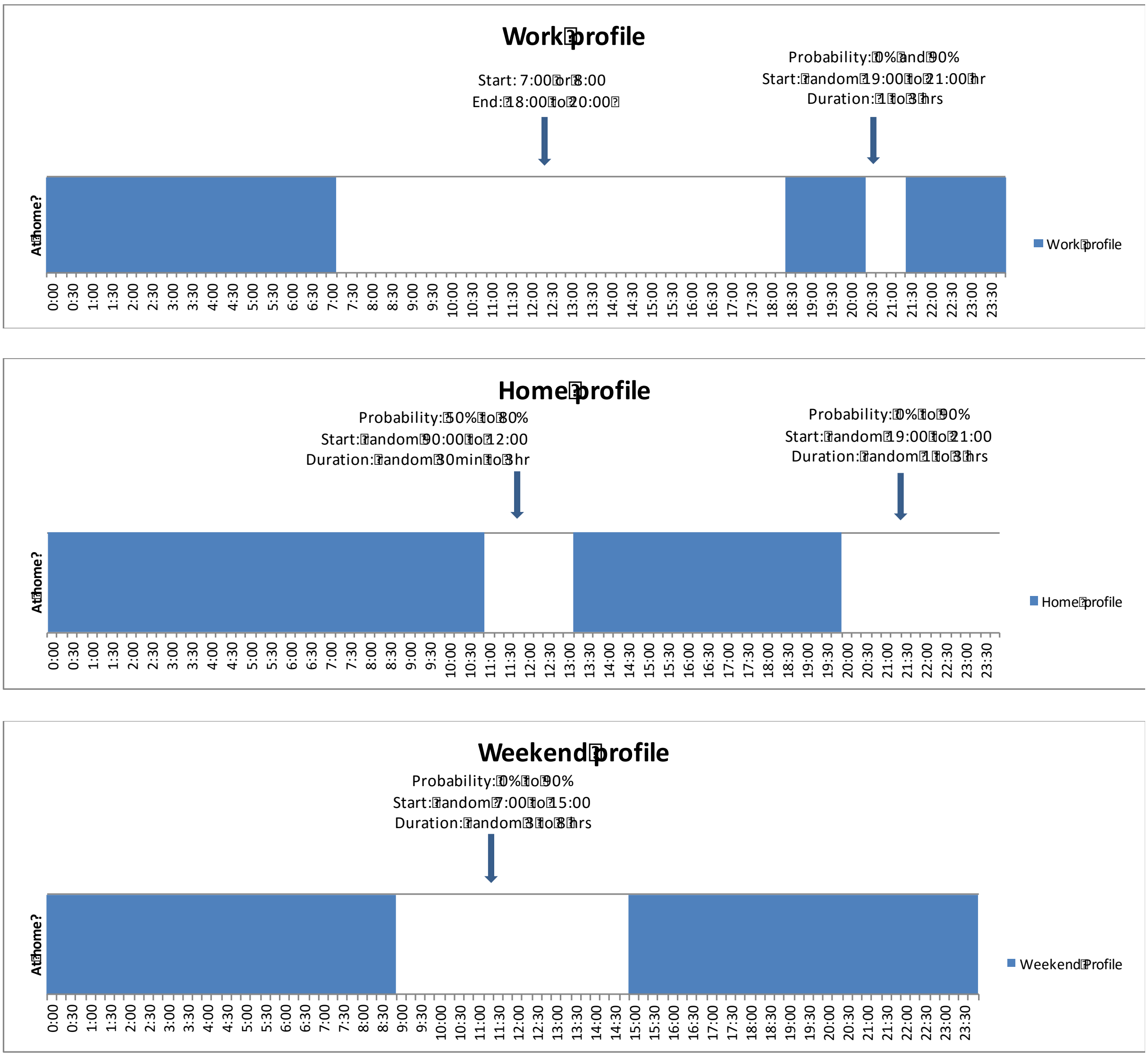

Figure 14: Example mobility profiles

The model is developed to simulate a specific number of weeks. At the start of each week FCEVs determine their mobility patterns. Partly based on that, FCEVs are scheduled for power production. Note, this could conceptually be interpreted determining mobility patterns and scheduling each morning, but that would modelling-wise be less practical.

5.5.2 FCEV Availability and Power Production Scheduling

If the mobility profile of a FCEV indicates that it is at parked at home, it is not necessarily available for power production scheduling. Some FCEV owners migth dislike producing electricity with their FCEV. To deal with this, the social characteristic 'production preference' is ascribed to FCEVs. The production preference can be either 'maximum' or 'minimum'. With the former relating to FCEVs that like to produce power (for example because of the financial compensation or social cohesion). The latter relates to residents that dislike to use their FCEV for power production (for example because they value the availability of their vehicle).

FCEVs with their production preference at 'maximum', will denote all possible production timeframes at which they are at home as 'available for power production'. On the other side, FCEVs with their production preference at 'minimum' will denote the prescribed number of timeframes per week, by the control element ‘minimum number of prodcution timeframes per week’, as available for power production. These timeframes are chosen randomly from the available timeframe set. Because power production happens in timeframes of two hours, a FCEV is required to be parked at home during both those hours in order to be available for power production scheduling in that timeframe. All FCEVs are at home during night-hours (0:00 to 6:00) generally resulting in sufficient supply at night. Therefore, night-hours are excluded from the set of timeframes FCEVs with a ‘minimum’ production preference can select as available for power production.

An expected demand is calculated for each hour of the week. The calculation takes the expected demand (see section 5.5.3) and the solar irradiance into account. The highest expected demand in a two hour timeframe and the FCEV output determine how many FCEVs the scheduling procedure tries to schedule. The scheduling control element ‘maximum amount of timeframes per day’ limits the times per day a FCEV can be scheduled for power production. The scheduling procedure starts in the evening because starting in the morning could reduce the available FCEV pool during the more demanding evening timeframes. FCEVs that have their production preference at ‘maximum’ will be scheduled before FCEVs with their preference at ‘minimum’. This leads to the performance factor ‘share of voluntary production hours’ as defined in the methodology.

After scheduling FCEVs for power production, a similar scheduling procedure occurs for backup power production. The control element ‘#FCEVs backup’ determines the amount of FCEVs the backup scheduling procedure tries to schedule. These backup scheduled FCEVs are used as supply response when needed. Being scheduled for backup can occur to a FCEV only once a day, and not on days on which a FCEV is already scheduled for normal power production.

A FCEV may not always show up when being scheduled for power production. Unexpected trips or forgetting the schedule are reasons why this could happen in practise. The system might also not accept FCEVs that want to produce power but with a fuel level below a certain threshold. To implement these possibilities, a consistency characteristic for each FCEV is used. The value for this characteristic is taken randomly between 0 and the adjustable global parameter ‘probability_not_show_up’ (by default 0.07) for each FCEV. The idea is that this accounts for all unexpected scenarios for the supply of the FCEVs.

The conceptual model in Figure 15 illustrates how the concepts discussed in the last two sections result in the FCEV electricity supply.

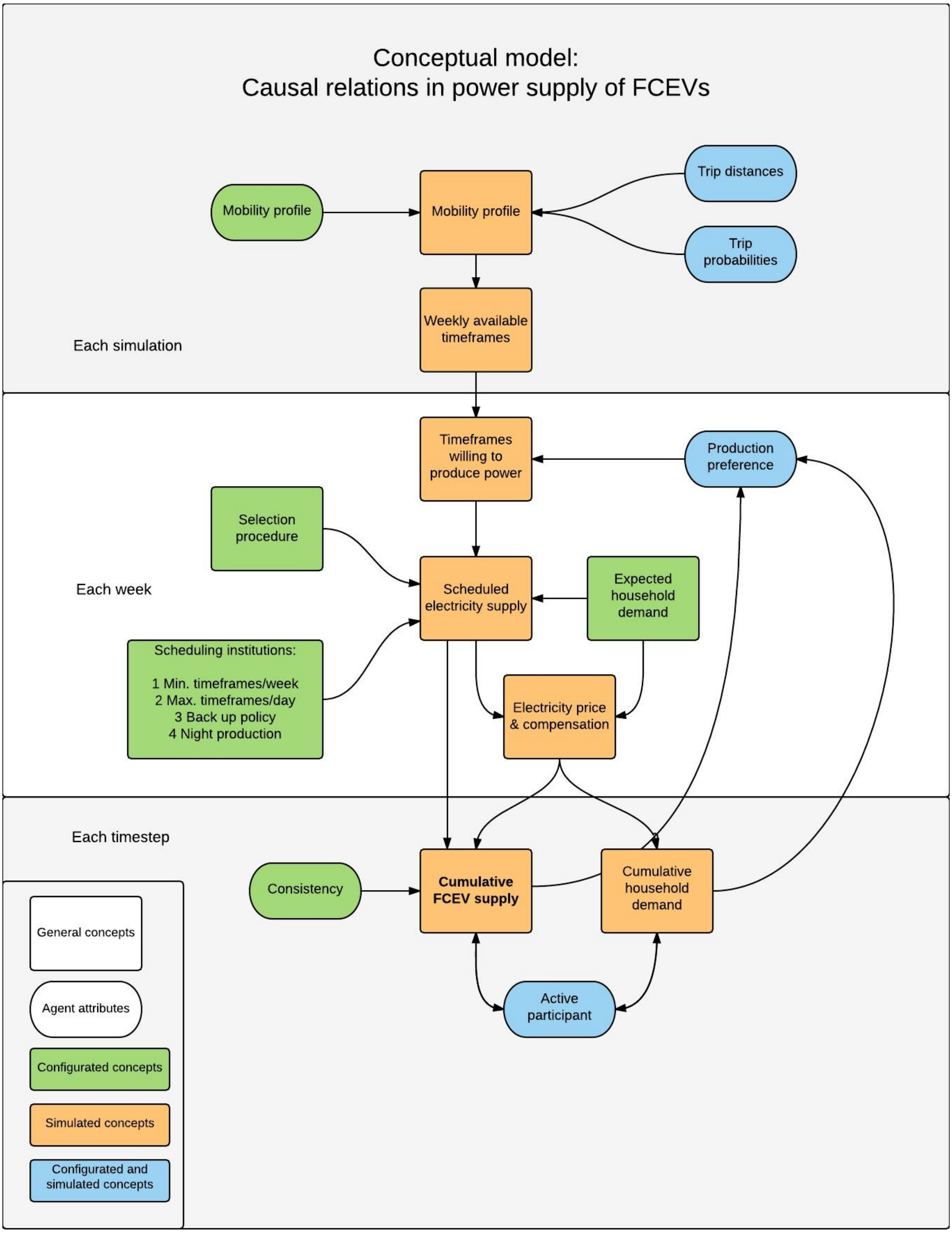

Figure 15: Conceptual model of FCEV electricity supply

5.5.3 Household demand

Several forms of household demand are distinguished: the standard electricity demand, the expected electricity demand, the electricity demand and the reduced electricity demand. The standard electricity demand of a specific hour is input for the model. It determines the overall electricity demand profile and is part of the case description. The way this standard demand profile is constructed is described in Appendix A: Complementary files. The expected electricity demand is a global variable that is used to determine how many FCEVs will be scheduled. It is the cumulative standard demand of the neighborhood minus the (forecasted) solar PV production.

The electricity demand is the demand of the neighborhood before any supply response. During timeframes in which no demand response is required, i.e. the electricity supply fits the demand, it is the final demand of the neighborhood. If demand response is used, the final demand of the neighborhood ends up being the reduced electricity demand. The electricity demand may differ significantly from the expected demand due to randomness that is introduced in both the individual household demand as well as in the collective demand. The randomness in individual household demand is a factor that remains constant for one day and is randomly taken between 0.5 and 1.5. the idea is that this represents, for example, a person not being home in the evening or a household using specific power-demanding appliances on certain days. Randomness in the collective demand is meant to represent the non-deterministic behavior of the electricty demand of a neighborhood. It is essential that the response mechanism provides the needs to adapt to unexpected situations with high electricity demand. This randomness is an hourly based factor ranging from 0.6 to 1.4.

The individual household demand is additionally determined by the standard demand factor and on homeside demand management. The standard demand factor is a household unique factor that accounts for its number of residents, the household type, the current season and the household's attitude towards sustainability. Homeside demand management might be part of the control structure. In the model its lets households shift part of the (high) evening demand to the hours with PV production. However, only households who are active participants react to home side demand control.

The last form of household demand is the reduced electrcity demand, which is the collective electricity demand after price level control. As with home side demand management will only active participants react to price level control. The reduction factor of price level control is introduced as a measure of the price level control strength. A relative small factor, such as 0.6 (reducing the household demand of active participants by 40%), represents a strong incentive to reduce individual household demands.

Figure 16 illustrates how the discussed concepts result in the cumulative household demand of the CaPP model.

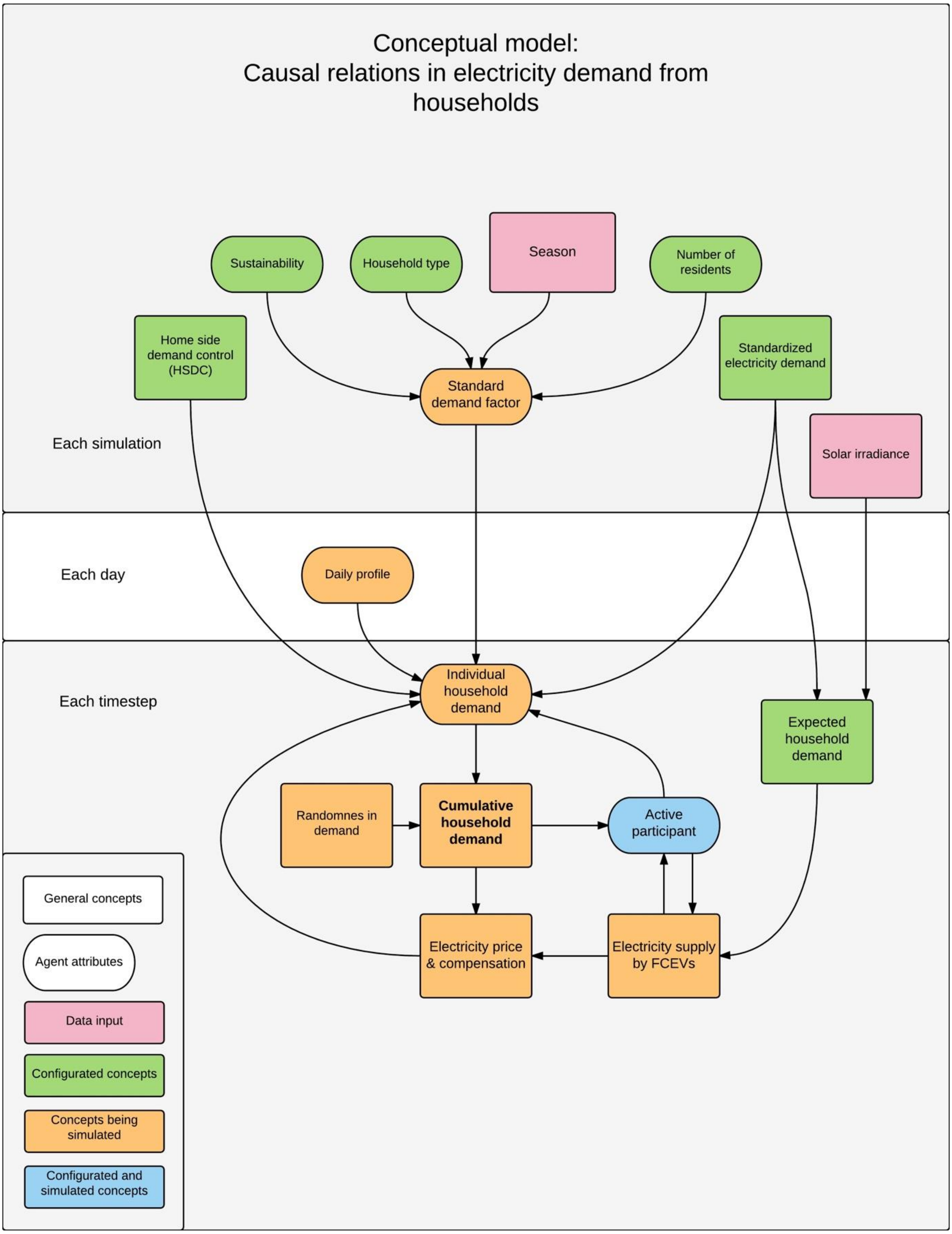

Figure 16: Conceptual model of electricity demand in households

5.5.4 Supply Response

Price level control is one response mechanisms to control the electricity supply and demand. However, price level control not only affects the electricity demand, as discussed in the previous section, but also the electricity supply. FCEV owners can react to the price level control by producing additional power. The FCEV activity ‘producing additional power’ corresponds to this. To produce additional power as a reaction to price level control a FCEV has to satisfy four criteria:

1. It is the first time of the day the FCEV will produce additional power
2. It’s original activity during this hour was parked at home
3. The FCEV has sufficient fuel in the tank
4. The FCEV is an active participant

Before price level control is used to deal with power deficits two other response mechanisms are applied. The first response lets scheduled backup FCEVs produce additional power. ‘Producing backup power’ is the FCEV activity related to this. If no backup FCEVs were scheduled or if the supply remains insufficient, the output power of the producing FCEVs is increased. The output power is increased to at most the ‘maximum FCEV output’ defined in the control structure. If a power deficit remains, price level control is used. Figure 17 illustrates these response mechanisms.

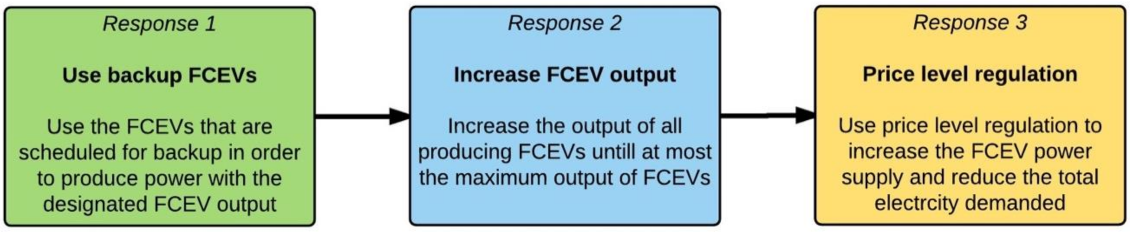

Figure 17: Supply response mechanisms

Only FCEVs and households that are ‘active participants’ react to price level control and home side demand control. As long as the electricity supply meets the demand there is little incentive for non-active participants to become active. Power deficits, however, directly affect the living comfort of the residents. Therefore, power deficits can cause non-active participants to become active participants with a small probability. With a similar line of argumentation can be argued that active participants may become non-active if no supply deficits occur continuously for a longer period of time. Because this research only runs simulations of 1 month, long term learning effects such as ‘if I do not participate, it apparently does not affect negatively’ are not considered. Hence, the probability of active participants becoming non-active is taken to be 0. The Figure 18 demonstrates the discussed concepts with a decision tree.

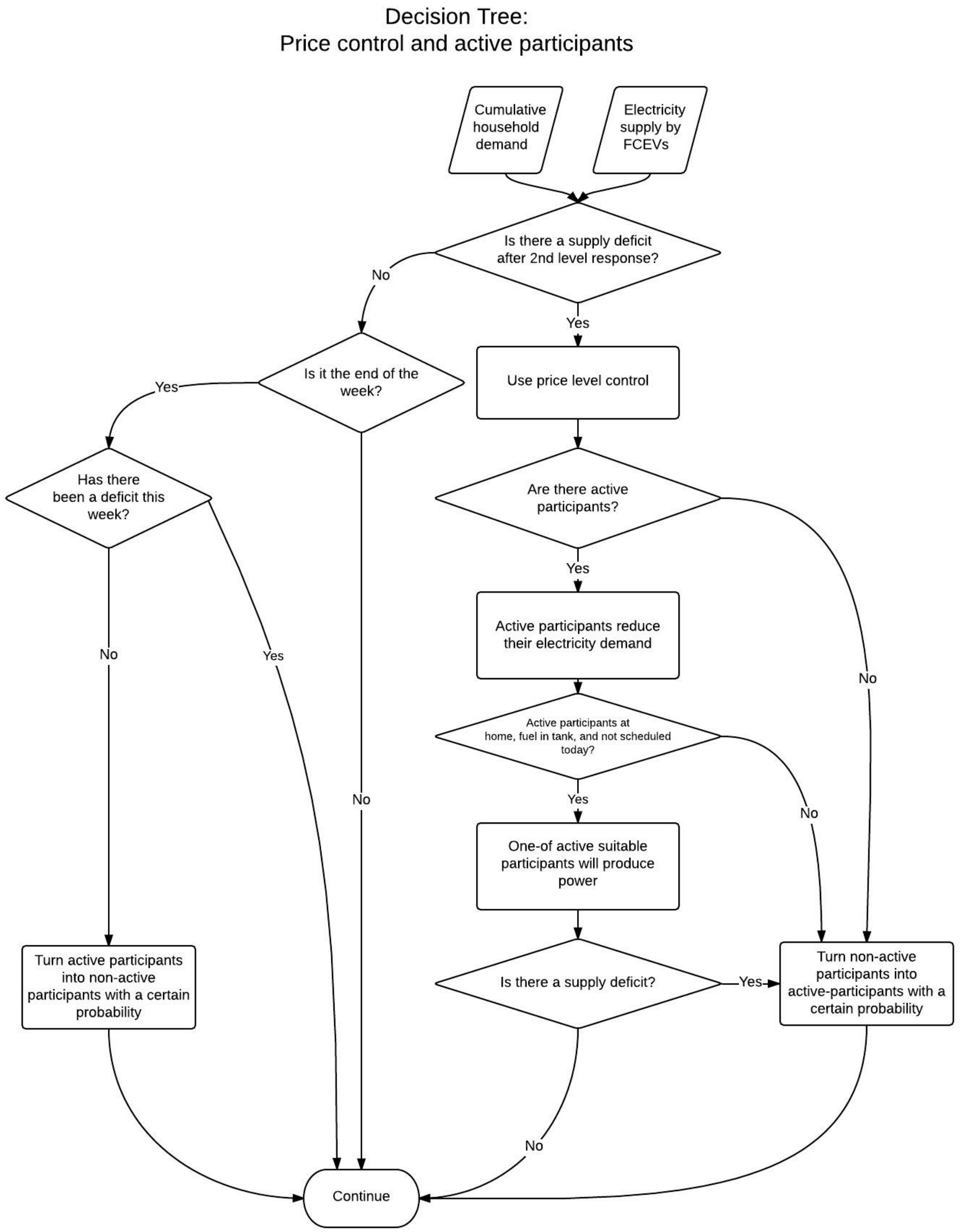

Figure 18: Desicion tree for price level control and adapting active participants

5.5.5 Electricity Flows and System Efficiency

One of the aspects of the third performance level is the system's efficiency (see section 3.3). This efficiency depends on 'the amount of solar electricity directly used in households' and 'the total electricity used in households'. The control structure influences this efficiency via home side demand control (meant to increase the share of solar electricity used in households as well as balancing electricity demand) and via all other control elements that have an effect on the total electricity demand. Figure 19 displays the two routes for electricity to reach the households. Direct electricity from the PV farm to the households is denoted as 100% efficient. Electricity delivered via FCEVs lose energy on the following processes: hydrogen compression, H_2O purification and two hydrogen conversion steps. As can be seen in Figure 19, the overall efficiency of that route is 35%. The values used in this figure are defined in section 4.3.2.

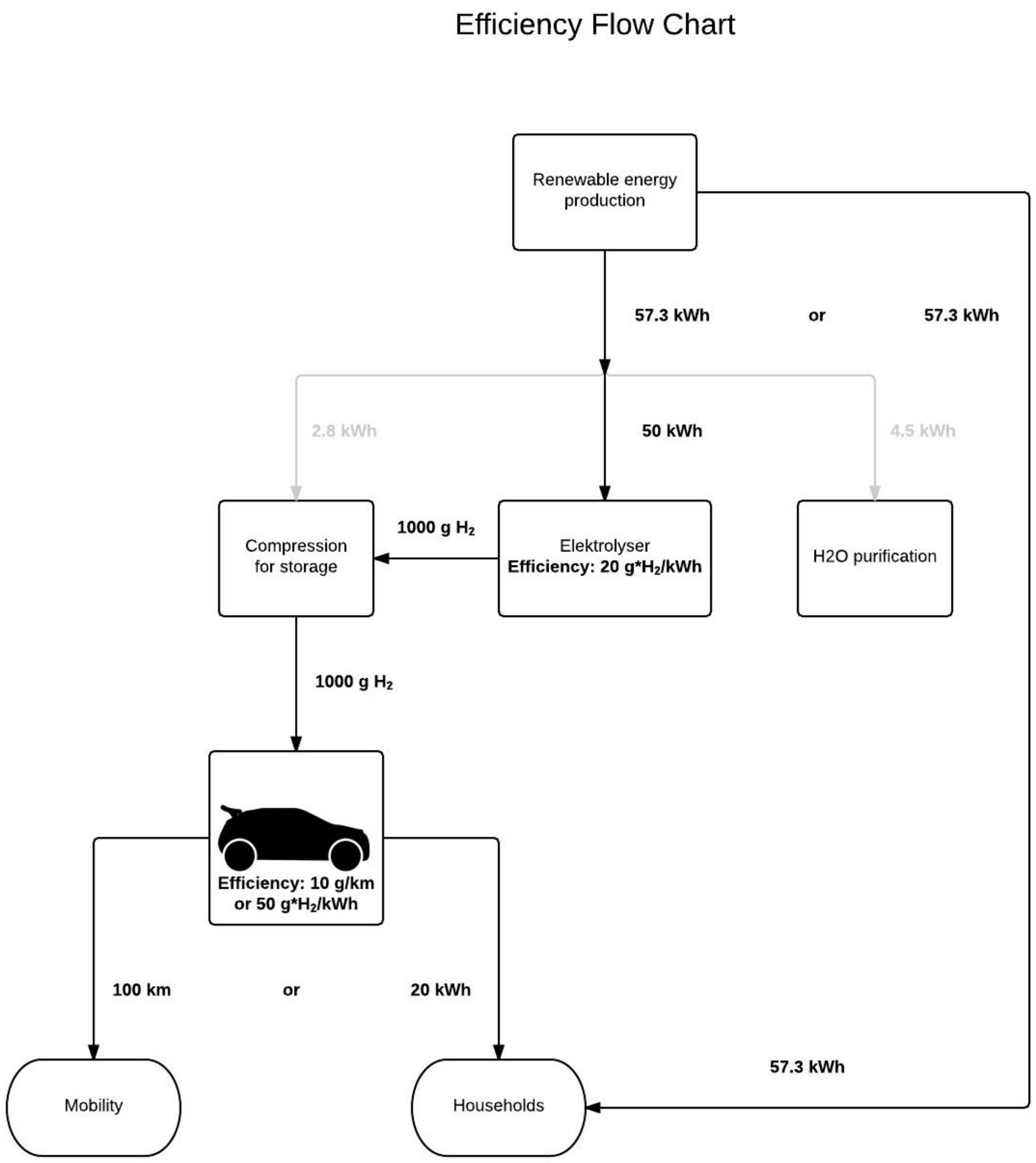

Figure 19: General overview of system electricity

6 Model Functionality

This chapter explains how the developed CaPP model can be used to run simulations. Section 6.1 treats the in- and the output of the user interface. Section 6.2 explains the general set up of the code and section 6.3 explains the configuration of the reference scenario. The CaPP model is developed in NetLogo 5.3. There are no guarantees that the model works in earlier versions of NetLogo. Several files complement the model: the rnd extension and several files containing input data. Appendix A discusses the complementary files in more detail.

6.1 The User Interface

The user interface of NetLogo is the environment in which users setup, run and analyze simulation runs. The user interface of the CaPP model consists of a setup part (on the left side) and an output part (on the right side). Both parts are subsequently discussed in the subsections below. The setup part is divided into three sections:

1. The base configuration, containing the general experiment setup and the control structure.
2. The buttons to setup and run the simulation.
3. The advanced system configuration, containing the parameters that define the case study.

6.1.1 Base Configuration and Simulation Buttons

The base configuration section contains the following elements regarding the general experiment setup of the simulation:

- Selection of input data (‘available input data’)
- The number of weeks the simulation should run (>0)
- The number of FCEVs (0-200)
- The distribution of home and work profiles (0-1)
- The distribution of minimum and maximum production preferences (0-1)
- The share of households and FCEVs that are active participants (0-1)

And the following elements regarding the control structure:

- Maximum production timeframes per day (1-3)
- Minimum weekly production timeframes (0-7)
- FCEV output (0-30)
- Maximum FCEV output (20-40)
- Number of FCEVs for backup (0-3)
- Home side demand control (true-false)
- The price level control reduction factor (0-1)

Figure 20 demonstrates how the base configuration section looks in the user interface.

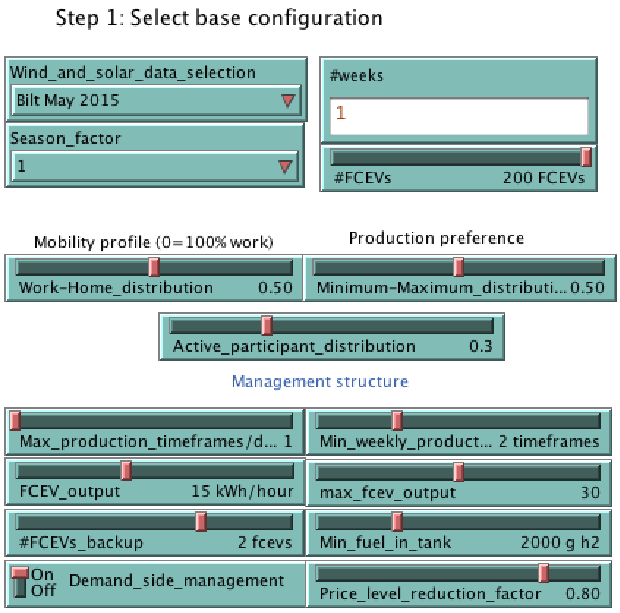

Figure 20: The base configuration of the user interface

The 'setup' button can be pressed to run the setup procedure of the model. This procedure defines the virtual CaPP neighborhood as configured in the user interface. Pressing the 'run' button, accordingly, runs the simulation. The chooser element 'delay', above the run button, allows the user to choose a certain delay for the simulation.

6.1.2 Advanced System Configuration

The advanced system configuration contains many globals that define the case study. These globals remain constant throughout this research. Table 14 contains all of these parameters. Some examples are:

- the number, type and heigh of the wind turbines,
- the characteristics of the mobility profiles, and
- the efficiencies of technologies and that of FCEVs.

Next to these globals, their default values are shown.

6.1.3 The Model World

The model world is the section that visualizes the state of the model. It contains several animations that provide (entertaining) information. However, it does not provide much analytical value. In the CaPP model it consists of 200 households whose shade of yellow is an indication of the amount of electricity it demands. The configured number of FCEVs are located below randomly selected households. The color of the FCEV indicates its current activity:

- Green: parked at home
- Red: away
- Blue: producing electricity
- Yellow: idle backup
- White: producing backup electricity

- Black: missing production
- Cyan: producing additional electricity

The current day and hour are displayed in the upper left corner of the model world. On the right side figures of a PV farm, a wind farm and a hydrogen storage are shown, but these are not connected to the state of the CaPP system. Figure 21 is an example shot of the model world.

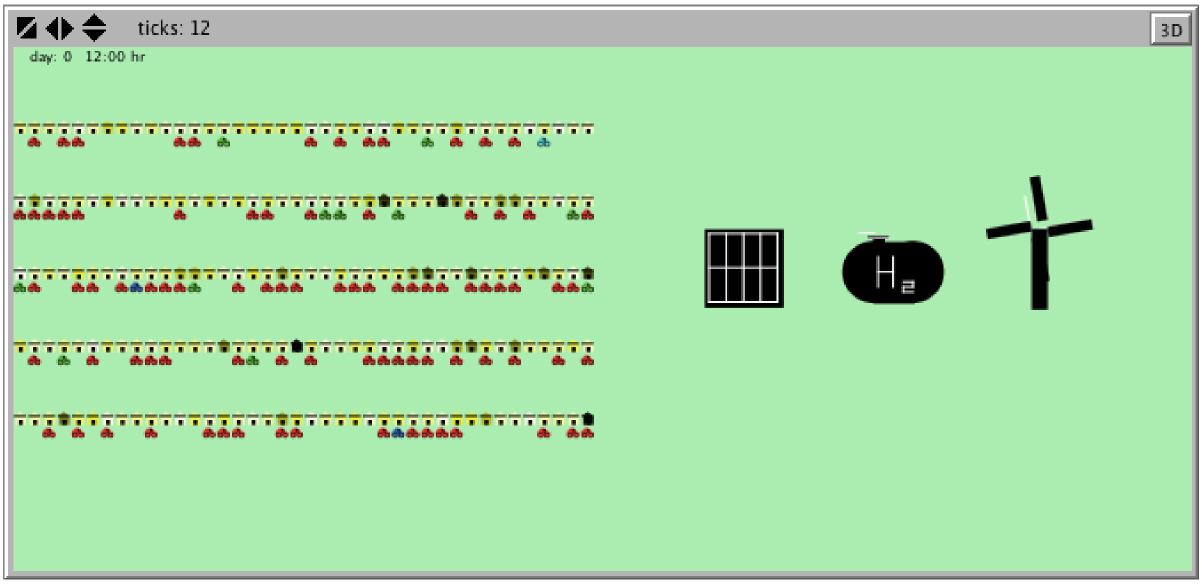

Figure 21: The model world

6.1.4 Monitored Output

System performance indicators that provide numerical information about the behavior of the model are displayed around the model world. The system performance indicators are shown in grouped monitors. The groups contain the following categories:

1. The total primary electricity used → Primary in the sense that 20 kWh produced by a FCEV requires 57 primary kWh from RE resources (see section 5.5.5).
2. The electricity supply and demand
3. Electricity production
4. Power production characteristics
5. FCEV mileage
6. Response profile
7. Hydrogen balance

Figure 22 illustrates the monitored output and provides example values.

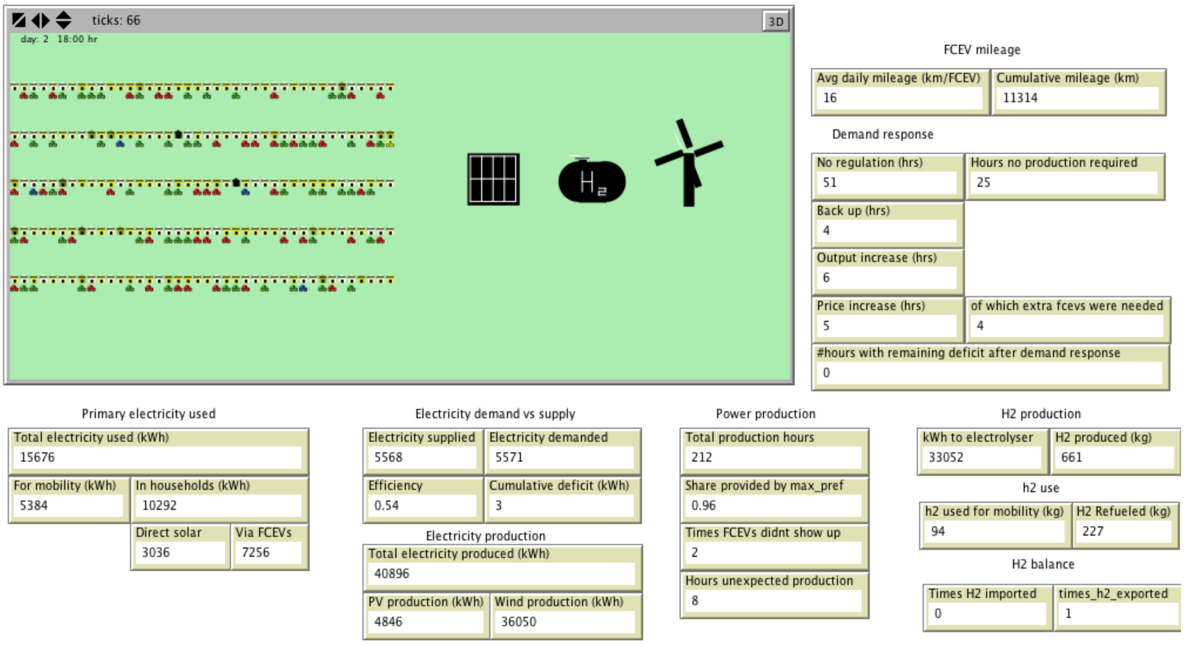

Figure 22: Monitored output

6.1.5 Graphical output

Besides the monitored output, the user interface provides a variety of graphs show the system's behavior related to the key model concepts defined in section 4.1. Each of these graphs is shortly described in Table 18 and an example is given in Figure 23 to Figure 30.

Table 18: Output graphs in the CaPP model

Graph	*Description*
FCEV availability	Shows four values related to FCEV scheduling
Power production	Shows the produced power by FCEV and energy balance
Household demand	Shows the demanded electricity and the share provided by the PV farm
Production output	Shows how many FCEVs are producing and at what output
PV output	Shows the PV production and in what direction that electricity flows
Windfarm output	Shows the windfarm production
H_2 levels	Shows the hydrogen production, hydrogen in storage and FCEVs and the amount refueled
Active participants	Shows the number of active participants

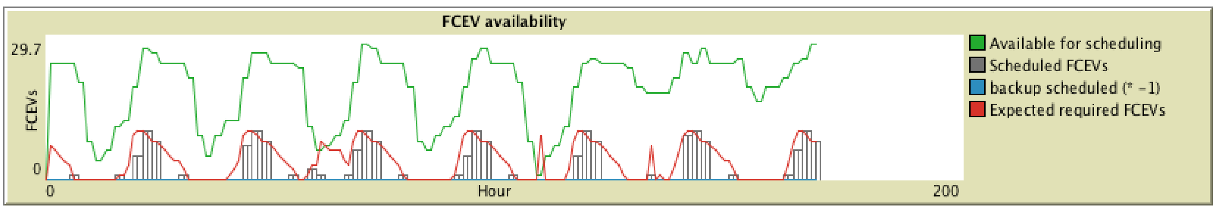

Figure 23: The FCEV availability graph

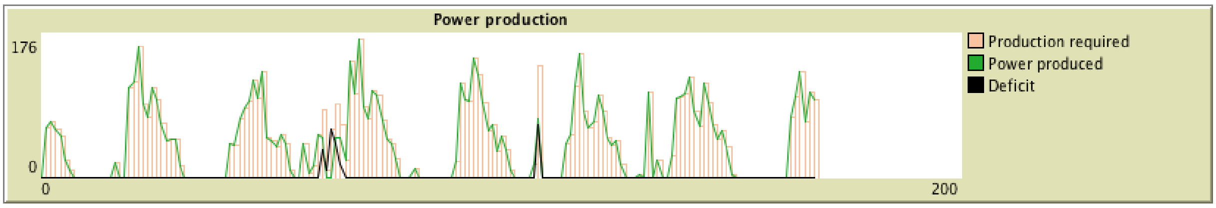

Figure 24: The power production graph

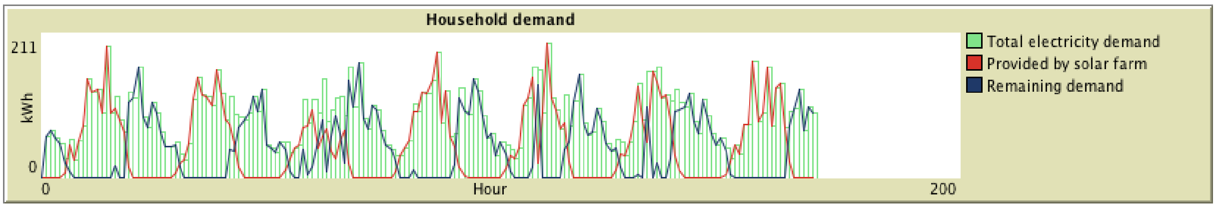

Figure 25: The household demand graph

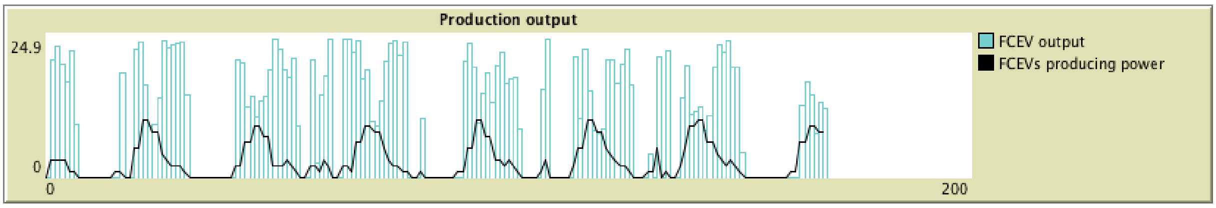

Figure 26: The production output graph

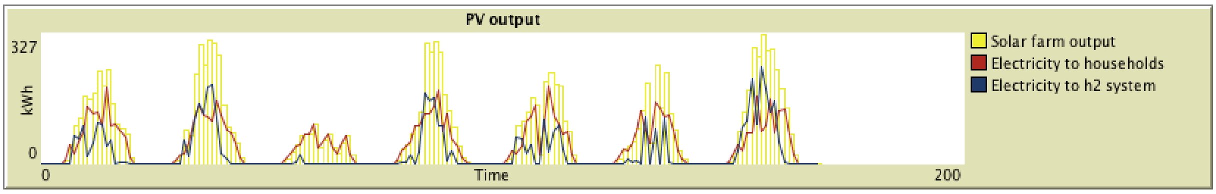

Figure 27: The PV output graph

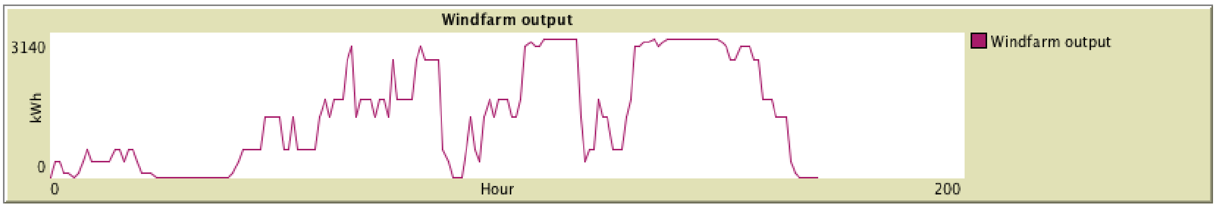

Figure 28: The windfarm output graph

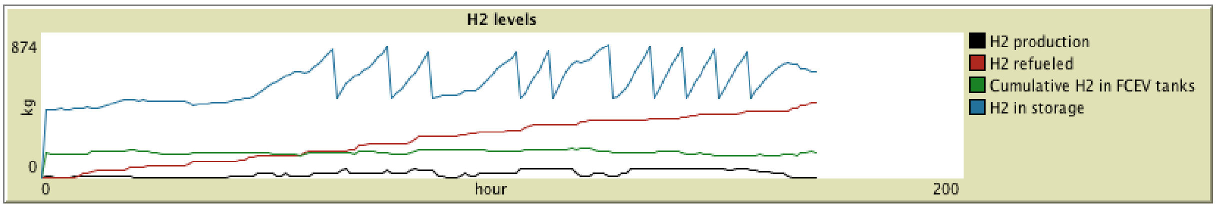

Figure 29: The H_2 levels graph

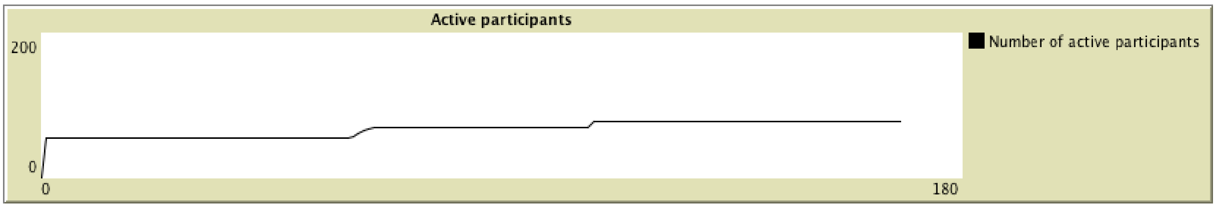

Figure 30: The active participants graph

6.2 The Code

The code tab of the model contains the model code. Most lines of code are accompanied with comments that make it understandable without knowledge of other code sections or even netlogo language. These comments can be read as normal text when connecting subsequent rows to each other.

The code section follows common NetLogo code structure. It starts with defining the agents, their characteristics and the global parameters that are not part of the user interface. NetLogo code works in procedures, separate modules of code. Procedures can initiate each other or they can be initiated by the observer. The first procedure, the setup, clears previous runs, graphs and other information in the memory. It then sets up the new model environment with the agents as described in the code, it also uses the values of the system configuration in the user interface. The setup procudere is followed by the procedures that describe the behavior of the model. These procedures are grouped into several subsections of the code:

Code subsections:

1. Agents and globals
2. Setup
3. FCEV profiles
4. Household procedures
5. PV calculations
6. Wind calculations
7. FCEV production planning
8. Run simulation

The next page contains an overview of how the procedures of the CaPP model are structured. More details can be found in Appendix C: Model Code, which treats the model code per procedure.

Procedure				Executed		Function	Perspective
Primary	Secondary	Tertiary	Quaternary	Via	When	Primary task	Main
Setup				Observer	Setup button or 'O'	Create CaPP neighborhood, and set up model world	Observer
	→ create-fcevs			Setup	Each setup run	Create FCEVs and set their characteristics	FCEV
		→→ set_status		create-fcevs	Each create-fcev run	Let FCEVs simulate their status for each hour of the simulation	FCEV
			→→→ plan_weekday_trips	set_status	Scheduling hour is 7-19 on weekdays	Simulate 'home' or 'away' for each FCEV during this timeframe	FCEV
			→→→ plan_evening_trips	set_status	Scheduling hour is 19-24 on weekdays	Simulate 'home' or 'away' for each FCEV during this timeframe	FCEV
			→→→ plan_weekend_trips	set_status	Scheduling hour falls in the weekend	Simulate 'home' or 'away' for each FCEV during this timeframe	FCEV
			→→→ plan_next_hour	set_status	If FCEVs have scheduled the current hour	Let FCEVs simulate the next hour	FCEV
	→ create-households			Setup	Each setup run	Create households and set their characteristics	Household
		→→ place_fcev_at_household		creater-households	Each create-housholds run	Replaces the FCEVs below a household in the model world	FCEV
		→→ calculate-SDF		creater-households	Each create-housholds run	Let households calculate the factor with which their demand is	Household
		→→ load-standardized-demand		creater-households	Each create-housholds run	Load in the standardized demand curve for households	Observer
		→→ determine_controlled_demand		creater-households	Each create-housholds run	Calculates the demand profile when home side demand control is active	Observer
	→ create-objects			Setup	Each setup run	Create the objects and set their characteristics	Objects
		→→ calculate_pv_output		create-objects	Each create-objects run	Load in the selected insolation data and calculates the PV output	Observer
		→→ load_windspeed_file		create-objects	Each create-objects run	Loads in the selected windspeed data	Observer
		→→ load_powercurve		create-objects	Each create-objects run	Loads in the selected power curve of the wind turbine	Observer
		→→ windloglaw		create-objects	Each create-objects run	Calculates the windspeed at hub height based on data and the wind farm	Observer
		→→ calculate_windturbineoutput		create-objects	Each create-objects run	Links the windspeed and power curve to determine a turbine's output	Observer
	→ show_mobility_profile			Setup	Each setup run	Prints the distribution of the mobility profiles of the FCEVs	Observer
Run				Observer	Run button or 'P'	Starts running the simulation	Observer
	→ determine_potential_production_timeframes			Run	At the start of a week	Let FCEVs calculate the 2 hr timeframes at which they are entirely parked at home	FCEV
	→ determine_preferred_production_timeframes			Run	At the start of a week	Let FCEVs determine the timeframes at which they are willing to produce power	FCEV
	→ calculate_required_fcevs_for_powerproduction			Run	At the start of a week	Calculate the required FCEVs based on the expected demand and solar output	Observer
	→ execute_scheduling_procedure			Run	At the start of a week	Determine which FCEVs will produce power at which hours	FCEV
		→→ process_daily_scheduling results		execute_scheduling_procedure	After the scheduling procedure finished	Keep track of the scheduling results	Observer
	→ update_fcevs_activity			Run	Each timestep	Let FCEVs follow their schedule, and refuel when required	FCEV
		→→ process_trip		update_fcevs_variables			
			→→→ refuel	process_trip			
		→→ produce_power_current_hour		A FCEV	When a FCEV produces power this hour	Let a FCEV set the variables corresponding to producing power	FCEV
		→→ miss_power_production_current_hour		A FCEV	When a FCEV misses producing power this hour	Let a FCEV set the variables corresponding to missing power production	FCEV
		→→ refuel		A FCEV	If a FCEV requires a refill	Let a FCEV refuel and reduce the h2 in the storage	FCEV
	→ calculate_total_electricity_demand			Run	Each timestep	Determine the current total electricity demand	Household
	→ production_management			Run			
		→→ update_production_fuel_used		production_management			
	→ update_variables			Run	Each timestep	Calculate many variables and KPI's of the current hour	Observer
		→→ update_storage		update_variables			
		→→ update_active_participants		update_variables			
	→ advance_hour_of_simulation			Run	If all steps of current hour are completed	Advance the simulation to the next hour	Observer
	→ print_results			Run	At the end of a simulated week	Print several results to the command center	Observer
Set directory				Observer	Set directory button	Let the user set a directory from which the model retrieves the	Observer

Figure 31: Procedure structure

6.3 Reference scenario

To compare the outcomes of the model for different scenarios, a reference scenario needs to be established. The parameters that will vary between scenarios are the ones as defined in the base system configuration (see section 6.1.1). The default values of these parameters, shown in Table 19, define the reference scenario of the CaPP neighborhood. This configuration corresponds the the base control structure as defined in the research scope.

Table 19: Reference scenario parameters

Base configuration parameter	*Default value*	*Unit*
Number of FCEVs	100	FCEVs
Mobility profile distribution	0.5	-
Production preference distribution	0.5	-
Share of active participants	0.3	-
Maximum production timeframes per day	1	timeframes/day
Minimum production timeframes per week	5	timeframes/week
Standard FCEV output (when producing electricity)	15	kW
Maximum FCEV output (when producing electricity)	30	kW
Number of FCEVs for backup production	1	FCEVs
Home side demand control	On	-
Price level control demand reduction factor	0.7	-

7 Model Verification and Validation

Verification and validation are two important steps in the development of a model. They treat the following questions:

- Verification: does the model do what the modeler intended it to do?
- Validation: does the model represent the system of the problem definition?

A model verification method suggested in the book ABM book is applied (van Dam, Koen. Nikolic, Igor. Lukszo, 2013). This method starts with assessing the behavior of the CaPP model with a single FCEV and, subsequently, testing the behavior with multiple FCEVs. Model validation is performed with sensitivity analyses of several parameters and with expert opinion.

7.1 Verification of the CaPP Neighborhood Model

Writing each line of code with repetitive verification is common practice for agent-based models. Not doing so will result in time consuming bug-fixing during later stages of the model development. The single- and multiple-FCEV testing, however, treats the verification of the completed CaPP model.

7.1.1 Single-FCEV Testing

All runs in this verification section are performed with 1 week and 1 FCEV in the reference scenario. Mobility patterns, FCEV scheduling, the control structure, and additional output are all discussed.

7.1.1.1 Mobility Patterns

The 'FCEV availability' graph is used to explore some general behavior of FCEVs. Figure 32 displays the mobility patterns of a FCEV with a workprofile, a low evening trip probability, a high weekend trip probability and a maximum production preference. The green line shows five commuting trips and two weekend trips. Because this FCEV did not take any evening trips and it has a maximum production preference, it is available for power production scheduling at all remaining timeframes. The grey lines show during which hours the FCEV is scheduled for power production. Since 'the maximum number of production timeframes per day' in the reference scenario is '1', this FCEV is scheduled only once a day. Each day the FCEV is scheduled for power production at the 22:00-24:00 timeframe. This is the result of the scheduling procedure that starts scheduling at 24:00 and accordingly works, timeframe by timeframe, back to the 0:00.

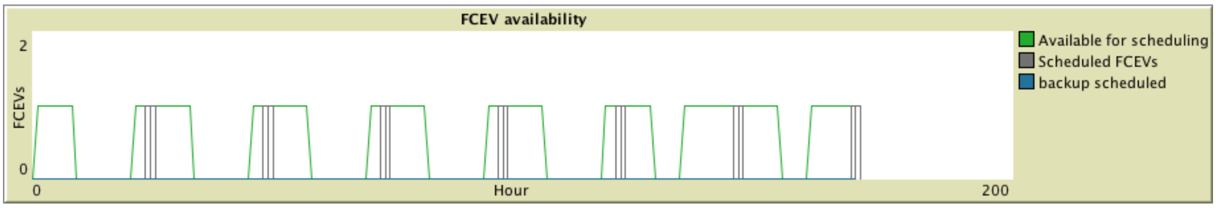

Figure 32: Mobility patterns of a FCEV with a work profile

Figure 33 shows the behavior of a FCEV with a home profile, small probabilities for all trips, and a maximum production preference. This FCEV only makes three trips during the simulated week and is available for scheduling during all remaining hours. In contrast to the previous example, 'the maximum number of production timeframes per day' is set at '2'. As a consequence, this FCEV produces power 14 times in one week. Note, there is always a timeframe between two production timeframes, this allows the FCEV to refuel.

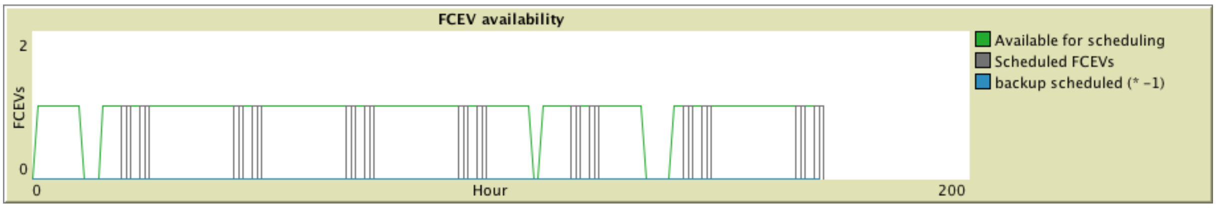

Figure 33: Mobility patterns of a FCEV with a home profile

7.1.1.2 Production scheduling

Figure 34 and Figure 35 show the FCEV availability of two distinct runs with a FCEV which has a 'minimum' production preference. The timeframes for which the FCEV is available for power production scheduling scheduling are randomly selected from the set of timeframes during which the FCEV's activity is 'parked at home' and which are not night timeframes (0:00-6:00). FCEVs with a minimum production preference are not limited by one production timeframe per day as can be seen in the first graph. FCEVs with a 'minimum' production preference specifically appoint those hours for scheduling, meaning that the owners consciously choose to produce more often than once a day (see section 5.5.2). The two non-filled availability spikes in the second graph display another interesting feature: even thought the FCEV was available for power production, it was not scheduled. Figure 36 shows why this happened. Apparently, the PV panels provided sufficient electricity to meet de households' demand. The PV production was forecasted, thus the FCEV was not scheduled for power production.

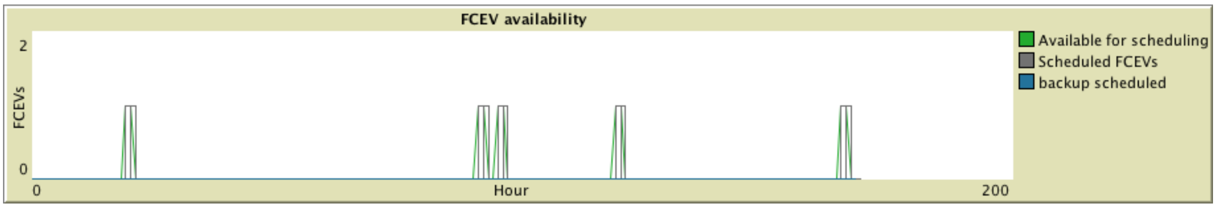

Figure 34: FCEV with minium production preference (1)

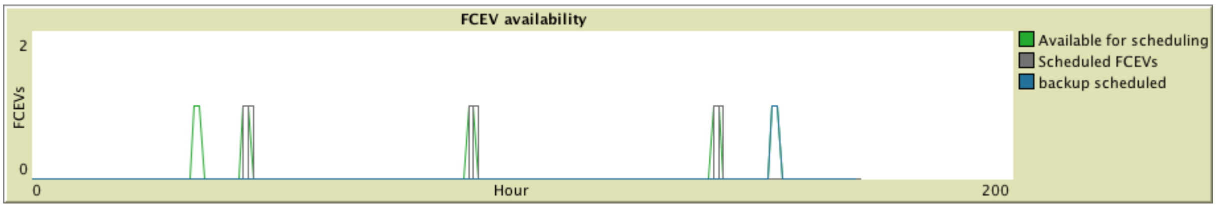

Figure 35: FCEV with minimum production preference (2)

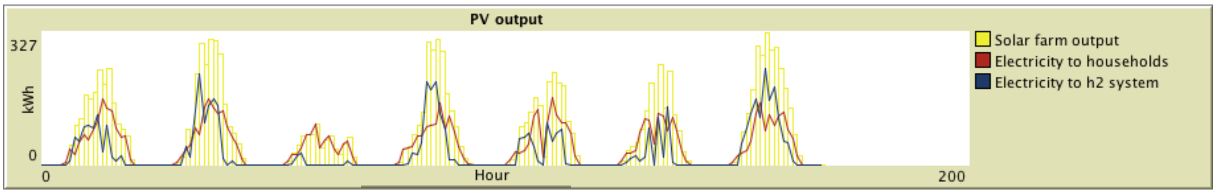

Figure 36: Sufficient PV output to supply the neighborhood

Both of the runs from Figure 34 and Figure 35 had no backup FCEVs scheduled. This complies with the model formalisation because only one FCEV is available for scheduling. The normal scheduling procedure schedules this FCEV if it is available one or two times per day (depending on the maximum production timeframes per day). This excludes the FCEV from being scheduled for backup because that requires a FCEV to not already be scheduled for normal power production on same day.

The power production graphs in the figures below show that it is possible for FCEVs with a production preference of 'mininmum' to produce more timeframes than the minimum number of timeframes prescribed by the control structure. These additional power production timeframes are timeframes during which the FCEV responds to price level control as an active participant. One of the criteria for active participants to produce additional power is to have sufficient hydrogen in their tank (see section 5.5.2). Fuel issues during two subsequent power production timeframes are therefore excluded.

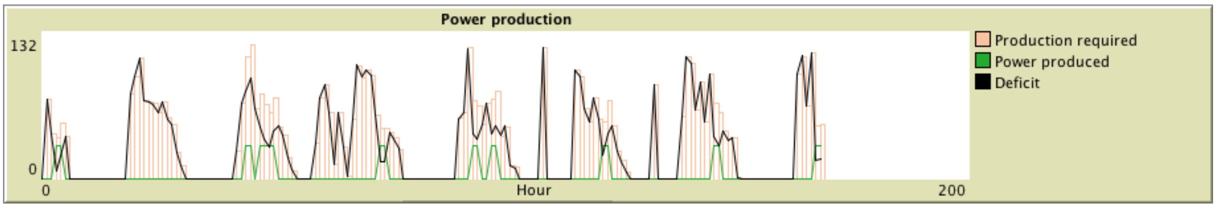

Figure 37: FCEV with a minimum production preferance and an active participant (1)

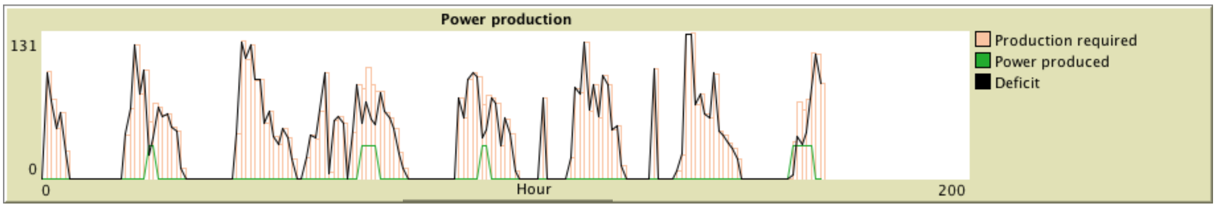

Figure 38: FCEV with a minimum production preferance and an active participant (2)

7.1.1.3 Control structure

This section verificates the control structure by exploring the system's behavior with respect to each control structure element.

Minimum Weekly Production timeframes and FCEV backup

The two figures below show the FCEV availability and scheduling results of two 1-FCEV runs with a 'minimum' production preference. In Figure 39 the minimum weekly production timeframes was 2, and in Figure 40 it was 5. The FCEV of Figure 40 was scheduled for backup production during a day in which it was not required for normal production. The first spike in Figure 40 represents a timeframe during which the FCEV is was not scheduled for power production even though it was available. The second spike illustrates the reason; the FCEV was already scheduled in another timeframe of that day.

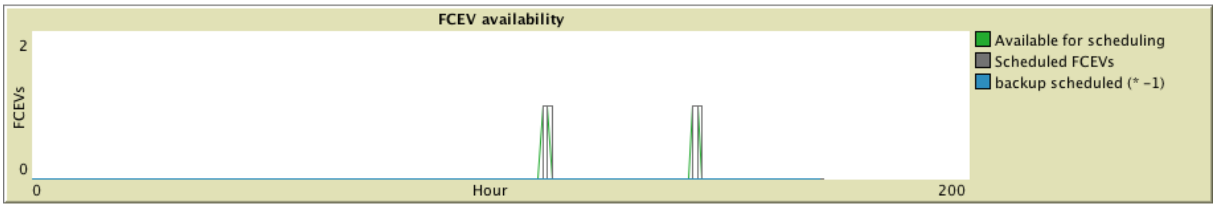

Figure 39: Minimum production timeframes per week: '2'

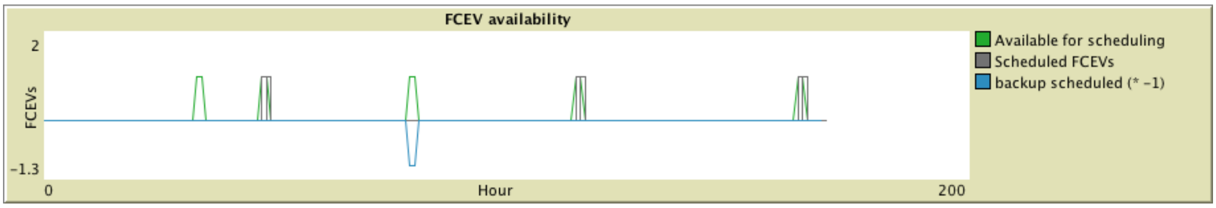

Figure 40: Minimum production timeframes per week: '5'

Max FCEV output

The FCEV shown in Figure 41 has a maximum production preference and is an active participant. It produced 17 timeframes in one week. The FCEV output did not exceed the maximum output of 30 kW. In most of the prodcuction timeframes the output was increased to this maximum. After all, there was only 1 FCEV producing electricity. A FCEV output of less than 30 kW was required during production timeframes that coincided with high PV production, this occurred 5 times in the simulated week.

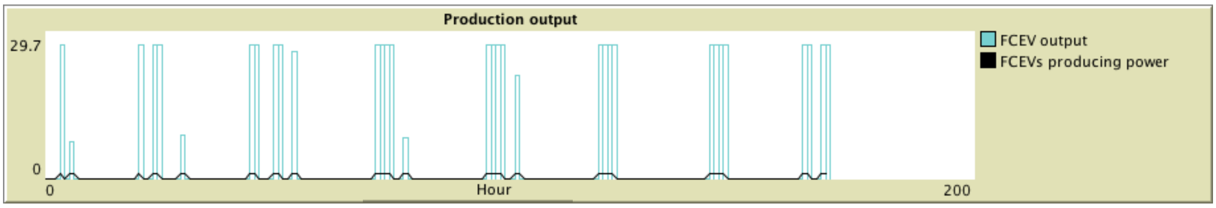

Figure 41: Prodcution output of FCEV with maximum production preference

Home side demand control

Figure 42 and Figure 43 show the typical household demand with and without home side demand control. The randomness in the electricity demand has been minimized such that the peak shift from home side demand control can clearly be identified. Figure 44 illustrates the demand with home side demand control and with randomness to illustrate the impact of the randomness.

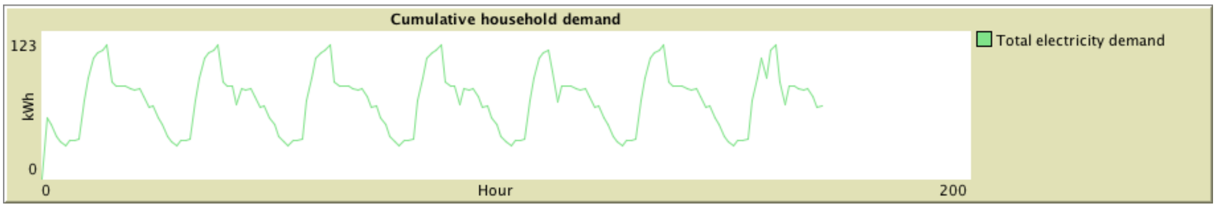

Figure 42: Household demand with homeside demand control

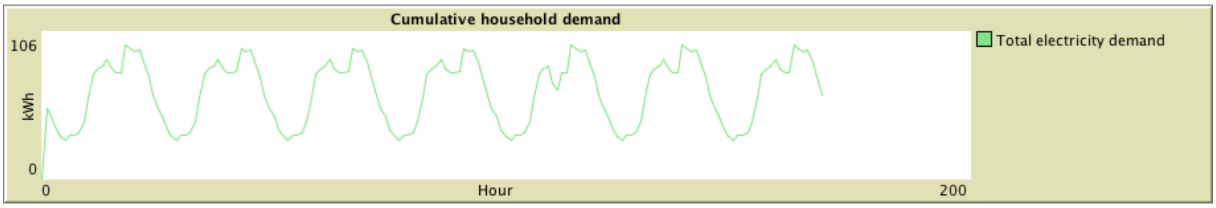

Figure 43: Household demand without homeside demand control

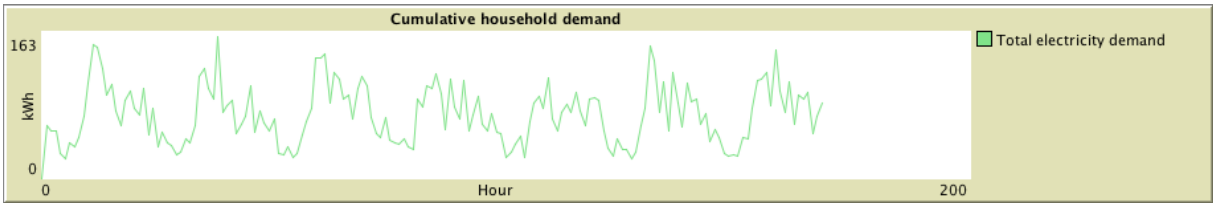

Figure 44: Household demand with randomness factors

Price level reduction factor

An extreme value test is used to assess the effects of the price level reduction factor. It should reduce the cumulative demanded electricity. Four runs are performed, two with a price level reduction factor of '0' and the two others with a price level reduction factor of '1'. There should be a noticeable difference in the total electricity demanded. The results, shown in table 20, verify this.

Table 20: Effects of price level reduction factor

Run	*Price level reduction factor*	*Total electricity demanded (kWh)*
1	0	11170
2	0	12512
3	1	6683
4	1	6620

Additional Output

Table 21 shows a selection of additional output from the model with 1 FCEV. To demonstrate the uniqueness of each entity in the model, a FCEV with a 'work profile' and a FCEV with a 'home profile' is discussed. In both scenarios the FCEV was not an active participant.

Table 21: General verification output

Output parameter	*Work Profile*	*Home Profile*
Distance to work	28.7 km	-
Cumulative mileage	373 km	0 km
avg mileage per day	53 km/day	0 km
times refueled	3	1
kg hydrogen refueled	13 kg H_2	4 kg H_2
Starting fuel	1266 g H_2	644 g H_2
Timeframes power produced	10	4
Times FCEV did not show up	0	1
Primary electricity used for mobility	172 kWh	0
System efficiency	0.93	0.99
kWh to electrolyser	204156 kWh	204118
H_2 produced	4084 kg	4083 kg
Electricity demanded by households	13571 kWh	13489 kWh
Electricity produced by PV farm	12650 kWh	12650 kWh
Electricity produced by wind farm	228750 kWh	228750 kWh
Hours no supply response required	60 hrs	63 hrs

Hours price level control required	108 hrs	104 hrs

The FCEV with the work profile drove 373 km and produced power during 10 timeframes. Starting with a relative empty tank, it was required to refuel three times. Once at the start of the first production hour, once after a few days commuting and producing power, and once again right before the last two production hours. FCEVs are quite likely to refuel before a production hour because of the requirement to have at least 2000 g H_2 in the tank before producing electricity. The FCEV with the home profile had low trip probabilities (0.5 for a weekday trip, 0,24 for evening trips and 0,05 for weekend trips). This resulted in zero trips during the week. It only produced power during four timeframes.

The overall efficiencies of the system are quite high (93% and 99%). After all there is only one FCEV producing electricity via the 'inefficient' route. The electricity produced by the PV panels and the wind farm were the same in both scenarios because they are not influenced by the model dynamics. During 60 hours of the selected week there was sufficient irradiance to supply the neighborhood's electricity demand. The exact value may vary due to the randomness in the electricity demand. The home profile run contained one hour in which an output increase of the FCEV was sufficient supply response. During 104 hours the system applied price level control. In 5 of those the reaction was sufficient to balance the electricity supply and demand, the others resulted in an power deficit.

The probability that non-active participants become active participants during electricity deficits is 3% in the reference scenario. It was demonstrated in the previous section that many electricity deficits occur when one FCEV operates in the CaPP system. The group of active participants should increase accordingly.

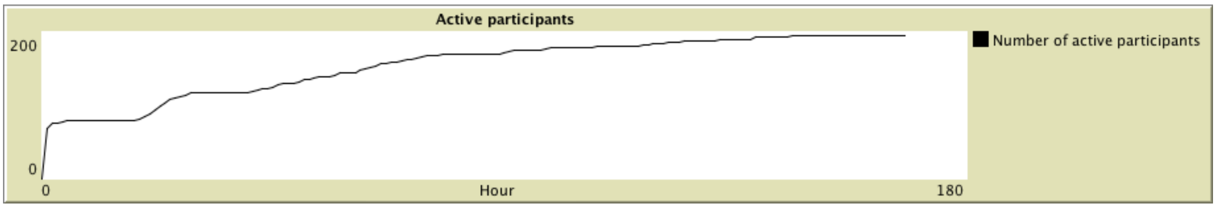

Figure 45: The increasing numbers of active participants

The amount of hydrogen in the tank of a FCEV at each hour of the simulation and when FCEVs refuel is printed in the command center. An example is shown below.

(fcev 0): "Gram H_2 in tank: [……1680 5000 5000 4740 4740 ….. 2040 2040 2040 1541 1541 1541 1541 1541 5000…..]"

(fcev 0): "Refuel hour and H_2 (gram) [[hour: 6 , refill: 3320] [hour: 40 , refill: 3459]]"

In this example the FCEV refueled two times, once on the 6th hour and once on the 40th hour. In both cases the reason for the refill was that it had less than 2 kg of hydrogen in it's tank.

7.1.2 Multiple-FCEV Testing

Several runs with 100 FCEVs are perfomed to assess the system's behavior with more FCEVs in the neighborhood. In the model world FCEVs can be seen to change their activities. The most common activities that occur are 'parked at home' and 'away'. At night and in the evening hours there are always some FCEVs that are blue, i.e. producing power. Some monitored output is shown in Figure

46. The elements 'no regulation', 'backup', 'output increase' and 'price increase' show the number of hours each type of response mechanism was used. They consistently add up to one week (168 hours) the runtime of the simulation.

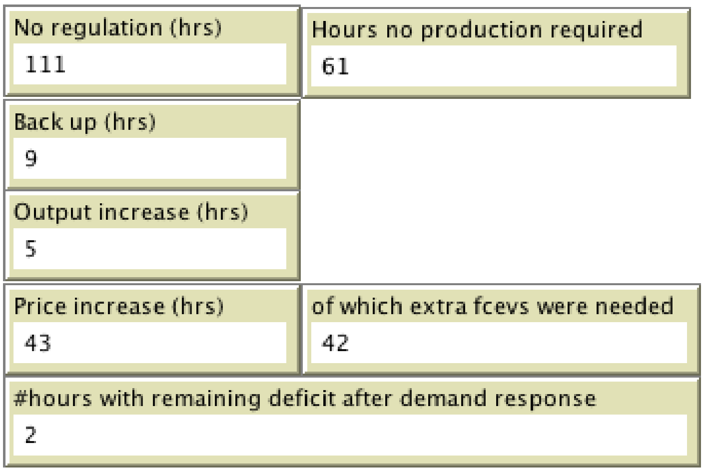

Figure 46: Supply response output with Multi FCEV verification

With 100 FCEVs in the neighborhood there should be many FCEV production hours. Some of them will be performed by FCEVs with a 'minimum' production preferences and during about 3,5% (half of the maximum change that FCEVs miss power production) of the production hours FCEVs should miss the power production. The two runs demonstrated below verify this behaviour. The output on the left side of Figure 47 was made with a minimum-maximum distribution of 0.5. This resulted the share of production hours provided by FCEVs with a 'maximum' production preference of 0.69. On the right that share was 1 becasuse all FEVs had a 'maximum' production preference.

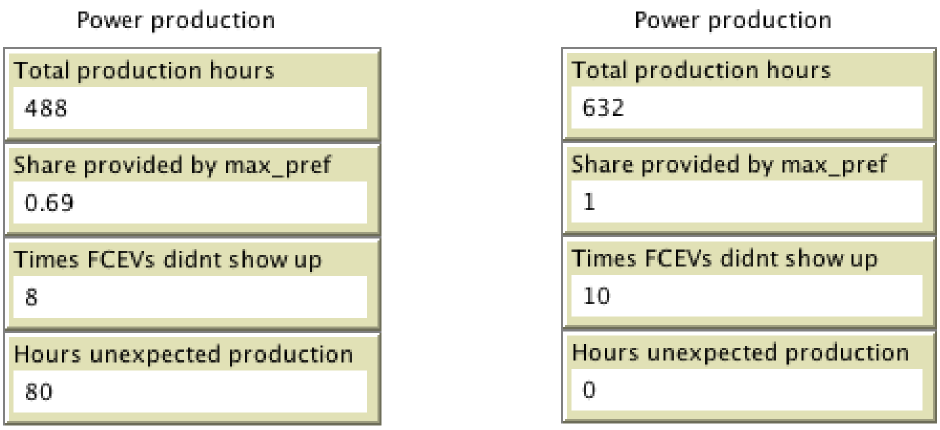

Figure 47: Power prodcution results for multi-FCEV verification

Next, the overal electricity flows of the system are discussed with the help of Figure 48. The total primary electricity used during the simulated week amounted to 37.326 kWh. 10.596 kWh was used for mobility, while the remaining sum was used in households. A quick verification of the kWh used for mobility can be made using the total mileage of the FCEVs, a simplification of the fuel economy of FCEVs and the overal efficiency of the hydrogen system:

$$Mobility\ demand\ (kWh) = mileage/(fuel\ economy * efficency) = 22339\ km/\left(6\frac{km}{kWh} * 0.35\%\right) = 10.637\ kWh$$

About 4/5th of the electricity delivered to the households was provided by FCEVs. This makes sense in a CaPP system where the PV prodcution is only available for about eight hours per day and with the peak demand outside those hours. The system's efficiency, being 0.52%, also reflects the large share of electricity provided by FCEVs. Noteworthy is the fact that the wind production is about an eight-fold of the primary electricity demanded. The PV production is around a factor 20 smaller than the wind production.

One inconsistency occured during these tests; during simulations without any hours of deficit, such as the one of Figure 48, the 'cumulative deficit monitor' displays small positive and negative numbers. This the result of rounding numbers at several steps in the code.

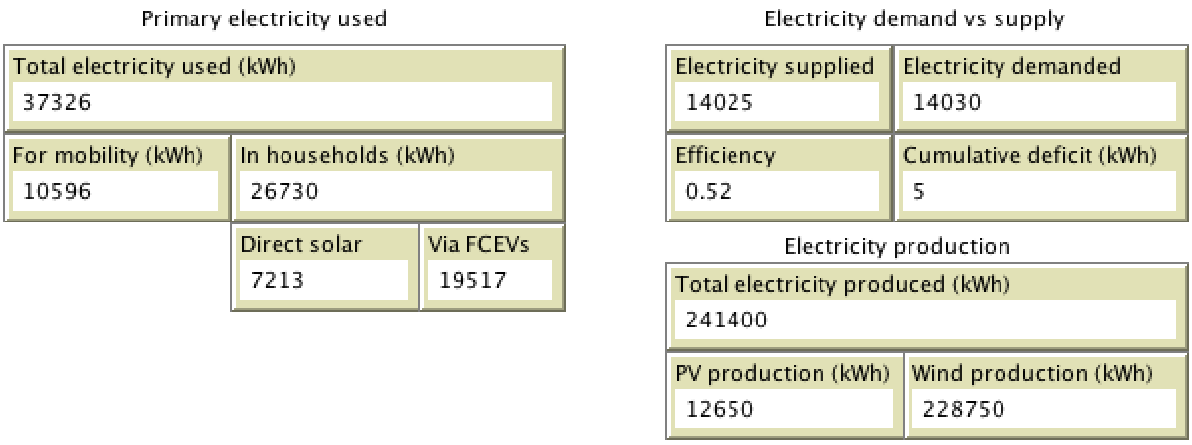

Figure 48: Electricity flows for multi-FCEV verification

7.2 Model Validation

The model is validated with a sensititvity analysis and an expert opinion. Three experiments performed with the BehaviorSpace tool of netlogo are used in the sensitivity analysis. Each experiment varies a case description parameter that is related to decision making of the agents. Most case desciption parameters are less interesting to explore because their lineair effects on the model behavior (such as the number of wind turbines, the FCEV efficiency and surface of PV panels on the household rooftops).

7.2.1 Participant switch probability

The participant switch probability determines the probability a resident decides to shift from being a non-active participant to an active participant. Active participants react to the response mechanisms, greatly influencing the performance of the system. The experiment to assess the sensitivity to the participant switch probability used a variation of the reference scenario with input data from December 2015. The number of hours an electricity deficit occured during the four week simulations is reported. 20 runs are performed for 6 values of the participant switch probability. The results are plotted in Figure 49.

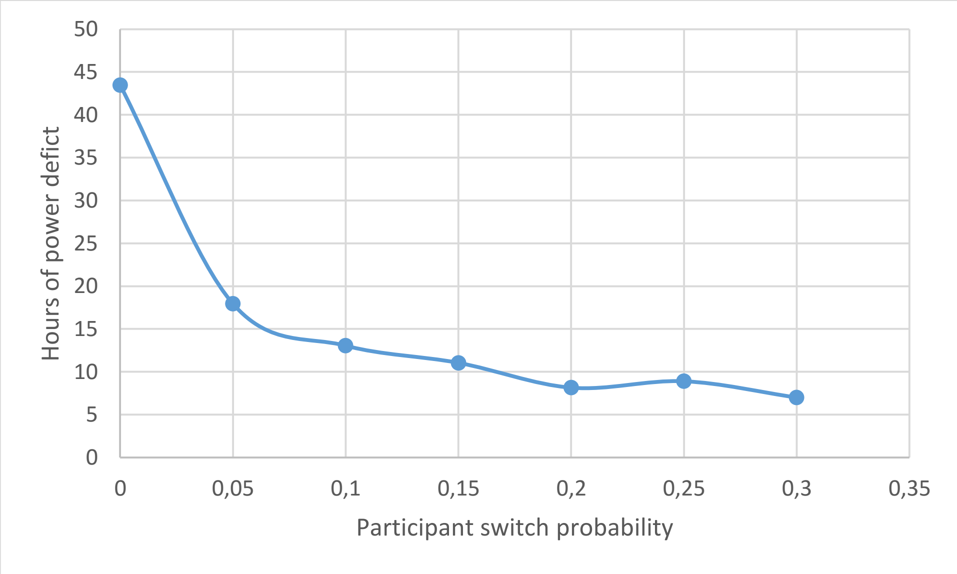

Figure 49: Sensitivity to participant switch probability

The system's performance seems to be sensitive to the range of the participant switch probability from 0 to 0.1. The value chosen for the case study, 0.07, falls within this range. The interpretation of the results should take this into account.

7.2.2 Randomness in electricty demand

The randomness in the electricity demand is a factor that varies each timestep and that determines the possible randomness of the cumulative household demand. A value of 0 represents no randomness in the cumulative household demand. A value of 0.6 means that the cumulative household demand in each timestep is multiplied with a random factor between 0.7 and 1.3. The number of hours in which no response is required is reported because unexpected high electricity demand results in the need of response mechanisms. The results are shown in Figure 50.

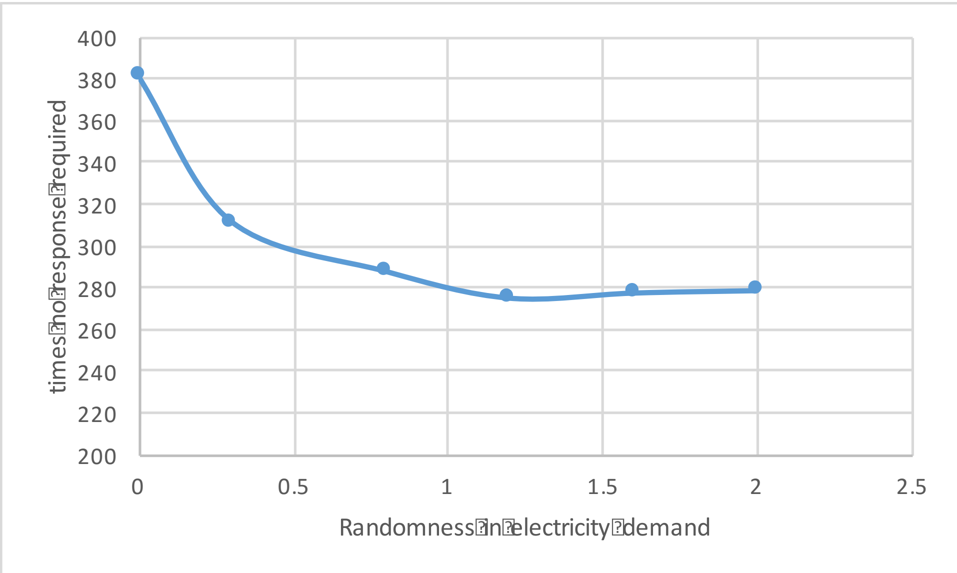

Figure 50: Sensitivity to randomness of electricity demand

The 'times no response required' ranged from 380 to 275. The neighborhood's performance is better the smaller the randomness in the cumulative electricity demand. If the value taken for the case study (0.8) turns out to be higher than in a real CaPP system, the system might require less response mechanisms than the model behavior indicated.

7.2.3 Obliged Production at Night

Obliged production at night is a control element that has the value 'no' in the case study. The philosophy is that during night hours there is sufficient supply. After all, FCEVs with a 'maximum' production preference will be available during those hours. Figure 51 shows that changing the value of this control element to 'yes' has very little effect on the performance of the system.

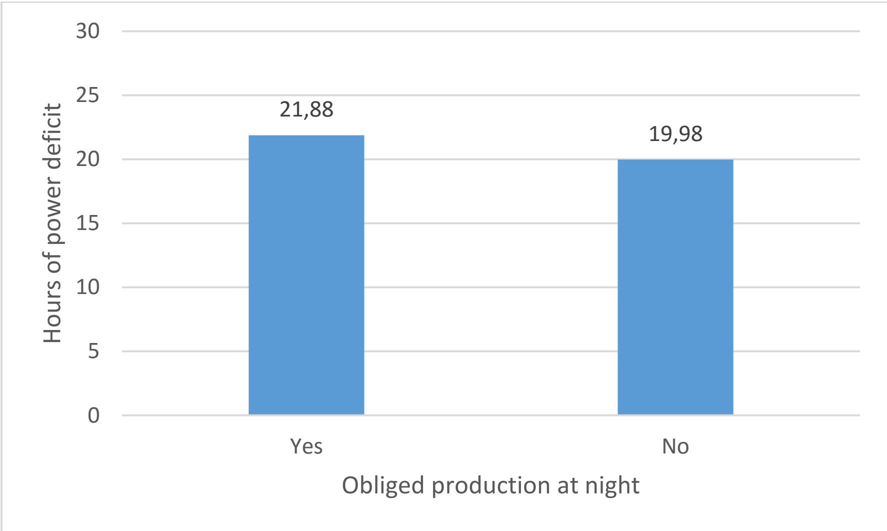

Figure 51: Sensitivity to obliged production at night

7.2.4 Expert opinion

Another method for model validation is to let experts in related research fields provide commentary on the used methods and mechanics of the model. Drs. A. Hoekstra from Technical University of Eindhoven provided feedback on the way the mobility patterns are implemented in the CaPP model (see appendix B). A. Hoekstra's expertise ranges from modeling of mobility behavior, electric vehicles and infrastructural development of sustainable mobility. He currently works on implementing the ALBATROSS model (A Learning Based Transportation Oriented Simulation System) into Gama (an agent-based environment) to develop a agent based model for assessing electricity grid and EV charging infrastructure needs in the Netherlands.

A. Hoekstra spend ran several simulations with the CaPP model to provide his expert opinion. He identified the most important model characteristic of the mobility patterns as: "when is a car in the front of the home". On the way this is incorporated in the CaPP model A. Hoekstra states: "This a reasonable simple way that can give a rather accurate estimation of when the car will be home. Especially since this is not (yet) a PhD model it captures the mobility patterns extraordinally well in a way that shows both the flexibility of agent based models and the modeling capabilities of the student in question". He further discusses the possibilities of extending the model by relating mobility patterns to human activities (such as in the ALBATROSS model) and by implementing EVs. Finally, he notes: "in the scope of this model we think adding activity based mobility patterns would have been and overkill and would have lead to neglect the rest of this very well done integral model".

The feedback of A. Hoekstra is very positive, however, it validates only part of the model. Ideally, the other parts of the model would be validated by domain experts as well. Unfortunatly, there was not sufficient time to schedule these validation processes. Table 22 is an overview of domain experts that would have been contacted to provide partial model validations.

Table 22: Validation experts

Validation Topic	*Person/expertise*
Integral model: system scope and model focus	Prof. A. van Wijk: expert in CaPP systems, developer of CaPP pilots (TU Delft)
Integral model: system scope and model focus	Ir. Vincent Oldenbeek: expert in CaPP systems (TU Delft)
Household demand profiles	Expert from the utility sector
Household demand profiles	A University researcher with expertise of the electricty grid
Hydrogen system	Prof. B. Dam: expert in solar to hydrogen
Control structure: demand side management and	Robin Berg: owner of LomboXnet, expert in field of smart charging and demand side control

8 Model behavior

This chapter assesses the performance of the CaPP neighborhood under a wide variety of scenarios. Recall that the performance is defined with four specific aspects of the system behavior: the occurence of electricity deficits, the supply response profile, the efficiency of the system, and the share of voluntary production hours (see section 3.3). The behavior of the system is captured in experiments that perform multiple runs. The output of the experiments is processed in Microsoft Excel to provide averages, standard deviations, graphs and diagrams. Sometimes a graph from the CaPP model is shown to illustrate a particular aspect of a situation.

8.1 Experiments

The BehaviorSpace tool of NetLogo is used to perform the experiments. The requirement to process the output manually in Excel restricted the number of runs in experiments with multiple reporters. Eight reporters, corresponding to the performance of the system, occur frequently:

Reporters with respect to the performance of the system

1. *times_no_control* – reports the hours of the simulation in which no response mechanisms are required
2. *times_no_production*_required – reports the hours of the simulation in which no FCEV power production is required
3. *times_backup_used* – reports the hours of the simulation with 1st level response, i.e. the use of backup vehicles balances the electricity
4. *times_power_increased* – reports the hours of the simulation with 2nd level response, i.e. the use of backup vehicles and power increase balances the electricity
5. *times_price_increased* – reports the hours of the simuation with 3rd level response, i.e. price control is used
6. *hours_power_deficit* – reporst the hours of the simulation with 3rd level response and still an electricitity deficit remained
7. *system_efficiency* – reports the system efficiency
8. *share_produced_hours_voluntralily* – reports the share of production hours in performed by FCEVs with a maximum production preference

Note, each simulated hour of the CaPP neighborhood falls in one of the following categories related to the response structure:

1. No response required → the scheduled FCEVs provide sufficient electricity
2. 1st level response → the use of backup FCEVs is needed to provide the demanded electricity
3. 2nd level response → the output of the producing FCEVs needs to be increased to supply the demanded electricity
4. 3rd level response → price level control is used to reduce demand and increase supply

The list below shows the performed experiments and the number of runs they simulated.

Base Scenario Experiment (50 runs)
No social residents experiment (20 runs)
Many social residents experiment (20 runs)
Economic oriented residents experiment (20 runs)
Winter experiment (25 runs)
Summer experiment (25 runs)
Winter with 200 FCEVs experiment (50 runs)
Winter with 150 FCEVs experiment (50 runs)
Summer with 50 FCEVs experiment (50 runs)
Summer with 75 FCEVs experiment (50 runs)
FCEV output experiment (120 runs)
Max FCEV output experiment (100 runs)
Power increase experiment (110 runs)
Production frames per day experiment (60 runs)
Production frames per week experiment (40 runs)
Home side demand control experiment 2 (50 runs)
Home side demand control experiment 1 (50 runs)
Home side demand control experiment 3 (50 runs)
Price level reduction experiment (180 runs)
Backup FCEVs experiment (30 runs)
Minimum FCEVs in winter experiment (300 runs)
Minimum FCEVs winter with base structure experiment (300 runs)
50 FCEVs in winter experiment (25 runs)
100 FCEVs in winter experiment (25 runs)
200 FCEVs in winter experiment (25 runs)
50 FCEVs in summer Base experiment (10 runs)
50 FCEVs in summer sub-optimal experiment (10 runs)
50 FCEVs in summer Optimal experiment (10 runs)
100 FCEVs in summer Base experiment (10 runs)
100 FCEVs in summer loose experiment (10 runs)
200 FCEVs in summer loose experiment (10 runs)
Summer #FCEVs experiment (180 runs)

8.2 Performance of the Reference Scenario

The first experiment assesses the reference scenario of the system. It performed 50 runs with the RE resources of May. Table 23 is a summary of the performance reporters. 100 FCEVs in the reference scenario result in a well performing system with an average of 0,38 hours of power deficit. On the second performance level the system used an average of 9,4 hours of price control. In 59,9 hours an increase of FCEV power output balancded the electricity and in 68,8 hours using backup FCEVs was sufficient. The overall system efficiency was 53%, and almost all production hours can be performed by FCEVs with a 'maximum' production preference.

Table 23: Performance of base scenario

Statistics over 50 runs	*Hours no production required*	*Hours no response*	*Hours 1st level response*	*Hours 2nd level response*	*Hours 3rd level response*	*Hours power deficit*	*System efficiency*	*Share produced hours voluntralily*
Average	273,7	533,8	68,8	59,9	9,4	0,38	0,53	0,99
Minimum	258	484	40	14	4	0	0,53	0,97
Maximum	293	602	102	125	18	5	0,53	1
Standard deviation	7,7	28,6	14,1	21,1	3,1	0,9	0,0	0,01

During 40% of the time (273,7 hrs) the PV production was sufficient to supply the neighborhood's electricity demand. No power production from FCEVs was required during those hours. Figure 52 shows that the PV production in the reference scenario has the same order of magnitude as the household demand (55.681 vs 61.250 kWh), while the wind production is a factor ten larger (658.350 kWh). The 100 FCEVs used a total of 43.015 primary kWh (with a standard deviation of 3033 kWh). The wind turbine had a load factor of 0.33. Table 24 shows the load factors of several other months as well. Note, the load factor is not scenario dependent. The month with the smallest load factor is October (0,11). With the load factor of October, a third of the 659.350 kWh produced by the wind farm would still be sufficient to provide both the electricity and mobility demand. Even with 200 FCEVs instead of 100 (as that adds about 43.000 kWh to the total energy demand). This implies that a 3 MW wind turbine provides sufficient energy for the 200 household CaPP neighborhood.

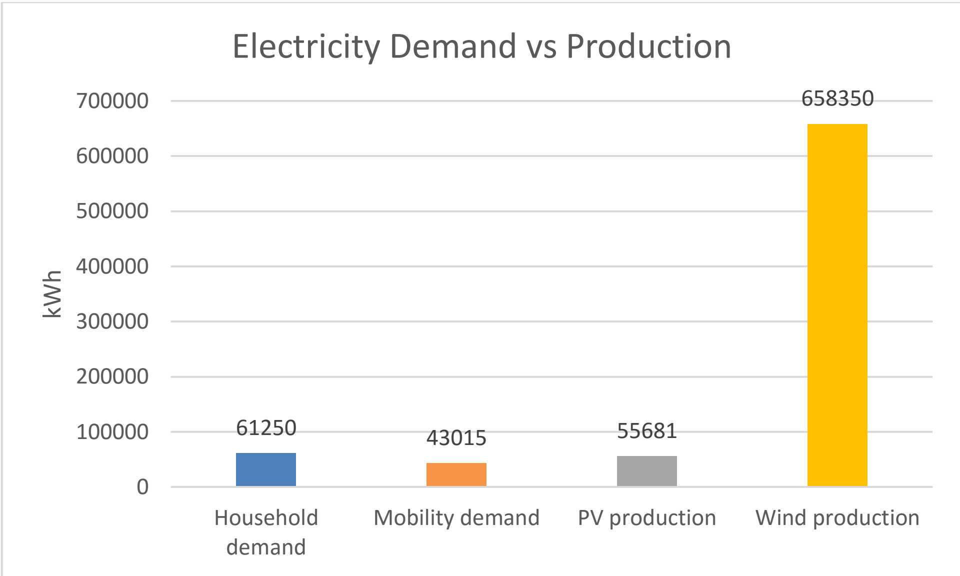

Figure 52: Key output of the base scenario

Table 24: Wind farm load factor per season

Month	*Load Factor*
May	0.33
Juli	0.35
October	0.11
December	0.26
Januari	0,48

Figure 53 shows that more than half of the demanded electricity is supplied by the PV farm (32.510 kWh of 61.250 kWh). The remaining demand is provided by FCEVs. This costed a total of 82.316 primary kWh, resulting in an overall system efficiency of 53% (Table 23).

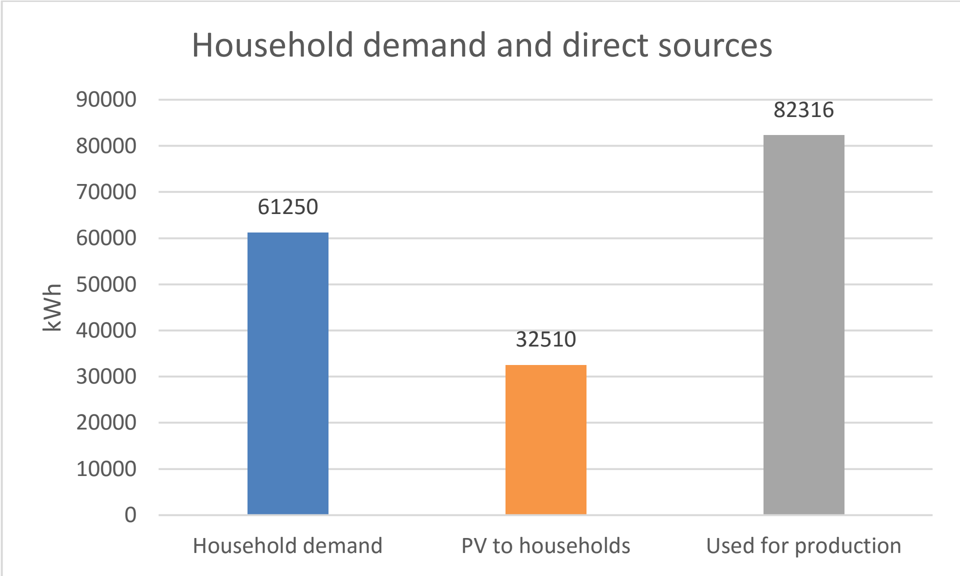

Figure 53: Household demand and electricity sources

Figure 54 to Figure 56 provide some further insights of the dynamics of the system in the reference scenario. The first figure shows that the 'available FCEVs for scheduling' were continuously higher than the 'expected required number of FCEVs'. As a result, the expected required number of FCEVs were scheduled at nearly all timframes. An exception occured during the third day. Apparently, some of the available FCEVs were already scheduled on that day and could not be scheduled again. Such a timeframe potentially needs supply response (depending on, among others, how the electricity demand of that timeframe turned out). The second graph confirms that this was indeed the case; the 'FCEV output' was increased to the 'maximum FCEV output' of 30 kW as prescribed by the base control structure. The use of the maximum FCEV output also means that the next response mechanism, price level control, was enacted. Figure 56 shows that price level control at that hour successfully balanced the electricity supply and demand, since no electricity deficit occurred during the simulated week.

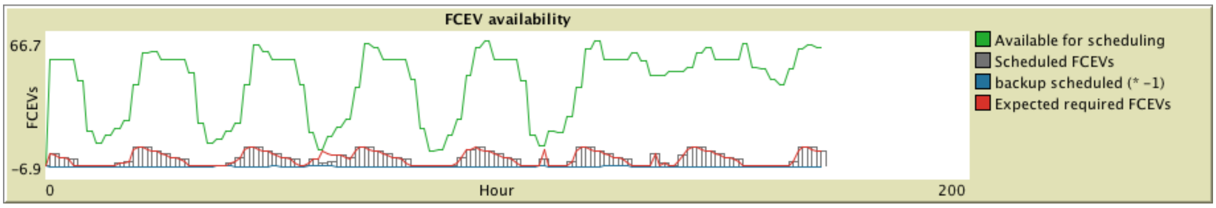

Figure 54: FCEV availability in the base scenario

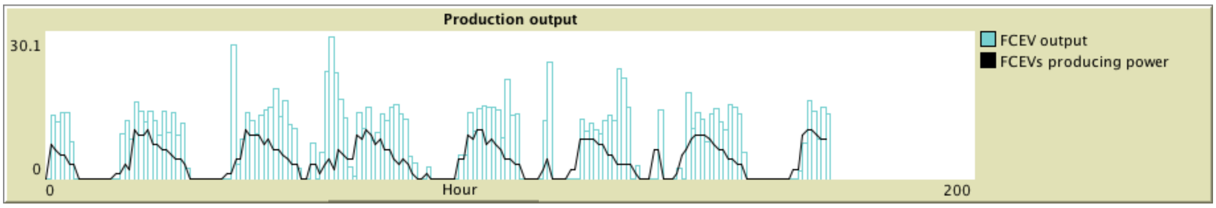

Figure 55: FCEV production in the base scenario

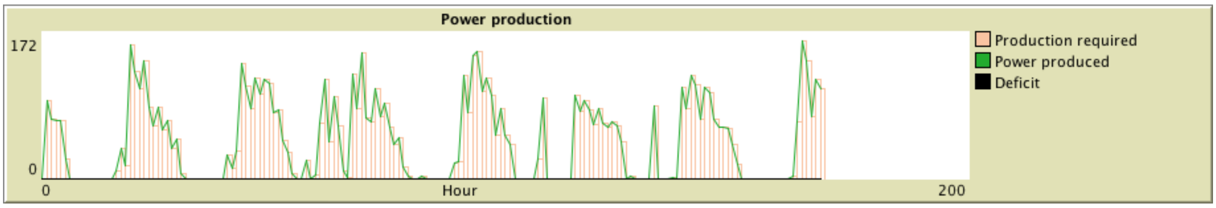

Figure 56: Electricity balance in the base scenario

8.3 The Importance Social Cohesion

The reference scenario features a well performing CaPP neighborhood in which the probability that a FCEV has a 'maximum' production preference is 50% and in which 30% of the residents are active participants. The social cohesion of the system may be represented by different figures. This section explores the extremes of the degree of social cohesion to assess their impacts on the performance. Three experimental set ups for the social cohesion are used: 1) residents do minimum efforts for the system, 2) residents do maximum efforts for the system, 3) residents do minimum efforts unless financially stimulated by price level control, see Table 25.

Table 25: Social cohesion scenarios

Set up	*Scenario*	*Production preference*	*Active participants*
1	No social residents	100% minimum	None
2	Very social residents	100% maximum	All
3	Economic oriented residents	100% minimum	All

To keep the number of active participants constant throughout each run, the advanced configuration parameter 'participant switch probability' is set to '0'. The average values of the performance reporters are compared to the reference scenario in Figure 57.

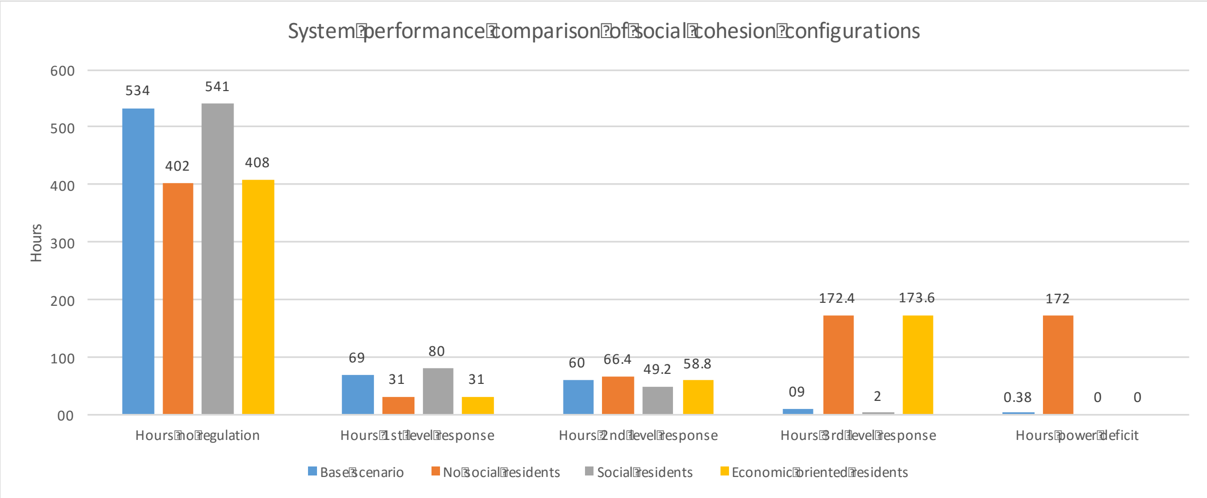

Figure 57: System performance per degree of social cohesion

Figure 57 provides the following observations:

- More social residents results in less response mechanisms: due to the availability of sufficient FCEVs for scheduling, the expected required number of FCEVs are scheduled in each timeframe. Response is only required in scenarios where the electricity demand is unexpected high due to the randomness factors.
- With less FCEVs available for scheduling, the use of the backup response mechanism is less efficient in balancing the electricity supply and demand
- Active participants have a great influence in the effects of price level control. No hours of deficit occured with economic oriented residents and 172 occured without social residents, while both had 172-173 hours of price level control.

Figure 58 shows the difference in total electricity demanded per scenario and the electricity that is used for production. In the economic oriented scenario, the price level response reduces the total demand by 5.5 percent (100 – 57.842/61.250). However, scenarios in which the system is more constraint (requires more response and stricter control), for example with less RE resources or with less FCEVs, the impact of economic oriented residents can be much larger. The smaller demand of the economic oriented residents resulted in less production by FCEVs. In the scenario with no social residents, the smaller production is caused by the 172 of hours deficit.

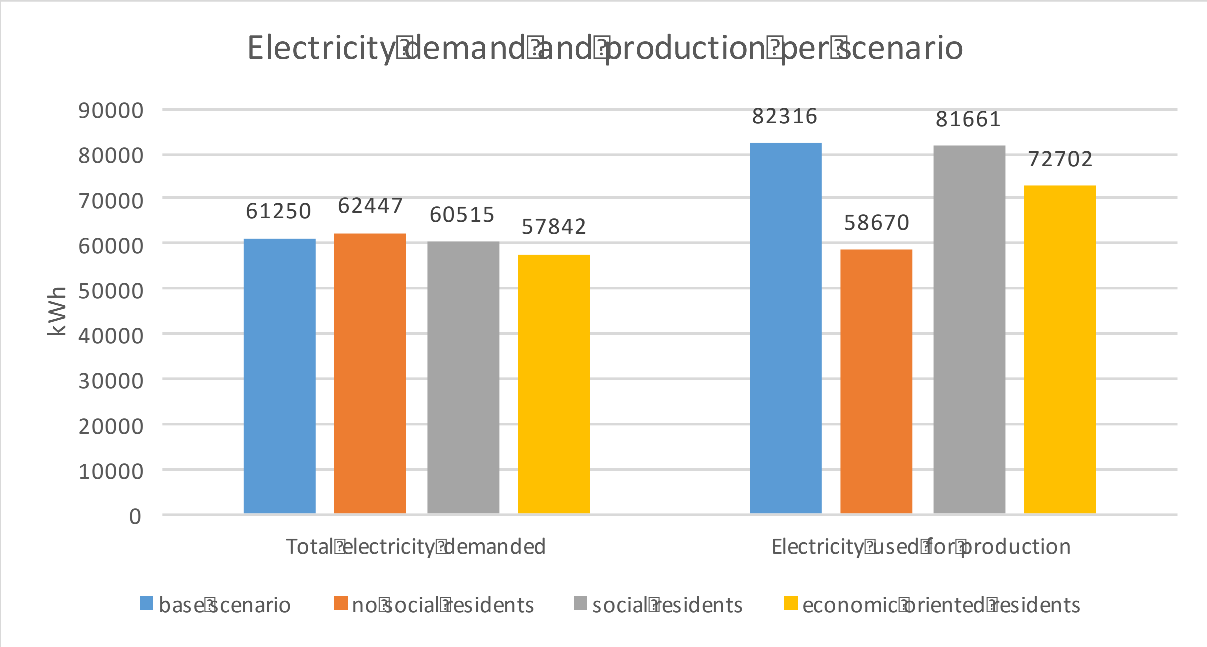

Figure 58: Electricity demand and production per social scenario

The number of FCEVs with a maximum preference in the system greatly influence the share of voluntary production hours. Table 26 shows these figures for the extreme cases of social cohesion.

Table 26: Share of voluntary production hours per social scenario

Experiment	*Share voluntary production hours*
base scenario	0,99
no social residents	0
social residents	1
economic oriented residents	0

The share of active participants and the production preference of the residents have been shown the affect each performance level. This section assessed these effects under the reference scenario, which is a scenario with sufficient FCEVs available to achieve acceptable performance. The effects of the social cohesion can be more influential in critical scenarios. For example, a scenario where more social residents result in a well performing system, while without many power deficits occur.

8.4 Seasonal Differences

Two seasonal differences are incorporated in the model: 1) a varying household demand factor and 2) different RE resources. This raised the subquestion: *how can seasonal differences in the energy system impact the control structure?* This section provides some insights related to that subquestion by comparing the performance of the system in winter and summer conditions. For the winter conditions, data from the Bilt in December 2015 is used and the seasonal demand factor is set at 1.2. For the summer month, data from Juli 2015 is used and a seasonal demand factor of 0.8. The average results with respect to electricity demand and production are shown in Figure 59.

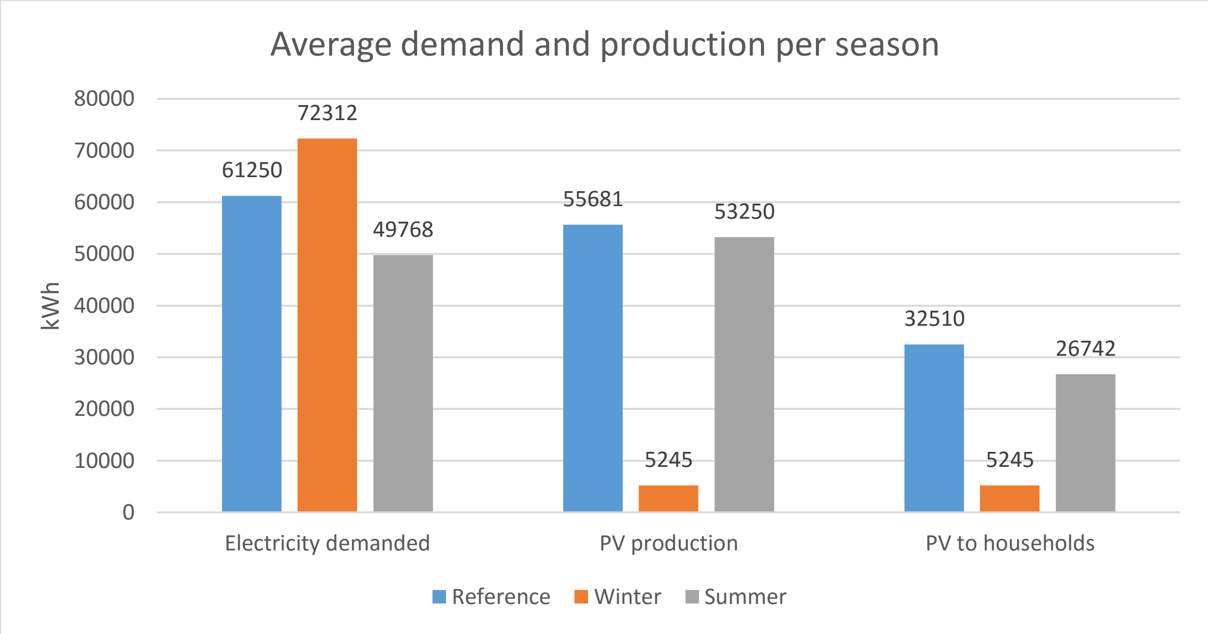

Figure 59: Average demand and production per season

In winter the electricity demand is higher and the PV production is lower. This leads to significant more hours in which supply- and demand response is required. The reference and summer scenarios require, respectively, 138 and 50 hours of response, while in winter this is 495 hours. Additionally, the system has less FCEVs available for both backup scheduling and additional power production because more vehicles are scheduled for daytime production. This leads to less potent but more frequently used control mechanisms. Over the course of four weeks this results in an average of 27 hours of power deficit, see Table 27.

Table 27: System performance per season

	Hours no production required	*Hours no response*	*Hours power deficit*
Base avg	273.6 (7.7)	533.8 (28.6)	0.38 (0.9)
Winter avg	0 (0)	176.8 (28.7)	26.8 (8.2)
Summer avg	279. 0 (7.1)	621.6 (17.0)	0.3 (0.7)

The differences between the winter and the other scenarios are directly related to a higher solar resource during May and Juli and a higher electricity demand in winter. The PV production in winter is about a tenth of that in summer. All of which is directly send to the households, implying that the solar production did not exceed the demand at any moment. In summer the PV production is often double the electricity demand. As a consequence of the small solar yield in winter, the system's efficiency is almost equal to the hydrogen route efficiency of 35%. In summer the system efficiency reaches 54% (see Figure 60).

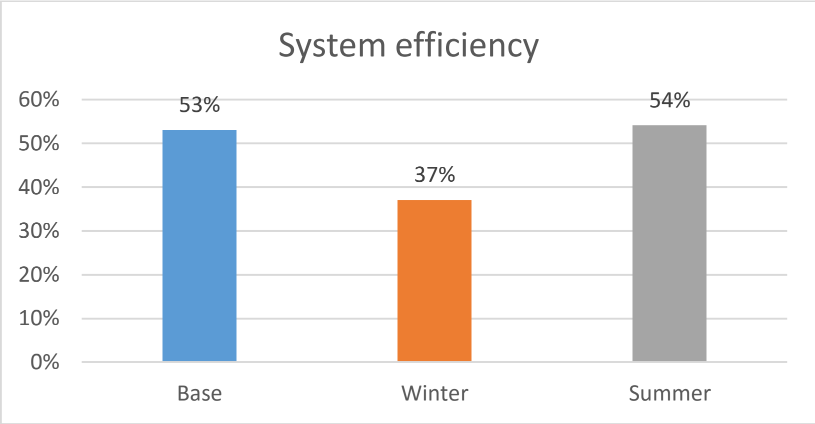

Figure 60: System efficiencies per season

Figure 61 and Figure 62 illustrate the differences between the PV production in summer and winter. Figure 63 is an example of the production deficit hours during the first week in December.

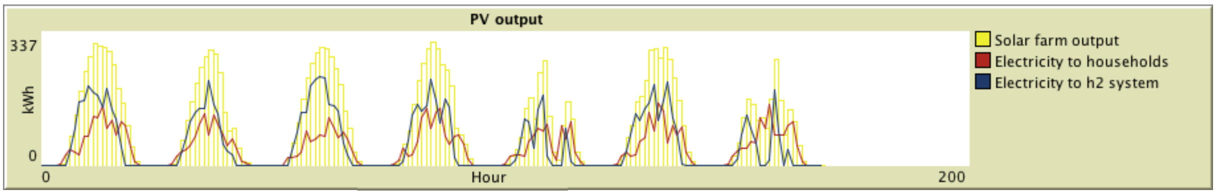

Figure 61: PV profile in Summer

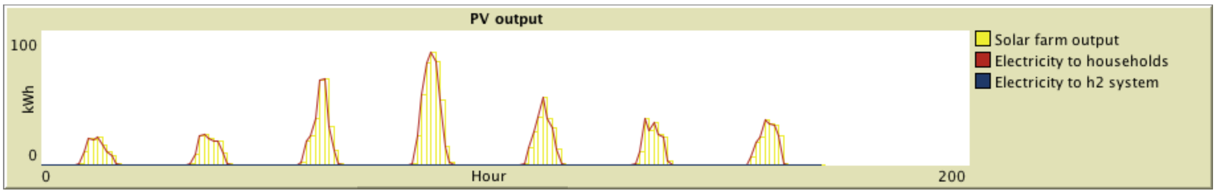

Figure 62: PV Profile in winter

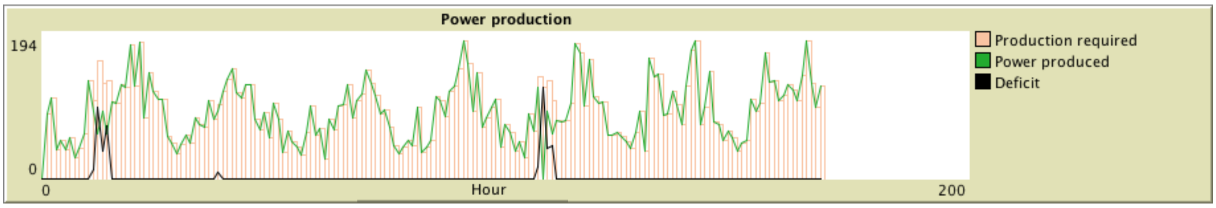

Figure 63: Example of production deficits in winter

Loose control structures are more desirable than a strict control structure (section 3.3). The analysis of this section has shown that seasonal differences have significant impacts on each performance level of the system. This indicates that the control structure should account for these differences and may take looser forms during summer periods.

8.5 The Number of FCEVs

Only scenarios with 100 FCEVs have been analyzed so far. This section explores what the influences of the number of FCEVs can be on the performance of the CaPP neighborhood. Summer months have been reported to perform well with 100 FCEVs and winter months have been reported to have an unacceptable performance with 100 FCEVs. With that in mind, the following three experiments have been designed:

Table 28: Number of FCEV experiments

Experiment	*Name*
1	Winter with 150 FCEVs
2	Winter with 200 FCEVs
3	Summer with 50 FCEVs
4	Summer with 75 FCEVs

The two reporters 'hours_power_deficit' and 'times_no_control' are used to assess the occurrence of electricity deficits and the amount of hours supply and demand response are needed to balance the electricity. The results in Table 29 demonstrate that more than one hour of power deficit occurred in all scenarios. With FCEVs 200 in winter and 75 FCEVs in summer the system almost performs acceptable (1.1 and 1.2 avg. hours of deficit per fours weeks, respectively).

Table 29: Performance of number of FCEV experiments

Experiment (50 runs each)	*Hours of power deficit (sd)*	*Hours no response (sd)*
150 in winter	5.3 (3.3)	254.3 (33.7)
200 in winter	1,1 (1,4)	271.8 (30.3)
50 in summer	5,5 (2,9)	478,8 (24,2)
75 in summer	1,2 (1,5)	579,9 (31,1)

An additional experiment is designed to sketch the profile of the hours of power deficit as a function of the number of FCEVs in summer. The results are shown in Figure 64. Around 80 to 85 FCEVs are required to get an average of less then 1 hour of power deficit per four weeks.

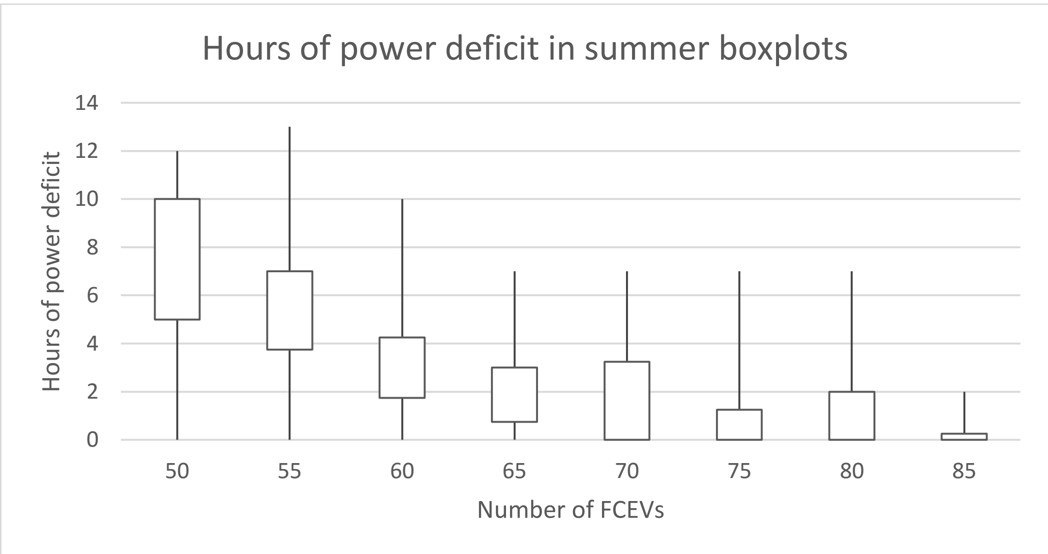

Figure 64: Required FCEVs in summer

8.6 Effects of the Control Elements

This section analyses experiments that vary elements of the control structure. Most of the experiments are performed with the reference scenario. Sometimes 75 FCEVs are used instead of 100 FCEVs because previous experiments proved that to be a critical scenario. The effects of the control elements with respect to the system's performance are more interesting in such a situation.

8.6.1 FCEV Production Output

There are two factors in the control structure that concern the FCEV production output: the 'FCEV output' and the 'Maximum FCEV output'. Both play conceptually distinct roles in the system behavior. The former is a determining factor in how many FCEVs will be scheduled for power production. At first sight, this only seems to play a role on the second performance level. Because when supply response is used, it is not the 'FCEV output' that determines the final electcity supply, but the 'maximum FCEV output'. However, the number of available FCEVs for scheduling can play an important role in the electricity supply. This results from the fact that the availability of FCEVs in a certain timeframe is dependent on the number of FCEVs that are scheduled in the other timeframes of that day. To summarize: both the 'FCEV output' and the 'maximum FCEV output' play a role in the first and second performance levels, but through different mechanisms.

Two experiments are designed to quantify the described dynamics. In the first, whose results are summarized in Table 30, the control element 'FCEV output' varies. The results show that as the FCEV output increases the response profile changes. With a FCEV output of 5 kW, 5.4 hours of deficit occur, with 30 kW output, just 0.6 hours of deficit occur. Figure 65 illustrates the impact of the FCEV output in a graph.

Table 30: Effects of FCEV output

FCEV Output	*Hours no response*	*Hours 1st level response*	*Hours 2nd level response*	*Hours 3rd level response*	*Hours with power deficit*
5	335,4	6,8	104,4	225,4	5,4
10	413,8	26,2	95,8	136,2	4,2
15	496	45,6	98,6	31,8	0,4
20	535	72,4	50,6	14	1,6
25	544,8	83,6	28	15,6	0,6
30	563,6	89,8	0	18,6	0,6

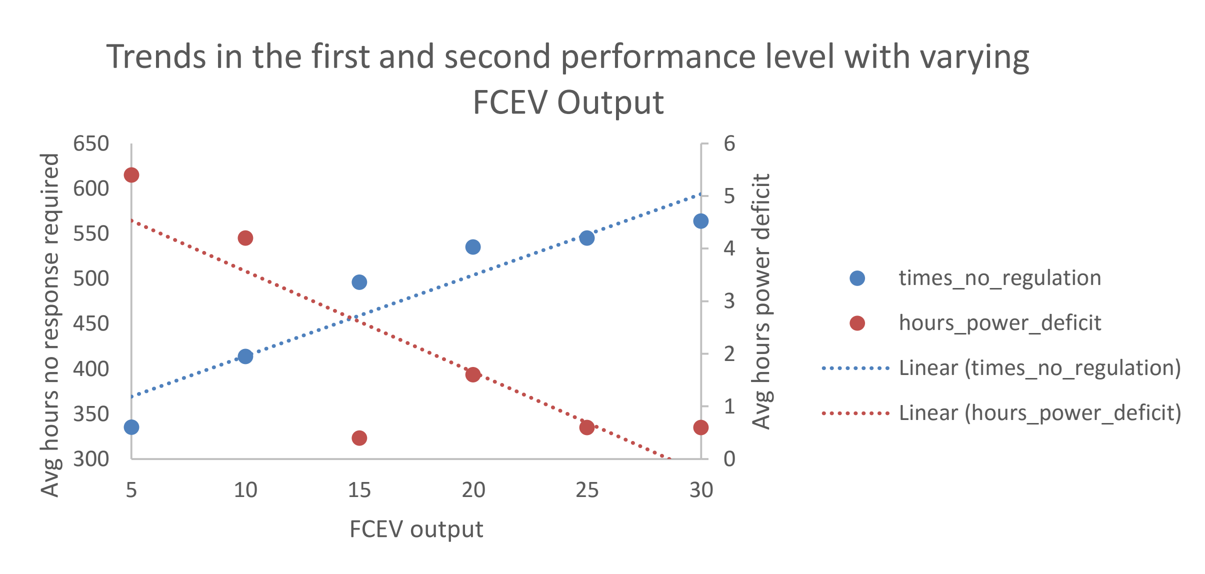

Figure 65: System performance sensitivity to FCEV output

The results of the experiment for the 'maximum FCEV output' are shown in Table 31. The first two columns show that the maximum FCEV output has no influence in the amount of hours 1st level response is needed. The influence of the 'maximum FCEV output' can be seen in the last three columns. An additional experiment is performed to clearly demonstrate the relation between the 'maximum FCEV output' and the amount of times 2nd level response (output increase) is applied. Figure 66 is a graph of this relation. The times 2nd level response is used increases from 60 to 100 as the 'maximum FCEV output' goes from 20 kW to 40 kW.

Table 31: Effects of maximum FCEV output

Max FCEV output	*Hours no response*	*Hours 1st level response*	*Hours 2nd level response*	*Hours 3rd level response*	*Hours power deficit*
20	473,6	39,2	63,2	96	5,6
25	499,6	42,4	81	49	2,8
30	486,6	37,2	100,6	47,6	3,4
35	494	42,8	102,4	32,8	0,8
40	456,2	41,6	99,8	74,4	1,4

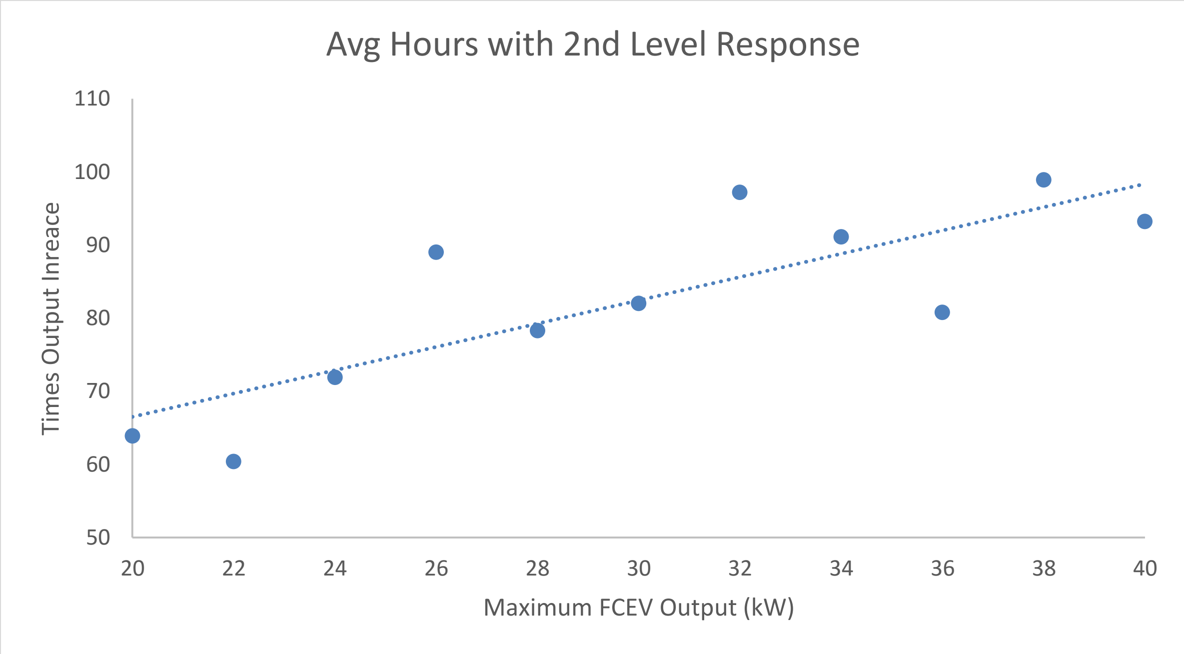

Figure 66: Times output increases response as a function of max FCEV output

8.6.2 Maximum Production Timeframes per day

The control element that determines the maximum amount of production timeframes per day has large impacts in scenarios with FCEVs that have a production preference of 'maximum'. Increasing this control element from 1 to 2 doubles the available timeframes for scheduling of FCEVs with a production preference of 'maximum'. This control element is explored in the reference scenario with with 75 FCEVs. The value of the maximum production timeframes per day is varied from 1 to 3. The reporters used are 'times_no_control' and 'times_production_deficit'.

Table 32 shows that around 539 hours without response occur in the neighborhood when maximum number of production timeframes per day is 2 or 3. This indicates that two power production timeframes per day is sufficient to schedule all the FCEVs that the scheduling procedure wants to schedule. This is also reflected in the fact that the system achieves acceptable performance with those values for the maximum production timeframes per day. With just 1 maximum production timeframe per day the system experiences on average 3,2 hours of deficits per four weeks.

Table 32: Effects of maximum production timeframes per day

Production timeframes per day	*Hours no response*	*Hours power deficit*
1	458,5	3,2
2	537,9	0,35
3	539,4	0,15

8.6.3 Minimum Production Timeframes per week

The mimimum production timeframes per week targets FCEVs that have a production preference of 'mimimum'. It dictates how often per week each FCEV is obliged to be available for scheduling. This can have a significant impacts on the FCEV availability. The three figures below show the cumulative availability of 200 FCEVs with a 'minimum' prodcution preference. The simulation of the first had a minimum production timeframes per week of ‘1’, in the second the value was ‘4’ and in the third the value was ‘7’, respectively. The graphs show that the higher value the more FCEV are availability for scheduling. Note, during night hours, FCEVs with a minimum production preference are not available for scheduling (as discussed in section 5.5.2).

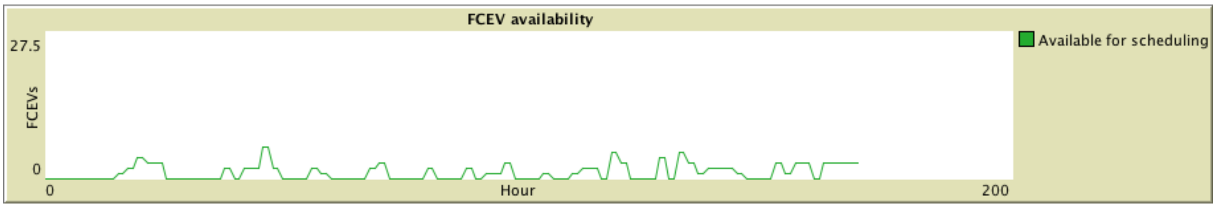

Figure 67: Availabile FCEVs with 1 minimum production timeframe per week

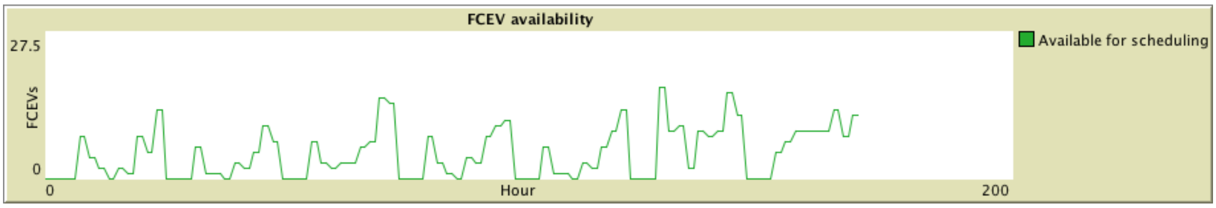

Figure 68: Availabile FCEVs with 5 minimum production timeframes per week

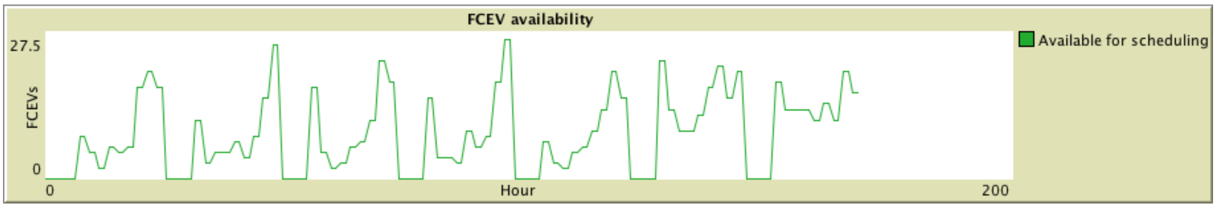

Figure 69: Availabile FCEVs with 7 minimum production timeframe per week

The experiment to assess the infuence of the mimium production timeframes per week, uses only FCEVs with a preference of ‘minimum’. The reporters used are ‘times_no_control’ and ‘times_production_deficit’. The minimum production timeframes per week are set at 1, 3, 5, and 7, each with 10 runs. Table 33 shows that 1 minimum hour of production timeframes leads to 27,8 hours of power deficit. 7 minimum prodcution timeframes per week reduces that amount to just 1,9.

Table 33: Effects of minimum production timeframes per week

Minimum prodcution timeframes per week	*Hours no response*	*Hours power deficit*
1	276,2	27,8
3	340,1	7,4
5	381,1	4,2
7	393,6	1,9

8.6.4 Home Side Demand Control

Because home side demand control is enabled in the reference scenario all previous experiments are performed with home side demand control. Home side demand control displaces part of the peak demand and spreads that over the mid-day hours. The main goal of home side demand control in a

CaPP neighborhood would be to increase the amount of solar electricity directly used in households. Figure 62 demonstrated that in winter all solar electricity is directly used in households when home side demand control is enabled. Figure 70 is made in a similar scenario, but without home side demand control. This means that the electricity demand during the day is smaller than the electricity demand of Figure 62. However, also without home side demand control is the household demand in winter higher than the PV production.

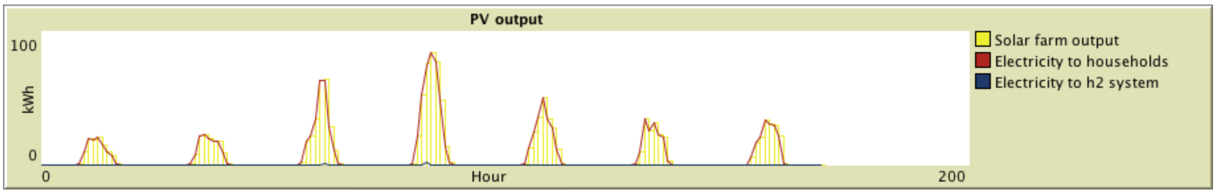

Figure 70: PV profile in winter without homeside demand control

The effects of home side demand control are studied with and experiment of the reference scenario with 75 FCEV. Three experiments with identical set ups are performed. Each reporting different reporters: the system_efficiency, times_no_control, and the share_produced_hours_voluntary. 25 runs with home side demand control and 25 runs without home side demand control were performed in each experiment. The results are shown in Table 34. Home side demand control increases the system's effiency in these scenarios from 50% to 53%. Also performances related to the share of voluntary produced hours and the hours in which no response are needed are slightly improved.

Table 34: Effects of home side demand control

Home side demand control	*Avg system efficiency*	*Hours no response*	*Share voluntary produced hours*
Yes	0,53	482,6	0,95
No	0,50	462,5	0,92

8.6.5 Price Level Reduction Factor

The price level reduction factor influences how strong active participants react to price level control. The effects of the price level reduction factor are most interesting in scenarios with frequent need of supply response. Therefore, the winter scenario with 100 FCEVs is used to study the effects of the price level reduction factor. The participant switch probability set to 0. Two input parameters are varied: the active_participant distribution and the price level reduction factor. Recall that with a reduction factor of 0.7, an active participant household reduces its household demand with 30% during price controlled hours. Each scenario is run 30 times. The number of hours power deficits occur is reported and shown in Table 35. The number between the brackets denote the standard deviation.

Table 35: Effects of price level reduction factor

		Active participant share		
		0.3	*0.5*	*0.7*
Price level reduction	*0.7*	26.7 (19.3)	4 (4.5)	0.5 (1.0)
	0.5	20.4 (12.5)	2.2 (3.9)	0.1 (0.3)

Stronger price level incentives (a smaller price level reduction factor), leads to less hours of power deficits. But the share of active participants is an important factor that influences the effects of the price level control. In the reference scenario in winter, an average 26.7 hours of power deficits occured. With sufficient price level control and more active participants, an acceptable performance of the neighborhood can be achieved.

8.6.6 Amount of FCEVs for Backup

Power production backup is a precaution for two unexpected events: higher electricity demand and a scheduled FCEV that misses power production. Scheduling backup only works in scenarios with sufficient FCEVs available for scheduling. The impact of backup scheduling on the second performance level is assessed in an experiment with the base scenario and 150 FCEVs. All reporters corresponding to supply response were reported. Backup scheduling varied between 0 and 2.

Table 36: Effects of number of FCEV backup

#FCEVs backup	*Hours no response*	*Hours 1st level response*	*Hours 2nd level response*	*Hours 3rd level response*
0	527,4	0	131,9	12,7
1	538,6	74,5	54,9	4
2	530,5	119,8	18,2	3,5

The results inidicate significant differences in the second performance level when different numbers of backup FCEVs are scheduled. Using backup production was not sufficient during only 21,7 hrs (18,2 + 3,5) with to backup FCEVs. With one backup vehicle 58,9 hrs required additional response, with no backup this was 144,6 hrs.

8.7 Combination Scenarios

The previous sections have provided some insights in how the season, the degree of social cohesion, the number of FCEVs, and the control structure influence the performance of the CaPP neighborhood. In this section some of these scenarios are combined to find some interesting cases.

8.7.1 The Mimimum Number of FCEVs

Winter has been shown to be the constraining season with respect to performance of the system. The minimum number of FCEVs the CaPP neighborhood needs is therefore explored with winter conditions. The control structure and social cohesion will be set at their most favorable conditions, see Figure 71. Note, the minimum weekly production timeframes (affecting only FCEVs with minimum production preferences) and #FCEVs for backup (playing only a role when more FCEVs are available than required for scheduling) have no impact in this scenario.

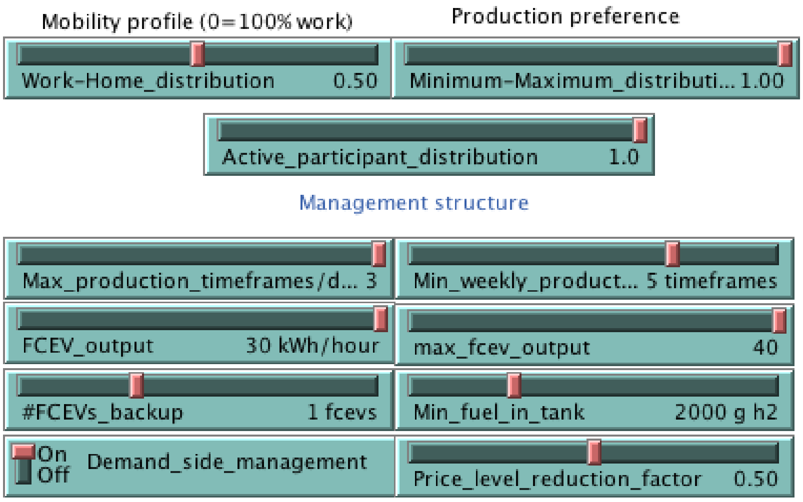

Figure 71: system configuration for minimum number of FCEVs

The experiment 'minimum FCEVs in winter' explores this scenario and reports the hours of power deficit. 50 runs for a variety of number of FCEVs were done. The results are shown in the boxplot below. They indicate that the minimum number of FCEVs required to have an acceptable performing CaPP system is around 34 FCEVs.

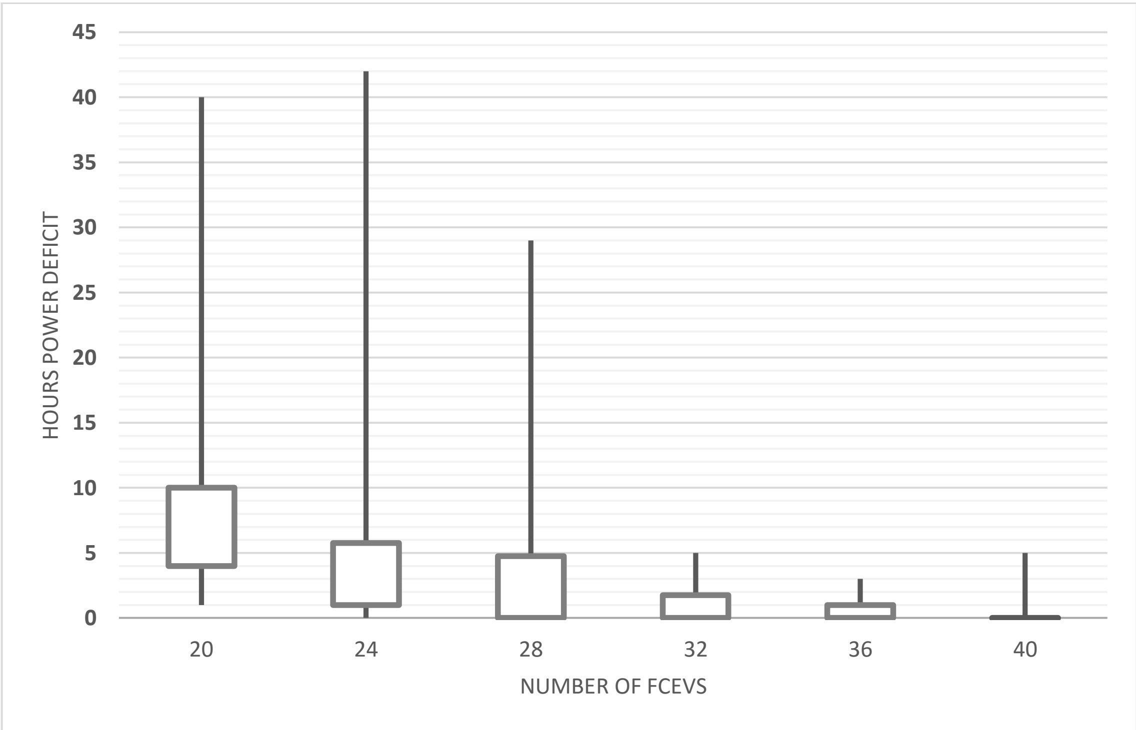

Figure 72: Boxplots for the minimum number of FCEVs required

Similarly, the minimum number of FCEVs with the base control structure is assessed in the experiment 'minimum FCEVs winter with base structure'. The graph below shows that, even with 200 FCEVs, more than 1 hour of deficit occurs with the base control structure. Implying that a stricter policy scenario is required in winter.

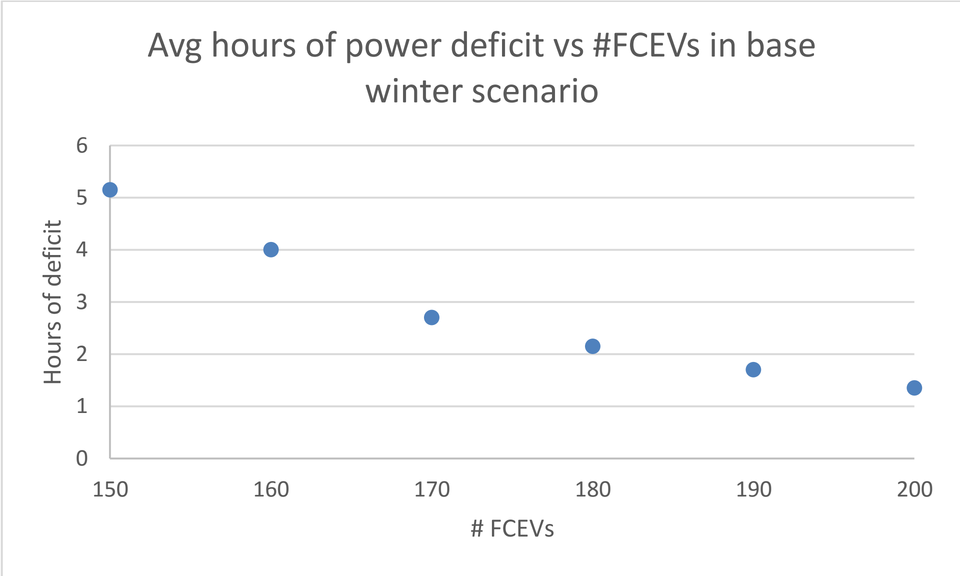

Figure 73: Hours of deficit in winter with base scenario

8.7.2 Control Structures for Specific Amounts of FCEVs

This section explores the neighborhood's performance for different control structures scenarios with 50, 100 and 200 FCEVs. Since the season is an important factor, each case is discussed in both winter and summer conditions. The four control structure scenarios defined in section 1.5 are used

8.7.2.1 Cases in Winter

To achieve acceptable performance, 34 FCEVs were minimally in the most optimal winter scenario, while 200 FCEVs are not sufficient in the reference winter scenario. A large contribution to the performance of the most optimal conditions comes from the social attitudes of that scenario: 100% active participants and 100% maximum production preference. Without these favorable social conditions, the strict control structure alone does not achieve acceptable performance with 50 FCEVs (see Table 37). With 100 FCEVs and a sub-strict control structure, the system achieves 1,08 hour of power deficit per four weeks. Slightly better social attitudes would result in an acceptable performing system in such a scenario. The sub-strict control structure is sufficient with 200 FCEVs in the neighborhood (reaching 0,52 hours of power deficit).

Table 37: Winter scenarios

Scenario	*Control structure*	*Hours power deficit*
50 FCEVs	Strict	11,28
100 FCEV	Sub-strict	1,08
200 FCEVs	Sub-strict	0,52

8.7.2.2 Cases in Summer

Summer conditions allow for increased performances and looser control structures. Table 38 is a summary of several experiments performed in summer conditions for different number of FCEVs. 50 FCEVs in summer demands for either the strict control structure or the sub-strict control structure with slightly increased social participation. Neighborhoods with 100 and 200 FCEVs perform well on all performance levels with the loose control structure.

Table 38: Performance in summer scenarios

Scenario	*Hours 1st level response*	*Hours 2nd level response*	*Hours 3rd level response*	*Hours power deficit*	*System efficiency*	*Share of voluntary production hours*
50 FCEVs, base	9,1	32,4	153,8	5	0,543	0,797
50 FCEVs, sub-strict	14,1	23,4	19,8	1,6	0,539	0,969
50 FCEVs, strict	22,5	3,2	2,5	0,3	0,536	0,998
100 FCEVs, base	19,6	9,6	13,3	0	0,535	0,982
100 FCEVs, loose	14,4	14,6	19,7	0,3	0,539	0,983
200 FCEVs, loose	24,3	1,1	0,8	0	0,538	1

9 Conclusion

This thesis set out to obtain quantitative knowledge about the influences of electricity supply and demand control structure scenarios on the electricity balance in a CaPP neighborhood. An agent-based model of the socio-technical system of a CaPP neighborhood is developed in NetLogo to capture the emergent dynamics of the CaPP neighborhood. The model is suitable to study different aspects of CaPP neighborhoods (such as sizing of RE and control structure scenarios) for wide variety of cases. The case studied in this research is a Dutch 200 household neighborhood. The main research question is defined as follows:

What are the influences of the electricity supply and demand control structure on the electricity balance of a Dutch 200 household CaPP neighborhood?

The control structure controls the electricity supply and demand based on prevailing circumstances. The influences of the control structure on the electricity balance are not only dependent on the control structure itself. The number of FCEVs, the RE resources (i.e. season) and the degree of social cohesion are also influential elements in the effects of the control structure. Therefore, these subjects are treated in the subquestions as well. To draw quantitative conclusions about the model behavior, three performance levels were defined that structure the performance of the system:

1. the number of hours electricity deficits occur,
2. the response mechanisms needed to balance the electricity (number of hours and types of response mechanisms),
3. the overall system efficiency and the share of voluntary production hours.

The criterion 'at most 1 hour of power deficit per four weeks' has been used to denote acceptable performance for the Dutch 200 household neighborhood. The model behavior was studied in experiments of four weeks with 1 hour timesteps. The experiments showed that the performance of a CaPP neighborhood and the influences of the control structure are highly dependent on the number of FCEVs, the season and the degree of social cohesion.

Home side demand control was found to have positive influences on the second and third performance levels. Using home side demand control increased the efficiency of the Dutch CaPP neighborhood in the reference scenario with 3% and it increased the share of voluntary production hours with 2%. This means that shifting demand from peak hours to hours with PV production leads to a slightly better distribution of using FCEVs throughout a day. After all, there is a lower change that a FCEV that can be used during daytime hours, is scheduled during evening hours. That effect of home side demand control also reduces the amount of hours in which no response mechanisms are required with 20 hours (from 482 to 462).

The control element 'maximum production timeframes per day' has a significant impact on the performance of the system. Increasing its value from 1 to 2 essentially means doubling the FCEV pool available for scheduling. It was found that in the reference scenario with 75 FCEVs the average number of hours with power deficits are 3.2, 0.35 and 0.15 when applying 1, 2 or 3 maximum production timeframes per day, respectively.

Price level control reduces the demand of households that are active participants when price level control is enacted to balance the electricity of the CaPP neighborhood. A price level reduction factor of the value 0.5 reduces the individual household demand with with 50%, a value of 0.7 reduces the individual household demand with 30%. In the winter variation of the reference scenario, the average hours of power deficits were 22.8 and 16.1, with price level reduction factors of 0.7 and 0.5, respectively. The share of active participants of the neighborhood has a large influence on these results. With a share of active participants of 80% (instead of 30% in the reference scenario) an average of 0.1 hours of power deficit occured with the price level reduction factor at 0.7. A similar scenario, with the price level reduction factor of 0.5, resulted in 0 hours of power deficit. These results partly highlight the importance of social cohesion of the neighborhood.

In the Netherlands the electricity demand in winter is higher than in summer, while the PV production is about a factor 10 lower. The performances of the CaPP system in winter and summer, are therefore quite different. Regardless the scenario, the system performs better with more FCEVs and with a stricter control structure. However, a stricter control structure reduces the degree of freedom of FCEVs. Four forms of control structures were defined: a loose control structure, the base control structure, a sub-strict control structure and a strict control structure (the specific values for the control elements can be found in Table 3. Table 39 summarizes the control structure required to achieve acceptable performances in a variety of summer and in winter scenarios.

Table 39: Achieving acceptable performance in a variety of scenarios

Number of FCEVs	*Control structure in summer*	*Control structure in winter*
50 FCEVs	Either the strict or sub-stict control structure is required. With the sub-strict control structure a slight increase in the degree of social cohesion is required, as the hours of power deficit per four weeks is 1.6 hours.	An average of 11,28 hours of power deficit per four weeks occur with the strict control structure. Strong incentives to increase the social cohesion of the residents are required to reach acceptable performance.
100 FCEVs	100 FCEVs are sufficient to apply the loose control structure. Practically all production will be covered voluntarily. The system efficiency in this scenario reaches about 53%.	The sub-strict control structure does not suffice; it has on average 1,08 hours of power deficit. Slightly higher social participation is required or the neighborhood should use the strict control structure.
200 FCEVs	The loose control structure can be applied. This scenario could even reach acceptable performance with less attractive social attitudes than in the base scenario.	200 FCEVs in winter is not sufficient to apply the base control structure. The sub-strict control structure results in an average of 0,52 hours of deficit per four weeks.

Several experiments have been performed to explore the minimum number of FCEVs required in the Dutch 200 household CaPP neighborhood. It involves the winter scenario with strict control structure and the highest possible degree of social cohesion (i.e. all residents are active participants and all FCEVs have a ‘maximum’ production preference). 34 FCEVs were found to be the minimum number of FCEVs required to achieve acceptable performance.

10 Discussion and Reflection

The conclusion section provides a general overview of the influences of the electricity supply and demand control structure on the electricity balance of a Dutch CaPP system. These influences were quantified in three performance levels. A large amount of additional factors (besides the control structure) have been shown to impact the performance of the CaPP neighborhood as well. These included the degree of social cohesion, the season and the specific case. The specific case includes renewable energy resources, mobility patterns and around 40 parameters describing the neighborhood. Here lies a complication: it is hard to draw general conlusions with so much specified input for a case. Even though the case study was meant to represent the 'average Dutch neighborhood', it should be clear that the results are not applicable to each Dutch 200 household neighborhood.

10.1 Reflection on Methods

Seven control elements have comprised the control structure in this research. It is debatable if this set is complete or even suitable for CaPP systems in practice. It could be very unpopular to have rules such as minimum production timeframes per week or even to schedule FCEVs at all. CaPP systems could adopt complete different methods for balancing the electricity. One potential candidate is an open electricity market, where prices determine the electricity supply and demand. Nevertheless, this research attempted to define a reasonable set of rules and incentives for the control stucture. A control element that could have been added is a maximum demand for households during certain timeframes or based on the amount of available FCEVs.

In the CaPP model, FCEVs are scheduled for power production in two hour timeframes. Such an elementary method does not provide a lot of flexibility in the power production scheme for an energy system that is meant to be 'smart, interconnected and interrelated'. It would make more sense to have FCEV owners decide during which timeframes and at what output they would like to produce power. One of the recommendations for further research is to improve this scheduling scheme.

The focus of this research has been the development of an integral CaPP model. Most of the time of this project has been spend on parametrisation, conceptualisation and programming. This has caused quite superficial attention to other elements, such as a thorough research on specific parameters. For example, the randomness factors in the household demand are quite arbitrary chosen. Electricity deficits occur mainly when the electricity demand is higher than expected, this is directly related to the randomness factors. The randomness factors, therefore, have significant impacts on the performance of the CaPP system and should have received more attention.

10.2 Societal Implications

To maintain global warming below the limit of 2°C radical changes in our energy systems are required. We need to achieve net-zero emissions by 2070 while dealing with an increasing energy demand. One of the key paths to net-zero emissions is large scale adoption of renewable energy (RE). But energy systems with high degree of RE have one major issue: how to balance electricity supply and demand without control of the RE resources? Smart energy systems, introducing effective demand response schemes, are part of the solution. Community energy systems, introducing local participation and benefits, are another part. An effective way to store renewable energy is essential in a zero-emission society. Besides changes in the power generation and distribution sector, radical changes in the building, transportation and industry sector are required as well. CaPP systems are a holistic approach, integrating all these sectors into a smart, interconnected energy system with energy storage in the form of hydrogen. Such a system might be one of the only ways to achieve our common aspiration for a healthy planet.

Providing the proof of CaPP starts with small scale pilot projects. The TU Delft currently prepares a CaPP pilot project with one FCEV. A next step would be to implement a CaPP system in a small neighborhood. The results of this thesis contribute knowledge of, and experience with, such small scale CaPP neighborhoods. That knowledge and experience serves as preliminary insights in the electricity balance of the neighborhood. It can be used as indications for sizing pilot projects and setting out adequate policy frameworks, such as:

- how many FCEVs are required for the CaPP neighborhood?
- What are the potential benefits of home side demand control?
- How constraint are FCEVs due to power production obligations?

Important connections between the electricity balance and the degree social cohesion have been pointed out. Project developers of CaPP neighborhoods are highly recommended to gather information about the attitudes of the neighborhood’s residents during early phases of the project. This allows a more accurate analysis of the performance of the CaPP neighborhood. It might also lead to the development of specific social participation related policies, improving the system’s performance and reducing the strictness of the control structure. Ideally, such policies should be developed collaboratively, by the policy makers and the neighborhood’s residents. Other topics the stakeholders should reach consensuses about are:

- How often are power deficits acceptable?
- How strong should price incentives be?
- What are the consequences for a FCEV when it doesn’t show up for power production?
- How should the control structure differ per season?

The specific case studied in this thesis might not be directly applicable to other small scale CaPP neighborhoods. The flexibility of the model, however, allows to study other cases with very minor alterations. This was defined in a secondary research goal (develop a model that allows to study other cases without much effort). Adapting input such as mobility patterns, RE resources and efficiencies to fit completely different cases could be performed in several hours. Therefore, this research has a high applicability to any future CaPP neighborhood pilot project. Hopefully, this research and the developed model will accelerate the proof of concept of CaPP systems.

11 Recommendations for further research

The agent-based CaPP model developed in this research provides explorative work to contribute to the proof of concept of CaPP systems. Several suggestions are made to improve and expand this explorative excercise:

1. *A comprehensive revision of the PV farm*. The PV production scheme used in the model does not take orientations of the PV panels and the indirect irradiance into account. Implementing calculations for these topics result in a more accurate division of the PV output during a day. However, such an exercise is only useful when the case study provides information about the orientation of the PV panels.
2. *Different scheduling procedures*. FCEV scheduling in the CaPP model currently starts at night and schedules random available FCEVs, this affects FCEV availability at other timeframes of the day. Scheduling of FCEVs could take complete different forms such as, optimized scheduling, smart scheduling or no scheduling. Smart scheduling and no scheduling have been discussed in the reflection. An optimized scheduling scheme could be similar to the one used in this research but it would take FCEV availability of all timeframes of a day into account.
3. *Targeted home side demand control*. To further optimize the system, home side demand control can be used in combination with an optimized scheduling procedure. For example, home side demand control can reduce the electricity demand during specific hours in which few FCEVs are available for power production. On the other had, it could increase the electricity demand during hours were many FCEVs are available.
4. *Researching resident's behavior*. Research on the motivation behind the behavior of CaPP participants is suggested to improve the decision making of agents in the CaPP model. Such research could include interviews with mobility experts or sending questionnaires to vehicle owners. The goal would be to determine what drives individuals to be willing (or not) to produce power with their FCEVs and to how they react to response mechanisms.
5. *Adding FEVs to the model*. As Drs. A. Hoekstra suggested, adding FEVs to the model could explore a new direction of a CaPP neighborhood. FEVs can store energy more efficient than hydrogen, but there are also limitiations (such as high cost anddegredations). What could be the benefits and downsides of combining FEVs and FCEVs in a hydrogen system?

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Appendix A: Complementary files

The CaPP NetLogo model is complemented with at least 5 additional files:

1. The rnd extension that can be downloaded at: https://github.com/NetLogo/Rnd-Extension
2. A text file containing the standard demand profile (stddemand.txt). Each line in the file contains a number representing the Wh average household demand of an hours of the day. The file is 24 lines long, with the first line representing 0:00 to 1:00, and so on.
3. A text file containing wind the turbine power curve (for example V90-3MW.txt). The file should be at least 40 lines long. Each line contains a value that represents the output power of the windturbine it represents at the windspeed (m/s) corresponding to the line-number.
4. A text file containing global irradiance values (W/m^2) for each hour of at least four weeks*. Each line in the represents an hour of the time period
5. A text file containing windspeed values (m/s) for each hour of at least four weeks*. Each line represents an hour of the time period

The model can simulate more weeks as long as these two files are sufficiently long.

Appendix B: Expert Opinion

This appendix contains the feedback on the model from Drs. A. Hoekstra from the TU Eindhoven. As and expert in modeling mobility patterns and sustainable mobility, A. Hoekstra was asked to form his opinion on the way mobility patterns are incorporated in the CaPP model. To this end he ran simulations with the CaPP model and the model mechanisms were discussed.

"Mobility patterns is just one of the five mechanisms the model captures. The most important characteristic here is: "when is the car parked in front of the home". The model captures this dynamic by giving agents one of two profiles (work and home) and sending them on four type of trips (commuting, week day, evening and weekend). Timing is randomly picked from a normal distribution and distance from a gamma distribution. This is a reasonably simple way to model mobility patterns that can give a rather accurate estimation of when the car will be home. Especially since this is not (yet) a PhD model it captures the mobility patterns extraordinarily well in a way that showcases both the flexibility of agent based models and the modeling capabilities of the student in question.

If extension of the model was ever considered we would suggest looking into the option of making the mobility patterns more realistic by giving people activity based behavior as we are doing with the ALBATROSS model. Examples of situations where this was relevant would be when modeling grid congestion and the integration of battery use in the FCEV. For grid congestion it is important to understand that the grid operator is mostly interested in that one hour every year when the grid congestion is maximal through a "perfect storm" of mobility and regular demand. With activity based travel we can realistically recreate the occurrence of these "perfect storms".

When incorporating batteries of EV's its important to realise that the energy loss is lower when charging and uncharging batteries. Thus imported hydrogen and hydrogen produced domestically during periods of excess renewable power production would keep the role envisioned in the model but excess renewable energy would only be converted to hydrogen after the batteries of EV's where topped of. Modeling this realistically requires giving agents different types of cars with different types of batteries and also take the state of charge of the battery into account.
However, in the scope of this model we think adding activity based mobility patterns would have been overkill and would have lead to neglect of the rest of this very well done integral model."

Appendix C: Model Code

Procedure 1: Set up

```
; Reset model world

To setup
  ca
  reset-ticks
  set hr 0
  set day 1
  set week 1
  set hourspast 0
  set dayspast 0
  ask patches [set pcolor 68]


  ; Define global lists as empty lists.

  set fcevs_in_neighborhood_list []
  set FCEV_available_for_scheduling_list []
  set total_electricity_demand_list []
  set standard_electricity_demand_list []
  set controlled_electricity_demand_list []
  set xcor_list []
  set ycor_list []
  set windspeed_data_list []
  set windspeed_at_hub_list []
  set powercurve_list []
  set windturbine_output_list []
  set solar_farm_output_list []
  set solar_electricity_to_households_list []
  set electricity_to_purifier_list []
  set electricity_to_storage_list []
  set electricity_to_electrolyser_list []
  set h2_produced_list []
  set fcevs_scheduled_list []
  set fcev_deficit_during_scheduling_list []
  set fcevs_scheduled_backup_list []
  set fcevs_backup_deficit_list []
  set fcev_output_list []
  set scheduled_deficit_list []
  set price_level_list []
  set power_produced_list []
  set remaining_household_demand_list []
  set no_regulation_hr_list []
```

```
  set backup_used_hr_list []
  set power_increased_hr_list []
  set price_increased_hr_list []
  set power_deficit_list []
  set active_participants_list []
  set total_fuel_in_tanks_list []
  set reduced_total_electricity_demand_list []

; Execute the procedures that define the FCEVs, households and objects.

  create_FCEVs
  create_households
  create_objects

; Color the model world and introduce the a clock in the upper left corner

  ask patches with [pxcor = (min-pxcor + 8) and pycor = max-pycor]
  [
    set plabel (word hr":00 hr")
    set plabel-color black
  ]
  ask patches with [pxcor = (min-pxcor + 3) and pycor = max-pycor]
  [
    set plabel (word "day: " day)
    set plabel-color black
  ]

 print ""
 show_mobility_profile
end
```

Procedure 2: create FCEVs

```
to create_fcevs

; Create the FCEV agents and give them their properties

  create-fcevs #fcevs
 [
   set shape "car”
   set color grey
   set evening_trip_probability (random-float max_probability_evening_trip - 0.4) + 0.4
   set weekend_trip_probability (random-float max_probability_weekend_trip - 0.4) + 0.4
   set fuel_in_tank (random fcev_tank_capacity - 1500) + 1500
   set avg_distance_trip ((random 30) + 10
   set avg_distance_weekend_trip (random 20 + 30)
   set scheduled_this_timeframe "no"
   set probability_not_show_up random-float max_prob_not_showup
   let z random-float 1
   ifelse work-home_distribution < z
   [
     set mobilityprofile "work"
   ]
   [
     set mobilityprofile "home"
   ]
   let y random-float 1
   ifelse minimum-maximum_distribution < y
   [
     set production_preference "minimum"
   ]
   [
     set production_preference "maximum"
   ]
   ifelse mobilityprofile = "work"
   [
     set startingtime one-of [7 8]
     set returntime one-of [17 18 19 20]
     set distance_to_work random-gamma (work_avg_distance * work_avg_distance /
work_variance) (1 / (work_variance / work_avg_distance))
   ]
   [
    set weekday_trip_probability one-of [0.8 0.7 0.6 0.5]
   ]
   set fuel_in_tank_list []
   set distance_traveled_list []
   set refuel_list []
   set scheduled_power_production_list []
```

```
    set scheduled_power_production_week_list []
    set activity_list []
    set scheduled_backup_list []
  ]

; Execute the set status procedure that lets FCEVs define their mobility schedules

  set_status
end
```

Procedure 3: Set status

```
to set_status

; This procedure simulates the timeframes FCEVs are 'away' or 'parked at home'.  Depending
on the 'dummy' time (not the real simulation time) an evening trip, day trip or weekend trip
is potentially scheduled.

 foreach sort fcevs
 [
  ask ?
  [
   set status_list []
   set hour_dummy 0
   set day_dummy 0
   set week_dummy 0
   set days_past 0
   while [days_past < 7 * #weeks]
   [
    ifelse day_dummy < 5
    [
     ifelse hour_dummy < 19
     [
      plan_weekday_trips
     ]
     [
      plan_evening_trips
     ]
    ]
    [
     plan_weekend_trips
    ]
    plan_next_hour
   ]
  ]
 ]

 let n 0
 while [n < 24 * 7 * #weeks]
 [
  set fcevs_in_neighborhood_list lput sum [item n status_list] of fcevs
fcevs_in_neighborhood_list
  set n n + 1
 ]
 end
```

Procedure 5: Plan weekday trip

```
; Schedules commuting trips and day trips for FCEVs at hours that fall in weekdays 7-18 from
mon-fri.

to plan_weekday_trips

   ifelse mobilityprofile = "work"
    [
     ifelse hour_dummy < startingtime
     [
      set status_list lput 1 status_list
     ]
     [
      ifelse hour_dummy < returntime
      [
       set status_list lput 0 status_list
      ]
      [
       set status_list lput 1 status_list
      ]
     ]
    ]

    [
     if hour_dummy = 0
     [
      let x random-float
      ifelse x < weekday_trip_probability
      [
       set day_trip_today? "yes"
       set startingtime one-of [8 9 10 11]
       let duration one-of [2 3 4 5 6 7]
       set returntime startingtime + duration
      ]
      [
       set day_trip_today? "no"
      ]
     ]
     ifelse day_trip_today? = "yes" and hour_dummy > (startingtime - 1) and hour_dummy
< returntime
     [
      set status_list lput 0 status_list
     ]
     [
      set status_list lput 1 status_list
     ]
```

```
    ]
end
```

Procedure 6: Plan evening trips

: Schedules trips for FCEVs at hours that fall in weekdays 19-24 from mon-fri.

```
to plan_evening_trips

 if hour_dummy = 0
  [
   let x random-float 1
   ifelse x < evening_trip_probability
    [
     set triptoday? "yes"
     set tripduration random 3 + 1
     set tripstarttime one-of [19 20 21]
     set tripendtime tripstarttime + tripduration
    ]
    [
     set triptoday? "no"
    ]
  ]
 ifelse triptoday? = "yes" and hour_dummy > (tripstarttime - 1) and hour_dummy <
tripendtime
  [
   set status_list lput 0 status_list
  ]
  [
   set status_list lput 1 status_list
  ]
end
```

Procedure 7: Plan Weekend trips

```
; Schedules trips in weekend days

to plan_weekend_trips

  if hour_dummy = 0
  [
    let x random-float 1
    ifelse x < weekend_trip_probability
    [
      set triptoday? "yes"
      set tripduration random 5 + 3
      set tripstarttime random 8 + 7
      set tripendtime tripstarttime + tripduration
    ]
    [
      set triptoday? "no"
    ]
  ]
  ifelse triptoday? = "yes" and hour_dummy > (tripstarttime - 1) and hour_dummy <
tripendtime
    [
      set status_list lput 0 status_list
    ]
    [
      set status_list lput 1 status_list
    ]
end
```

Procedure 8: Plan next hour

```
; Procedes the mobility planning to the next hour

to plan_next_hour
 ifelse hour_dummy = 23
   [
    set hour_dummy 0
    set days_past days_past + 1
    ifelse day_dummy = 6
    [
      set day_dummy 0
      set week_dummy week_dummy + 1
    ]
    [
    set day_dummy day_dummy + 1
    ]
   ]
   [
    set hour_dummy hour_dummy + 1
   ]
end
```

Procedure 9: Show mobility profile

```
; Prints mobility profile information to the command center

to show_mobility_profile
 ifelse #fcevs > 7
  [
   let x count fcevs with [mobilityprofile = "work"]
   let y count fcevs with [production_preference = "minimum"]
   print (word "Mobility profile: " x " FCEVs 'work'. " (#fcevs - x)" FCEVs 'home'")
   print (word "Production preference: " y " FCEVs 'minimum'. " (#fcevs - y)" FCEVs
'maximum'")
  ]
  [
   foreach sort fcevs
   [
    ask ?
    [

     ifelse mobilityprofile = "work"
      [
       show (word mobilityprofile" profile, departure time "startingtime":00 hr, return time
"returntime":00 hr. " "  Production preference: " production_preference)
      ]
      [
       show (word mobilityprofile"profile, probability of weekday trip:
"weekday_trip_probability ".             Production preference: " production_preference)
      ]
    ]
   ]
  ]
  print ""
 end
```

Procedure 10: Create households

```
; Sets up the households and their characteristics

to create_households
  set #households 200
 create-households #households
 [
  set electricity_demand_list []
  set reduced_electricity_demand_list []
  set shape "house"
  set residents one-of [2 3 4]
  let P [["appartment" 0.2]["detached" 0.6]["semi-detached" 0.2]]
  set house-type   first rnd:weighted-one-of P [last ?].
  set sustainability random-float 0.8 + 0.6
  setxy 10 30
  while [distance min-one-of other households [distance myself] < 1]
   [
    set xcor random 40 set ycor one-of [10 15 20 25 30
   ]
  let y random-float 1
  ifelse active_participant_distribution < y
  [
   set active_participant "no"
  ]
  [
   set active_participant "yes"
  ]
 ]
 place_fcev_at_household
 calculate-SDF
 load-standardized-demand
 determine_controlled_demand
end
```

Procedure 11: place FCEV at households

```
; Displaces FCEVs to a household


to place_fcev_at_household
 let n 0
 while
  [n < #fcevs + #households]
  [
   ask households with [who = n]
   [
    set xcor_list lput xcor xcor_list
    set ycor_list lput ycor ycor_list
   ]
   set n n + 1
  ]
 let r 0
 while [r < #fcevs]
 [
  ask fcevs with [who = r]
  [
   set xcor item r xcor_list
   set ycor item r ycor_list - 1
   set r r + 1
  ]
 ]
end
```

Procedure 12: calculate standard demand factor

```
; Lets each household calculate its standard demand factor

to calculate-SDF
 ask households
 [
  set demand_factor sustainability * season_factor
  ifelse residents = 2
  [
   set demand_factor demand_factor * 0.8
  ]
  [
   ifelse residents = 3
  [
   set demand_factor demand_factor * 1.2
  ]
  [
   set demand_factor demand_factor * 1.4
  ]
  ]
  ifelse house-type = "appartment"
  [
   set demand_factor demand_factor * 0.5
  ]
  [
   if house-type = "semi-detached"
   [
    set demand_factor demand_factor * 0.75
   ]
  ]
  set color scale-color yellow demand_factor 2 0
 ]
end
```

Procedure 13: Load standardized demand

```
; Loads in the standard demand text file

to load-standardized-demand

  ;open and import standardized household demand data
  let tempfile "stddemand.txt"
  ifelse file-exists? tempfile
  [
    file-open tempfile
  ]
  [
    user-message "Standard demandfile not found"
  ]
  while [not file-at-end? ]
  [
    set standard_electricity_demand_list lput (file-read / 1000 )
standard_electricity_demand_list
  ]

  ; check if the demand list has been constructed correctly
  if length standard_electricity_demand_list != 24
  [
    user-message "Error: standardized household demand data does not contain 24 items,
adjust or choose a different file"
  ]
  let x 0
  while [x < length standard_electricity_demand_list]
  [
    if not is-number? item x standard_electricity_demand_list
    [
      user-message "Error: standardized household demand data does not contain numbers
for every hour"
    ]
    set x x + 1
  ]
  file-close
end
```

Procedure 14: Determine controlled demand

```
;  Determines the standard demand profile if home side demand control is used


to determine_controlled_demand
  let x standard_electricity_demand_list
  let a 0.2
  let y precision (((item 17 x * a) + (item 18 x * a) + (item 19 x * a) + (item 20 x * a) + (item 21
x * a) + (item 22 x * a) + (item 23 x * a)) / 6) 2
  let n 0
  while [n < 6]
  [
    set x replace-item (17 + n ) x precision ((item (17 + n) x) * (1 - a)) 2
    set x replace-item (8 + n) x precision ((item (8 + n ) x) + y) 2
    set n n + 1
  ]
  set controlled_electricity_demand_list x
  If demand_side_management = true
  [
    set standard_electricity_demand_list controlled_electricity_demand_list
  ]
  show standard_electricity_demand_list
end
```

Procedure 15: Create objects

```
; Creates the solar farm, wind farm and hydrogen system


to create_objects
 create-pvsystems 1
 [
  setxy 50 20
  set shape "solarcell"
  set size 6
  set color grey
  set efficiency pvefficiency
  set capacity #households * solarsurface
  ;set label "PV farm"
 ]
 calculate_pv_output

 create-windfarms 1
 [
  setxy 70 23
  set shape "rotors"
  set size 12
  set color black
 ]
 load_windspeed_file
 load_powercurve
 windloglaw
 calculate_windturbineoutput

 create-turtles 1
 [
  setxy ([xcor] of (turtle (201 + #fcevs))) (([ycor] of turtle (201 + #fcevs)) - 3)
  set shape "turbine_paal"
  set size 10
  ;set label "windfarm"
 ]
  create-h2_storages 1
 [
  setxy 60 20
  set shape "storage"
  set size 7
  set color 6
 ]
 set h2_in_storage h2_storage_capacity / 2

 if share_to_purificator + share_to_electrolyser + share_to_compression != 1
```

```
 [
  user-message "Set the sum of the flow-ratios into the h2 system equal to 1 before running
the model"
 ]
end
```

Procedure 16: Calculate PV output

```
; Calculates the electricity output of the solar farm

to calculate_pv_output

  if wind_and_solar_data_selection = "Bilt December 2015"     [set solar_file "biltinsolation2015December.txt"]
  if wind_and_solar_data_selection = "Bilt October 2015"      [set solar_file "biltinsolation2015October.txt"]
  if wind_and_solar_data_selection = "Bilt Juli 2015"         [set solar_file "biltinsolation2015Juli.txt"]
  if wind_and_solar_data_selection = "Bilt May 2015"          [set solar_file "biltinsolation2015May.txt"]
  if wind_and_solar_data_selection = "Bilt Januari 2015"      [set solar_file "biltinsolation2015Januari.txt"]
  if wind_and_solar_data_selection = "Vlieland May 2015"      [set solar_file "vlielandinsolation2015May.txt"]
  if wind_and_solar_data_selection = "Vlieland Januari 2015"   [set solar_file "vlielandinsolation2015Januari.txt"]
  if wind_and_solar_data_selection = "Load other data"        [user-message "Select global insolation data" set solar_file user-file]

  ifelse ( file-exists? solar_file )
  [
    set solar_data_list []
    file-open solar_file
    while [ not file-at-end? ]
    [
      set solar_data_list sentence solar_data_list (list file-read-line)
    ]
    file-close
  ]
  [ user-message "File is not in current directory!" ]
  print (word "Global insolation: " solar_data_list)
  if length solar_data_list < (24 * 7 * #weeks)
  [
    user-message (word "solar_data_list contains less datapoints than required (" (length solar_data_list) "/"(#weeks * 7 * 24) ") for simulation of the current amount of weeks. The simulation cannot run correctly")
  ]
  if length solar_data_list > (24 * 7 * #weeks) and wind_and_solar_data_selection = "Load other data"
  [
    user-message (word "Note: solar_data_list contains more datapoints (" (length solar_data_list) "/"(#weeks * 7 * 24) ") than needed for simulation of the current amount of weeks. This does not cause any problems in the simulation")
```

```
   ]
   let n 0
   while [n < 24 * 7 * #weeks ]
   [
     set solar_farm_output_list lput round (read-from-string item n solar_data_list / (3.6 *
100 ) * (pvefficiency / 100) * pvperformancefactor * solarsurface * #households)
solar_farm_output_list
     set n n + 1
   ]
   print (word "PV production (kWh):" solar_farm_output_list)

end
```

Procedure 17: Load windspeed file

```
; Loads the selected wind resource data

to Load_windspeed_file

   if wind_and_solar_data_selection = "Bilt December 2015"     [set windspeed_file
"biltwind2015December.txt"]
   if wind_and_solar_data_selection = "Bilt October 2015"      [set windspeed_file
"biltwind2015October.txt"]
   if wind_and_solar_data_selection = "Bilt Juli 2015"        [set windspeed_file
"biltwind2015Juli.txt"]
   if wind_and_solar_data_selection = "Bilt May 2015"         [set windspeed_file
"biltwind2015May.txt"]
   if wind_and_solar_data_selection = "Bilt Januari 2015"      [set windspeed_file
"biltwind2015Januari.txt"]
   if wind_and_solar_data_selection = "Vlieland May 2015"      [set windspeed_file
"biltwind2015May.txt"]
   if wind_and_solar_data_selection = "Vlieland Januari 2015"   [set windspeed_file
"biltwind2015Januari.txt"]
   if wind_and_solar_data_selection = "Load other data"        [user-message "Select
windspeed data" set windspeed_file user-file]

  ifelse (file-exists? windspeed_file)
  [
   file-open windspeed_file
   while [ not file-at-end? ]
   [
     set windspeed_data_list lput (file-read-line) windspeed_data_list
   ]
   file-close
  ]
  [
   user-message "Windspeed file not in current directory"
  ]
  if length windspeed_data_list < (24 * 7 * #weeks)
  [
   user-message (word "The windspeed data contains less datapoints than required ("
(length windspeed_data_list) "/"(#weeks * 7 * 24) ") for simulation of the current amount of
weeks. The model cannot run correctly")
  ]
  if length windspeed_data_list > (24 * 7 * #weeks) and wind_and_solar_data_selection =
"Load other data"
  [
   user-message (word "The windspeed data contains more datapoints than needed ("
(length windspeed_data_list) "/"(#weeks * 7 * 24) ") for simulating the current amount of
weeks")
```

```
  ]

end
```

Procedure 18: load power curve

```
; Loads in the powercurve file of the selected wind turbine


to load_powercurve

  if turbinetype = "Vesta V90-3MW" [set powercurve_file "V90-3MW.txt"]
  if turbinetype = "Vesta V90-2MW" [set powercurve_file "V90-2MW.txt"]
  if turbinetype = "Load own powercurve" [user-message "select powercurve data" set
powercurve_file user-file]

  ifelse ( file-exists? powercurve_file)
  [
    file-open powercurve_file
    while [ not file-at-end? ]
    [
      set powercurve_list lput file-read-line powercurve_list
    ]
    file-close
  ]
   [ user-message "Powercurve file not found in current directory" ]

end
```

Procedure 19: Wind log law

```
; Calculates the wind speed at hub height based on the windloglaw

to windloglaw

  let n 0
  while [n < length windspeed_data_list]

    set windspeed_at_hub_list lput round ((read-from-string item n windspeed_data_list) * (ln
(height_turbines / roughnesslength)) / (ln (height_wind_data / roughnesslength)))
windspeed_at_hub_list

    set n n + 1
  ]
  end
```

Procedure 20: Calculate wind turbine output

```
; This procedure calculates the output of the windfarm given the system configuration and
the windspeeddata

to calculate_windturbineoutput

  foreach windspeed_at_hub_list
  [
    let n ?
    set windturbine_output_list lput read-from-string item n powercurve_list
windturbine_output_list
  ]
   print " "
   print (word "Powercurve:     "powercurve_list)
   print (word "Windspeed Href: "windspeed_data_list)
   print (word "Windspeed H:    "windspeed_at_hub_list)
   print (word "Windturbineoutput: "windturbine_output_list)
end
```

Procedure 21: Run simulation

```
; Runs simulation and keeps track of the ticks

to run_simulation

  if ticks < 24 * 7 * #weeks
   [
    if day = 1 and hr = 0
    [
      if #fcevs < 8
      [
        print ""
        print (word "--------------------------------------------Week: " week " ---------------------------------
--------------------------------------------------------------------------------------------------------------------------
----------------")
        print (word "0=no, 1=yes, 2=yes appointed through institution")
        print ""
      ]
      determine_potential_production_timeframes
      determine_preferred_production_timeframes
      calculate_required_fcevs_for_powerproduction
      execute_scheduling_procedure
    ]
     if hr = 0
    [
      ask fcevs [set chipped_in_today 0]
    ]
    set price_increased_current_hour "no"

    update_fcevs_activity
    calculate_total_electricity_demand                                        ;
    production_management
    update_variables

    ask windfarms [set heading heading + 7]
    if simulation_delay = "1 ms" [ wait 0.1 ]
    if simulation_delay = "3 ms" [ wait 0.3 ]
    if simulation_delay = "5 ms" [ wait 0.5 ]
    advance_hour_of_simulation
    tick
    if ticks = (24 * 7 * #weeks - 1)
    [
      print_results
    ]
   ]
end
```

Procedure 22: Determine potential production timeframes

```
; Lets FCEVs determing the timeframes in which they could potentially produce power

to determine_potential_production_timeframes

 foreach sort fcevs
 [
  ask ?
  [
   set availability_list []
   let n 0
   while [n < (24 * 7) ]
   [
    ifelse item (n + ((week - 1) * 24 * 7)) status_list = 1 and item (n + ((week - 1) * 24 * 7) +
1) status_list = 1
      [
      repeat 2
       [
        set availability_list lput 1 availability_list
       ]
     ]
     [
      repeat 2
       [
        set availability_list lput 0 availability_list
       ]
     ]
    set n n + 2
   ]
  ]
 ]
end
```

Procedure 23: Determine preferred production timeframes

```
;  This procedure determines the schedule that FCEV owner give up for planning of the
power production hours.

to determine_preferred_production_timeframes

  set night_timeframe_list [0 1 2 12 13 14 24 25 26 36 37 38 48 49 50 60 61 62 72 73 74]
  foreach sort fcevs
  [
   ask ?
   [
    ifelse production_preference = "minimum"
    [
     set potential_power_production_timeframes_list []
     let timeframe 0
     repeat min_weekly_production_timeframes
     [
      while [member? timeframe potential_power_production_timeframes_list or member?
timeframe night_timeframe_list or item (timeframe * 2) availability_list = 0 or item
(timeframe * 2 + 1) availability_list = 0]
      [
       set timeframe random 84
      ]
      set potential_power_production_timeframes_list lput timeframe
potential_power_production_timeframes_list
     ]
     let n 0
     set potential_power_production_hours_list []
     while [n < 7 * 24]
     [
      ifelse member? (n / 2) night_timeframe_list
      [
       ifelse obliged_charging_at_night = true
       [
        set potential_power_production_hours_list lput 1
potential_power_production_hours_list
        set potential_power_production_hours_list lput 1
potential_power_production_hours_list
       ]
       [
        set potential_power_production_hours_list lput 0
potential_power_production_hours_list
        set potential_power_production_hours_list lput 0
potential_power_production_hours_list
       ]
      ]
```

```
        [
          ifelse member? (n / 2) potential_power_production_timeframes_list
          [
            set potential_power_production_hours_list lput 2
potential_power_production_hours_list
            set potential_power_production_hours_list lput 2
potential_power_production_hours_list
          ]
          [
            set potential_power_production_hours_list lput 0
potential_power_production_hours_list
            set potential_power_production_hours_list lput 0
potential_power_production_hours_list
          ]
        ]
       set n n + 2
      ]
     ]
     [
     set potential_power_production_hours_list availability_list
     ]
     if #fcevs < 8
     [
       show (word "Parked at home? " sublist status_list ((week - 1) * 7 * 24) ((week * 7 * 24)
))
       show (word "Parked at home during 2 hr timeframe? " availability_list)
       show (word "Available for electricity production? "
potential_power_production_hours_list)
       print " "
     ]
   ]
  ]
  let n 0
  while [n < 168]
  [
    set FCEV_available_for_scheduling_list lput (count fcevs with [item n
potential_power_production_hours_list != 0]) FCEV_available_for_scheduling_list
    set n n + 1
  ]
  if #fcevs > 7
  [
    print (word "week " week)
    print (word "FCEVs available for power production: " sublist
FCEV_available_for_scheduling_list ((week - 1) * 168) (week * 168))
  ]
end
```

Procedure 24: Calculate required FCEVs for power production

```
; This procedure lists how many FCEVs are required for power production during each hour of the coming week.


to calculate_required_fcevs_for_powerproduction

  set expected_required_#fcevs_list []
  set fcevs_scheduled_list []
  repeat 7
  [
    let n 0
    while [n < 24]
    [

      ifelse solar_forecasting = true
      [
        set expected_required_#fcevs_list lput ceiling ((max list 0 (item n standard_electricity_demand_list * #households - item solar_hour solar_farm_output_list)) / FCEV_output) expected_required_#fcevs_list
      ]
      [
        set expected_required_#fcevs_list lput ceiling ((max list 0 (item n standard_electricity_demand_list * #households)) / FCEV_output) expected_required_#fcevs_list
      ]
      set n n + 1
      set solar_hour solar_hour + 1
    ]
  ]
end
```

Procedure 25: Execute scheduling procedure

```
; Scheduled FCEVs for power production

to execute_scheduling_procedure

 let m 0
 repeat 7
 [
  let n 23
  set fcevs_scheduled_today [0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0]
  set fcevs_deficit_today   [0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0]
  ask fcevs
  [
   set scheduled_previous_timeframe 0
   set scheduled_today 0
   set scheduled_hours_current_day []
  ]
  while [n > 0]
  [
   ask fcevs
   [
    set scheduled_this_timeframe "no"
    set scheduled_previous_timeframe max (list 0 (scheduled_previous_timeframe - 1))
   ]
   repeat max (list (item (m * 24 + n) expected_required_#fcevs_list) (item (m * 24 + (n - 1))
expected_required_#fcevs_list))
   [
    ifelse any? fcevs with [production_preference = "maximum" and item (n + m * 24)
potential_power_production_hours_list != 0 and scheduled_today <
max_production_timeframes/day and scheduled_this_timeframe = "no" and
scheduled_previous_timeframe = 0]
     ask one-of fcevs with [production_preference = "maximum" and item (n + m * 24)
potential_power_production_hours_list != 0 and scheduled_today <
max_production_timeframes/day and scheduled_this_timeframe = "no" and
scheduled_previous_timeframe = 0]
     [
      set scheduled_today scheduled_today + 1
      set scheduled_this_timeframe "yes"
      set scheduled_previous_timeframe 2
      set scheduled_hours_current_day lput n scheduled_hours_current_day
      set scheduled_hours_current_day lput (n - 1) scheduled_hours_current_day
      set fcevs_scheduled_today replace-item n fcevs_scheduled_today (item n
fcevs_scheduled_today + 1)
      set fcevs_scheduled_today replace-item (n - 1) fcevs_scheduled_today (item (n - 1)
fcevs_scheduled_today + 1)
     ]
```

```
      ]
      [
        ifelse any? fcevs with [production_preference = "minimum" and item  (n + m * 24)
potential_power_production_hours_list != 0 and scheduled_this_timeframe = "no" and
scheduled_previous_timeframe = 0]
        [
          ask one-of fcevs with [production_preference = "minimum" and item (n + m * 24)
potential_power_production_hours_list != 0 and scheduled_this_timeframe = "no" and
scheduled_previous_timeframe = 0]
          [
            set scheduled_today scheduled_today + 1
            set scheduled_this_timeframe "yes"
            set scheduled_previous_timeframe 2
            set scheduled_hours_current_day lput n scheduled_hours_current_day
            set scheduled_hours_current_day lput (n - 1) scheduled_hours_current_day
            set fcevs_scheduled_today replace-item n fcevs_scheduled_today (item n
fcevs_scheduled_today + 1)
            set fcevs_scheduled_today replace-item (n - 1) fcevs_scheduled_today (item (n - 1)
fcevs_scheduled_today + 1)
          ]
        ]
        [
          set fcevs_deficit_today replace-item n fcevs_deficit_today ((item n
fcevs_deficit_today) + 1)
          set fcevs_deficit_today replace-item (n - 1)  fcevs_deficit_today ((item (n - 1)
fcevs_deficit_today) + 1)
        ]
      ]
    ]
    set n n - 2
  ]
  set m1 m
  execute_backup_scheduling
  process_daily_scheduling_results
  set m m + 1
 ]
 show (word "fcevs required:  " expected_required_#fcevs_list)
 show (word "fcevs scheduled: " fcevs_scheduled_list)
 show (word "fcevs deficit:   " fcev_deficit_during_scheduling_list)
 show (word "Backup scheduled:" fcevs_scheduled_backup_list)
 print ""
end
```

Procedure 26: Execute back up scheduling

```
; Performs the back up scheduling procedure

to execute_backup_scheduling

  let n 23
  set fcevs_backup_today    [0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0]
  set backup_deficit_today  [0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0]
  ask fcevs
  [
    set times_backup_today 0
    set scheduled_backup_hrs_today_list []
  ]
  while [n > 0]
  [
    repeat #fcevs_backup
    [
     ifelse any? fcevs with [scheduled_today = 0 and item (n + m1 * 24)
potential_power_production_hours_list != 0 and times_backup_today = 0]
     [
       ask one-of fcevs with [scheduled_today = 0 and item (n + m1 * 24)
potential_power_production_hours_list != 0 and times_backup_today = 0]
       [
         set times_backup_today times_backup_today + 1
         set scheduled_backup_hrs_today_list lput n scheduled_backup_hrs_today_list
         set scheduled_backup_hrs_today_list lput (n - 1) scheduled_backup_hrs_today_list
         set fcevs_backup_today replace-item n fcevs_backup_today ((item n
fcevs_backup_today) + 1)
         set fcevs_backup_today replace-item (n - 1) fcevs_backup_today ((item (n - 1)
fcevs_backup_today) + 1)
       ]
     ]
     [
       set backup_deficit_today replace-item n backup_deficit_today ((item n
backup_deficit_today) + 1)
       set backup_deficit_today replace-item (n - 1)  backup_deficit_today ((item (n - 1)
backup_deficit_today) + 1)
     ]
    ]
    set n n - 2
  ]
end
```

Procedure 28: Process daily scheduling results

```
; Processes the cumulative results of the scheduling procedure

to process_daily_scheduling_results
 let x 0
 while [ x < 24 ]
  [
   set fcevs_scheduled_list lput item x fcevs_scheduled_today fcevs_scheduled_list
   set fcev_deficit_during_scheduling_list lput item x fcevs_deficit_today
fcev_deficit_during_scheduling_list
   set fcevs_scheduled_backup_list lput item x fcevs_backup_today
fcevs_scheduled_backup_list
   set fcevs_backup_deficit_list lput item x backup_deficit_today fcevs_backup_deficit_list
   ask fcevs
   [
    ifelse member? x scheduled_hours_current_day
    [
     set scheduled_power_production_list lput 1 scheduled_power_production_list
    ]
    [
     set scheduled_power_production_list lput 0 scheduled_power_production_list
    ]
    ifelse member? x scheduled_backup_hrs_today_list
    [
     set scheduled_backup_list lput 1 scheduled_backup_list
    ]
    [
     set scheduled_backup_list lput 0 scheduled_backup_list
    ]
   ]
   set x x + 1
  ]
end
```

Procedure 28: Update FCEV activity

```
;  This procedure updates the fuel level, refueling activities and distance traveled of the FCEVs. It also lets the color of FCEVs change depending on the availability.

to update_fcevs_activity

  set current_scheduled_producing_#fcevs 0
  set current_scheduled_backup_#fcevs 0
  ask fcevs
    [
      if item ticks scheduled_power_production_list = 1 and item ticks scheduled_backup_list = 1 [user-message "a fcev is backup and production during same timeframe"]
      if item ticks scheduled_power_production_list = 1 and item ticks status_list = 0 [user-message "a fcev is away and production during same timeframe"]
      if item ticks status_list = 0 and item ticks scheduled_backup_list = 1 [user-message "a fcev is backup and away during same timeframe"]

      set active_participant [active_participant] of min-one-of households [distance myself]
      if item ticks status_list = 0
      [
        set color red
        set current_activity "on trip"
        set activity_list lput 0 activity_list
        if item (max (list 0 (ticks - 1))) status_list = 1
        [
          process_trip
        ]
      ]
      if item ticks status_list = 1 and item ticks scheduled_power_production_list = 0 and item ticks scheduled_backup_list = 0
      [
        set color green
        set current_activity "parked at home"
        set activity_list lput 1 activity_list
      ]
      if item ticks scheduled_backup_list = 1
      [
       set color yellow
       set current_activity "idle backup"
       set activity_list lput 5 activity_list
       set current_scheduled_backup_#fcevs current_scheduled_backup_#fcevs + 1
       if fuel_in_tank < min_fuel_in_tank [ refuel ]
      ]
      ifelse item ticks scheduled_power_production_list = 1 and item (max (list 0 (ticks - 1))) scheduled_power_production_list = 0
      [
```

```
    ifelse random-float 1 > probability_not_show_up
    [
     if fuel_in_tank < min_fuel_in_tank [ refuel ]
     produce_power_current_hour
    ]
    [
     miss_power_production_current_hour
    ]
   ]
   [
    if item ticks scheduled_power_production_list = 1 and miss_scheduled_production !=
"yes"
     [
      produce_power_current_hour
     ]
    if item ticks scheduled_power_production_list = 1 and miss_scheduled_production =
"yes"
     [
      set current_activity "missing production"
      set activity_list lput 3 activity_list
      set miss_scheduled_production "no"
      set hours_missed_production hours_missed_production + 1
     ]
   ]
  ]
end
```

Procedure 29: Process trip

```
; Calculates the distances and fuel used for each specific type of trip if the FCEV started driving in the current hour. It also lets FCEVs refuel if the trip gets the fuel level below the refuel level

to process_trip

 ifelse day < 6 and mobilityprofile = "work" and hr < 11
    [
     set fuel_in_tank round (fuel_in_tank - distance_to_work * 2 * fcev_fuel_economy)
     set distance_traveled_list lput (distance_to_work * 2)  distance_traveled_list
    ]
    [
     ifelse day < 6
     [
      set trip_distance random-gamma (avg_distance_trip * avg_distance_trip / 250) (1 /
(250 / avg_distance_trip))
      set fuel_in_tank round (fuel_in_tank - trip_distance * fcev_fuel_economy)
      set distance_traveled_list lput trip_distance distance_traveled_list
     ]
     [

      set weekend_trip_distance random-gamma (avg_distance_weekend_trip *
avg_distance_weekend_trip / 250) (1 / (250 / avg_distance_weekend_trip))
      set fuel_in_tank round (fuel_in_tank - weekend_trip_distance * fcev_fuel_economy)
      set distance_traveled_list lput weekend_trip_distance distance_traveled_list
     ]
    ]
    if fuel_in_tank < recharge_level
    [
     refuel
    ]
    set distance_traveled sum distance_traveled_list
end
```

Procedure 30: Produce power current hour

```
; Lets FCEVs produce power

to produce_power_current_hour

  set hours_power_produced hours_power_produced + 1
  set current_activity "producing"
  set activity_list lput 2 activity_list
  set color blue
  set current_scheduled_producing_#fcevs current_scheduled_producing_#fcevs + 1
end
```

Procedure 31: Miss power production current hour

```
; Lets FCEVs miss a power production hour

to miss_power_production_current_hour

  set miss_scheduled_production "yes"
  set hours_missed_production hours_missed_production + 1
  set current_activity "missing production"
  set activity_list lput 3 activity_list
  set color black
  set times_fcevs_missed_power_production times_fcevs_missed_power_production + 1
end
```

Procedure 32: Refuel

```
; Lets FCEVs refuel

to refuel

  set refuel_list lput (list "hour:" hourspast", refill: " (fcev_tank_capacity - fuel_in_tank))
refuel_list
  set H2_in_storage ( h2_in_storage - ((fcev_tank_capacity - fuel_in_tank) / 1000))
  set total_h2_refueled round ( total_h2_refueled + ((fcev_tank_capacity - fuel_in_tank) /
1000) )
  set fuel_in_tank fcev_tank_capacity
end
```

Procedure 33: Calculate total electricity demand

```
; Calculates the electricity demanded by the neighborhood

to calculate_total_electricity_demand

  ask households
   [
    if hr = 0                                        ;
    [
      set dailyvariation (1 - random-float household_daily_variation +
household_daily_variation / 2)
    set electricity_demand_list lput (precision ((item hr standard_electricity_demand_list *
demand_factor) * dailyvariation) 2) electricity_demand_list
    set color scale-color yellow (item hr electricity_demand_list) 1.6 0
    ifelse active_participant = "yes"
    [
      set reduced_electricity_demand_list lput (item hr electricity_demand_list *
price_level_reduction_factor) reduced_electricity_demand_list
    ]
    [
      set reduced_electricity_demand_list lput (item hr electricity_demand_list)
reduced_electricity_demand_list
    ]
   ]
  let hourly_variation ( 1 + randomness_electricity_demand / 2 - random-float
randomness_electricity_demand)
  set total_electricity_demand_list lput (precision ((sum [item hr electricity_demand_list] of
households) * hourly_variation) 2) total_electricity_demand_list
  set reduced_total_electricity_demand_list lput (precision ((sum [item hr
reduced_electricity_demand_list] of households) * hourly_variation) 2)
reduced_total_electricity_demand_list
end
```

Procedure 34: Demand and supply response

```
; Executes the demand response mechanisms if needed

to demand_supply_response

 ifelse (item ticks total_electricity_demand_list - item ticks solar_farm_output_list) > 0
 [
  ifelse (fcev_output * current_scheduled_producing_#fcevs) > (max list 0 (item ticks total_electricity_demand_list - item ticks solar_farm_output_list))
  [
   set times_no_regulation times_no_regulation + 1
   set no_regulation_hr_list lput ticks no_regulation_hr_list
   set price_level_list lput 0 price_level_list
   set fcev_output_list lput ((max list 0 (item ticks total_electricity_demand_list - item ticks solar_farm_output_list)) / current_scheduled_producing_#fcevs) fcev_output_list
   set power_produced_list lput (item ticks fcev_output_list * current_scheduled_producing_#fcevs) power_produced_list
  ]
  [
   ask fcevs with [current_activity = "idle backup"]
   [
    set current_activity "backup production"
    set activity_list replace-item hr activity_list 6
    set color white
   ]
   set scheduled_deficit_list lput (ceiling (((max list 0 (item ticks total_electricity_demand_list - item ticks solar_farm_output_list)) - (fcev_output * current_scheduled_producing_#fcevs)) / fcev_output)) scheduled_deficit_list
   ifelse (fcev_output * (current_scheduled_producing_#fcevs + current_scheduled_backup_#fcevs)) > (max list 0 (item ticks total_electricity_demand_list - item ticks solar_farm_output_list))
   [
   set times_backup_used times_backup_used + 1
   set backup_used_hr_list lput ticks backup_used_hr_list
   set price_level_list lput 0 price_level_list
   set fcev_output_list lput ((max list 0 (item ticks total_electricity_demand_list - item ticks solar_farm_output_list)) / (current_scheduled_producing_#fcevs + current_scheduled_backup_#fcevs)) fcev_output_list
   set power_produced_list lput (item ticks fcev_output_list * (current_scheduled_producing_#fcevs + current_scheduled_backup_#fcevs)) power_produced_list
  ]
   [
    ifelse (max_fcev_output * (current_scheduled_producing_#fcevs + current_scheduled_backup_#fcevs)) > (max list 0 (item ticks total_electricity_demand_list - item ticks solar_farm_output_list))
```

```
      [
       set times_power_increased times_power_increased + 1
       set power_increased_hr_list lput ticks power_increased_hr_list
       set price_level_list lput 0 price_level_list
       set fcev_output_list lput ((max list 0 (item ticks total_electricity_demand_list - item
ticks solar_farm_output_list)) / (current_scheduled_producing_#fcevs +
current_scheduled_backup_#fcevs)) fcev_output_list
       set power_produced_list lput (item ticks fcev_output_list *
(current_scheduled_producing_#fcevs + current_scheduled_backup_#fcevs))
power_produced_list
      ]
      [
       set price_increased_current_hour "yes"
       set times_price_increased times_price_increased + 1
       set price_increased_hr_list lput ticks price_increased_hr_list
       set price_level_list lput 1 price_level_list
       set extra_fcevs_required ceiling (((max list 0 (item ticks
reduced_total_electricity_demand_list - item ticks solar_farm_output_list)) -
(max_fcev_output * (current_scheduled_producing_#fcevs +
current_scheduled_backup_#fcevs))) / max_FCEV_output)
       if (extra_fcevs_required > 0 )
       [
        set times_extra_vehicles_required times_extra_vehicles_required + 1
       ]
       repeat min list (extra_fcevs_required) (count FCEVs with [active_participant = "yes"
and fuel_in_tank > min_fuel_in_tank and current_activity = "parked at home" and
chipped_in_today < 2])
       [
        ask one-of fcevs with [active_participant = "yes" and fuel_in_tank > min_fuel_in_tank
and current_activity = "parked at home" and chipped_in_today < 2]
          [
           set current_activity "additional production"
           set activity_list replace-item hr activity_list 4
           set chipped_in_today chipped_in_today + 1
           set color cyan
           set hours_power_produced hours_power_produced + 1
           set additional_hours_power_produced additional_hours_power_produced + 1
           set total_extra_vehicles_used total_extra_vehicles_used + 1
          ]
       ]
       set current_producing_fcevs (count fcevs with [current_activity = "producing"] + count
fcevs with [current_activity = "additional production"] + count fcevs with [current_activity =
"backup production"]
       ifelse current_producing_fcevs > 0
       [
```

```
          set fcev_output_list lput (min list ((max list 0 (item ticks
reduced_total_electricity_demand_list - item ticks solar_farm_output_list)) /
current_producing_fcevs) (max_fcev_output)) fcev_output_list
        ]
        [
          set fcev_output_list lput 0 fcev_output_list
        ]
        set power_produced_list lput ((item ticks fcev_output_list) * current_producing_fcevs)
power_produced_list
      ]
    ]
   ]
  ]
  [
   set times_no_production_required times_no_production_required + 1
   set times_no_regulation times_no_regulation + 1
   set fcev_output_list lput 0 fcev_output_list
   set power_produced_list lput 0 power_produced_list
  ]
  update_production_fuel_used
end
```

Procedure 35: Update production fuel used

```
; Keeps track of how much hydrogen is used for power production

to update_production_fuel_used

  ask fcevs with [current_activity = "producing" or current_activity = "additional production"
or current_activity = "backup production"]
  [
    set fuel_in_tank fuel_in_tank - (production_h2_consumption * (item hr fcev_output_list))
  ]
  ask fcevs
  [
    set fuel_in_tank_list lput fuel_in_tank fuel_in_tank_list
  ]
end
```

Procedure 36: Update variables

```
; Calculates output variables for the current hour of simulation

to update_variables

  ifelse price_increased_current_hour = "yes"
  [
    set current_total_electricity_demand item ticks reduced_total_electricity_demand_list
  ]
  [
    set current_total_electricity_demand item ticks total_electricity_demand_list
  ]

  set fcevs_at_home item ticks fcevs_in_neighborhood_list

  set cumulative_distance_traveled round sum [distance_traveled] of fcevs

  set h2_used_for_mobility round (cumulative_distance_traveled * fcev_fuel_economy /
1000)

  set primary_kWh_used_for_mobility round ((h2_used_for_mobility * 1000 /
electrolyser_efficiency ) / share_to_electrolyser)

  set total_electricity_demanded round (total_electricity_demanded +
current_total_electricity_demand)

  set solar_farm_current_output item ticks solar_farm_output_list

  set solar_electricity_to_households min (list current_total_electricity_demand
solar_farm_current_output)

  set solar_electricity_to_households_list lput solar_electricity_to_households
solar_electricity_to_households_list

  set total_solar_electricity_to_households  sum solar_electricity_to_households_list

  set total_solar_electricity_produced total_solar_electricity_produced +
solar_farm_current_output

  set remaining_household_demand current_total_electricity_demand -
solar_electricity_to_households

  set remaining_household_demand_list lput remaining_household_demand
remaining_household_demand_list
```

```
  set current_solar_electricity_to_h2_system solar_farm_current_output -
solar_electricity_to_households

  set total_solar_electricity_to_h2_system total_solar_electricity_to_h2_system +
current_solar_electricity_to_h2_system

  set windfarm_current_output  #turbines * (item ticks windturbine_output_list)

  set total_wind_electricity_produced total_wind_electricity_produced +
windfarm_current_output

  set windfarm_max_output read-from-string item 19 powercurve_list * hourspast

  set total_electricity_to_h2_system current_solar_electricity_to_h2_system +
windfarm_current_output

  set electricity_to_purifier total_electricity_to_h2_system * share_to_purificator

  set electricity_to_electrolyser total_electricity_to_h2_system * share_to_electrolyser

  set electricity_to_storage  total_electricity_to_h2_system * share_to_compression

  set electricity_to_purifier_list lput electricity_to_purifier electricity_to_purifier_list

  set electricity_to_electrolyser_list lput electricity_to_electrolyser
electricity_to_electrolyser_list
  set electricity_to_storage_list lput electricity_to_storage electricity_to_storage_list

  set current_h2_produced precision (electricity_to_electrolyser * electrolyser_efficiency /
1000) 1

  set total_h2_produced total_h2_produced + current_h2_produced

  set h2_produced_list lput current_h2_produced h2_produced_list

  set current_FCEV_available_for_scheduling item ticks FCEV_available_for_scheduling_list

  set current_fcev_deficit_for_scheduling item ticks fcev_deficit_during_scheduling_list

  set current_expected_required_#fcevs item (ticks - 168 * (week - 1))
expected_required_#fcevs_list

  set current_scheduled_fcevs item (ticks - 168 * (week - 1)) fcevs_scheduled_list

  set current_scheduled_fcevs_deficit item ticks fcev_deficit_during_scheduling_list

  set #fcevs_producing_scheduled_power count fcevs with [current_activity = "producing"]
```

set #fcevs_producing_additional_power count fcevs with [current_activity = "additional production"]

set #fcevs_producing_backup_power count fcevs with [current_activity = "backup production"]

set #fcevs_producing_power count fcevs with [current_activity = "producing"] + count fcevs with [current_activity = "additional production"] + count fcevs with [current_activity = "backup production"]

set #fcevs_idle count fcevs with [current_activity = "parked at home"]

set #fcevs_idle_backup count fcevs with [current_activity = "idle backup"]

set #fcevs_away count fcevs with [current_activity = "away"]

set #fcevs_missing_production count fcevs with [current_activity = "missing production"]

set current_power_produced item ticks power_produced_list

set current_fcev_output item ticks fcev_output_list

set current_power_deficit precision (remaining_household_demand - current_power_produced) 0

set h2_in_FCEVs_for_households h2_in_FCEVs_for_households + current_power_produced * production_h2_consumption

set total_electricity_supplied (sum solar_electricity_to_households_list) + (sum power_produced_list)

set electricity_used_for_production (sum power_produced_list) / fcev_production_efficiency

set current_backup_scheduled item ticks fcevs_scheduled_backup_list

set total_fuel_in_tanks_list lput (sum [fuel_in_tank] of fcevs) total_fuel_in_tanks_list

set total_fuel_in_tanks sum [fuel_in_tank] of fcevs

set system_efficiency precision (total_electricity_supplied / (0.00001 + electricity_used_for_production + (sum solar_electricity_to_households_list))) 2

set share_produced_hours_voluntralily precision ((sum [hours_power_produced] of fcevs with [production_preference = "maximum"]) / (0.0001 + sum [hours_power_produced] of fcevs)) 2

```
  if current_power_deficit > 0
  [
    set hours_power_deficit hours_power_deficit + 1
  ]

  update_storage
  update_active_participants

end
```

Procedure 37: Update storage

```
; Updates and monitors the hydrogen stock

to update_storage

  set h2_in_storage h2_in_storage + current_h2_produced
  if h2_in_storage > h2_storage_capacity
  [
    set times_H2_exported times_h2_exported + 1
    set h2_exported h2_in_storage - h2_storage_capacity * (1 - h2_export_amount)
    set h2_in_storage h2_storage_capacity * (1 - h2_export_amount)
  ]
  if h2_in_storage < 50
  [
    set times_H2_imported times_h2_imported + 1
    set h2_imported h2_imported + H2_import_amount
    set h2_in_storage h2_in_storage + h2_import_amount
  ]

end
```

Procedure 38: Update active participants

```
; Increases or decreases the number of active participants in the system

to update_active_participants

  if current_power_deficit > 0
  [
   set power_deficit_list lput (word "hr: "ticks ", deficit: "current_power_deficit " kWh")
power_deficit_list
   ask households with [active_participant = "no"]
   [
    if random-float 1 < participant_switch_prob
    [
      set active_participant "yes"
    ]
   ]
  ]
  set active_participants_list lput (count households with [active_participant = "yes"])
active_participants_list

end
```

Procedure 39: Advance hour of simulation

```
; Advances the simulation to the next timestep

to advance_hour_of_simulation

 set hourspast hourspast + 1
 ifelse hr = 23
  [
   set dayspast dayspast + 1
   set hr 0
   ifelse day = 7
    set day 1
    set week week + 1
   ]
   [
    set day day + 1
   ]
  ]
  [
   set hr hr + 1
  ]
 ask patches with [pxcor = (min-pxcor + 8) and pycor = max-pycor]
 [
  set plabel-color black
  set plabel (word hr":00 hr")
 ]
  ask patches with [pxcor = (min-pxcor + 3) and pycor = max-pycor]
 [
  set plabel-color black
  set plabel (word "day: "dayspast)
 ]

end
```

Procedure 40: Print results

```
; Prints some model output in the command center


to print_results

if #fcevs < 8
 [
   foreach sort fcevs
   [
     ask ?
     [
       show (word "Gram H2 in tank:          " fuel_in_tank_list)
       ifelse empty? refuel_list
       [
         show (word "Refuel hour and H2 (gram): No refueling done")
       ]
       [
         show (word "Refuel hour and H2 (gram)  "refuel_list)
      ]
     ]
   ]
 ]
 print ""
 if week < #weeks
 [
   show (word "FCEVs required for power production: "expected_required_#fcevs_list)
 ]

end
```