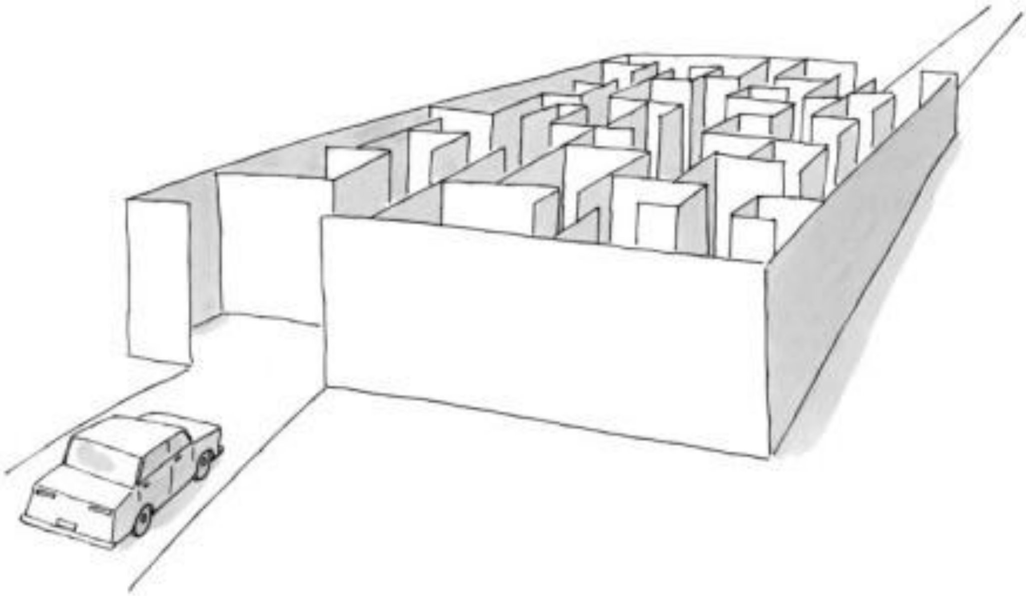

Exploring the operation of a Car Park Power Plant

Formalising the operation of a system innovation with the Actor-Option Framework

Jurriaan Coomans
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Exploring the operation of a Car Park Power Plant

Master Thesis

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Preface

Writing the preface of my masters' thesis makes me aware that my time as a student at the TPM faculty really is coming to an end. When I read the prefaces of others I imagined how it would be to reach this point myself. I am glad to say that the feelings that dominate are those of eagerness for the future, gratefulness for the past and a sense of pride of the present. This document is the embodiment of the knowledge and skills that I have learned during my time in Delft. I am very happy with how both the scientific and practical aspects of my research have blended into my final academic contribution towards my master's degree in Systems Engineering, Policy Analysis and Management.

Writing a thesis is a complex process itself. Although solely my name stands on the cover, this work would not have been possible without the contribution of many others.

I highly appreciate the dedication Zofia has shown for my process. Although having a busy schedule I received feedback on the most detailed questions on national holidays or at times when (freely translated) "I will have another look at it tomorrow as I am cooking as we speak. We are receiving guests within an hour". Thank you for always being so well willing to contribute to my work at the most detailed level, but also on the highest abstraction level.

The anchor of my research project has been Martijn. From the very start of my efforts when I was looking for a subject, until the end when I asked the incredible important question if a hardcopy with a glued spine or a binding comb would be best, you have always welcomed me and gave me exact the right type of feedback I was (sometimes unknowingly) looking for. The speed at which you deliver requested feedback is unrivalled and is a blessing for a student. I am very thankful for your excellent guidance that sometimes extended beyond the graduation project.

Strangely, when walking out Émile's office I usually had more questions than I began with. These questions most definitely did not concern my research, as you would already have clearly highlighted your ideas on paper and also gave additional suggestions for further improvements. No, during the meetings we wandered off and started to talk about infinity, the depths of transition literature and my personal situation. Besides the exceptional sharp comments you provided, I very much appreciated the welcome and collegial feeling you gave me.

A true vault of information opened when I was introduced to Esther. Although it was very early in your research and I think you were also still struggling with positioning your work, you took a large amount of time to bring me up to speed concerning the current CaPP research and your views upon it. Your involvement was extremely valuable for the expert insights with respect to CaPP and the view upon the relevance of my work.

Besides the members of my committee I would like to thank the people from the Green Village, and especially Leendert, Vincent and Willy for taking time to help me forward with specific questions and refreshing views upon my efforts. Furthermore I would like to thank Sophie, Hester, Sebas and Luuk for providing feedback upon my work.

I am extremely thankful for the time I have had in Delft within the walls of the university, but definitely also outside those walls. I am grateful for having had the chance to build up so many great friendships. I would like to thank all my friends who made my time in Delft as amazing as it was. Special thanks go to Fieke who has been always been there to support me when I needed it most, and for sharing your natural positivism with me.

The final word of appreciation goes to those who I am most grateful. I would not have been where I am now without the continuous confidence, support, advice and love from my parents. Since the difficult times we had to face recently I only have come to value your share in my life even more. I see this thesis as a final result of your parenting and as such dedicate it to both of you.

Jurriaan Coomans
Delft, 28 May 2015

Summary

The Car Park Power Plant (CPPP) concept is in its essence a parking garage in which parked fuel cell vehicles (FCVs) are used for the generation of electricity. By including on-site hydrogen production methods, the CPPPs could purchase electricity when it is cheap, store it, and convert it back to electricity when the electricity price is high.

System innovations such as the CPPP concept lead to large scale changes in infrastructure systems such as the electricity and the passenger transport infrastructure. The infrastructural systems are complex systems in which designers of new elements are unable to control the use of these elements once deployed. Knowledge is currently lacking concerning the influence of CPPP design choices and environmental uncertainties, on the possible future operational performance of the installation. In order to aid in the delineation of the possible design space of CPPPs, we have set the objective of providing an approach that is capable of identifying possible barriers for the successful operation of a CPPP. To structure our research we have used the following research question:

Which CPPP design elements or environmental factors could form barriers for the successful operation of an introduced Car Park Power Plant installation?

To answer this question a literature study was conducted to find an appropriate theory to guide the identification of a relevant but delineated system representation. The Actor Option Framework was selected to serve this purpose. The system delineation was used to construct an agent based model that has been explored for possible behaviours of the CPPP and its surroundings. With the aid of the model we identified six factors that in sets of three form possible barriers for a successful operation of a CPPP:

The usage of simple CPPP operation tactics will result in CPPPs to produce electricity at all moments that satisfy the selected use-case. As a result the CPPP desires to produce electricity during many hours of the day.

FCVs are expected to have production capacities of around 100 kW. If the conversion efficiencies of FCVs remain in the range of what they are now, the FCVs could require an amount of hydrogen per hour that comes close to the daily capacities of today's on-site hydrogen production devices. Combined with the desire to produce electricity during many hours a day, an unsatisfiable hydrogen demand and a continuous hydrogen production emerges.

Without the possibility to determine profitable hours of hydrogen production, the possibility of making use of the price differences of electricity during a day will no longer be present. As a result the value of storage becomes too small to compensate for the conversion losses within the CPPP. In these cases the CPPP can be expected to make operational losses due to the absence of a positive profit margin.

Choosing to reward drivers who park at a CPPP with a free refill of hydrogen is unlikely to have significant effects on their perceptions. Due to the fact that FCVs consume a small amount hydrogen per driven kilometre, the perceived monetary value of the received free hydrogen is insufficient to structurally persuade drivers to park at the CPPP.

Also the effect of the existence of a CPPP on the decision of driver with respect to the choice between purchasing an FCV or a conventional vehicle could be limited. Benefits that a CPPP could offer for FCV owners are a reduction in fuel costs and an improved environmental performance of their vehicle. The valuation of these benefits by drivers is however insignificant when compared to the valuation of the purchase price of vehicles.

If both the share of drivers with an FCV and the share of these drivers that park their car at a CPPP are low, the CPPP will have to rely on a very large driver population. This would make it difficult to find a suitable location that such a large base population would consider to use as a daily parking location.

We observe that the approach as we have used it is capable of identifying possible operational barriers for CPPPs and possibly for system innovations in general. The knowledge gained from this study can be used as a base to further explore the possible operation of CPPPs, as a base for discussion concerning possible CPPP designs or as substantiation for research towards the identified factors.

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1. Introduction

This chapter aims to introduce the motivation of the research as reported in this thesis. The chapter starts with the introduction into the problem context that we are interested in; and closes with the establishment of the used academic perspective and specification of the research framework. By the end of this chapter a good understanding about what this document is and what it is not should have been obtained.

1.1 Context

1.1.1 Car as a PowerPlant

One of the spearheads of the TU Delft concerning renewable energy is the GreenVillage Project. The GreenVillage is to be a "sustainable, lively and entrepreneurial environment where we discover, learn and show how to solve society's urgent challenges" (van Wijk, 2013b). The most developed concept at the GreenVillage is the Car as a PowerPlant (CaPP) project. Professor Ad van Wijk, the founder of both the GreenVillage and CaPP explains his vision in a less than twelve minute talk at TEDxGroningen in 2013[1]. A slightly rephrased transcript of his presentation goes as follows;

> *Hydrogen cars can be operated at 45% overall energy efficiency. That is a factor 2 more than the efficiency of your gasoline car. With hydrogen cars we can transport ourselves much more energy efficient.*
> *But 45% efficiency of the fuel cell overall... That is better than the efficiency of the average power plants we have. For example in the Netherlands average power plant efficiency is 40%. But we are only using our cars for 5% of the time... The rest of the time they are parked somewhere. So when we use the fuel cell in the car for electricity production when it is parked, we could generate electricity more efficient than we currently do. Can we build a car park power plant? (Adopted from (van Wijk, 2013a))*

CaPP is in its very essence the idea to use the fuel cells in hydrogen cars -once they are sufficiently developed and used- during the times they are not used for driving, to produce electricity from supplied hydrogen in central parking locations. The main advantages are a higher energy efficiency of electricity production, estimated 20% less CO_2 emissions, no other local air pollution and a quiet system. Furthermore, usable heat and clean drinking water are produced as by-products. CaPP compatible parking garages, called Car Park Power Plants (CPPPs) could provide us with a valuable possibility to store renewable energy. Excess electricity can be used to electrolyse water and store the produced hydrogen for later use. If little to no excess electricity is available, gas reforming can be used to produce the hydrogen on demand. A hydrogen infrastructure would not be needed as gas reforming can be done on site with gas from the grid (van Wijk & Verhoef, 2014). The provided flexibility of storing energy can be highly valuable in our future energy system. In these systems the role of intermittent sources is expected to significantly increase.

Figure 1-1: CaPP concept illustrations from (van Wijk & Verhoef, 2014).

[1] Available at youtu.be/uARLQ1w95Ec

Van Wijk continues his presentation with the potential of CaPP[2];

> *A network of Car Park Power Plants can produce all the electricity we need. One car engine is 100 kW which could thus produce enough electricity for a hundred European households. That is what our car is capable of.*
>
> *Our cars can replace all the power plants in the world. We have about 5000GW electricity production capacity in the world. And every year we are buying in total 80 million cars worldwide. 80 million cars times that 100 kW engine is 8000 GW. So every year we buy more production capacity on the road than that there is installed in the electricity system worldwide. In one year we can change our electricity production system.*
>
> *Of course we have to develop the fuel cell. But if this fuel cell is coming, we can achieve this change in the next decades. Will this happen? Of course! These cars are owned by you and me; we are the owners of these cars. We can change the system. Let's do it. (Adopted from (van Wijk, 2013a))*

Van Wijk ends confidently with 'let's do it', but that might not be as easy as he suggests. This is where the underlying motivation for this thesis starts. The overall concept and the potential of CaPP are well documented by the Green Village but a large gap exists between concept and realization. These types of gaps are the main focus of this thesis.

1.1.2 Moving from concept to viable design

The investigated challenge for the CaPP project is moving from concept to a viable design. Such a design should at this stage comprise an ex-ante detailed definition of the functionalities and workings of an artefact. In this thesis we will use the term 'CPPP design' as being the combination of the technical and institutional design, unless stated otherwise. Coming up with a viable CPPP design is challenging as the CPPPs are to become part of our infrastructure. Infrastructure systems are complex systems characterised by distributed control. This means that they cannot be engineered by one actor but instead evolve as a result of the (inter)actions of all involved actors, where each actor can only partially influence the path of the system over time (Chappin, 2011). For the CaPP case we do not know how different aspects of the CPPP designs or existing environmental uncertainties will influence the operational performance of the installation and the perception of the involved actors towards the CPPPs. The actor that is to design the CPPPs will only have limited control over the way these CPPP artefacts will actually be used in time. How can we then come to a design that is most likely going to be adopted and operated according our goals? The importance of a design is clear seeing the limited possibility to intervene in the lay-out of the physical network once the artefact is deployed. Herder, Bouwmans, Dijkema, Stikkelman, and Weijnen (2008) summarise this dilemma by pointing towards the contradiction in terms of complex system design: "Complex systems evolve and have fluid boundaries, while design generally is concerned with an artefact which purpose and system boundary are both well-known and static." To make matters worse, the CaPP project is aiming at integration within three infrastructures: the gas, electricity and passenger transport infrastructure.

The design of CaPP will have to encompass the uncertainty concerning the way it will be operated and the state of its environment in the future. Due to the large amount of complexity, the amount and which objectives and constraints are imposed on the design is still uncertain. This makes it difficult to determine the 'solution space' for these kind of design efforts (Herder et al., 2008).

1.1.3 CaPP as a System Innovation

CPPPs are to be implemented in the electricity and transport system and are projected to contribute to a substantial change in these systems. A substantial change in the state of a system is called a transition (Chappin, 2011). In literature numerous theories exist on how transitions occur, how they should be managed, how the emergence of innovations can be stimulated and how these new innovations can be nurtured. An overview of this body of literature is given in chapter 2.

[2] Again, this transcript is slightly rephrased for the sake of readability.

The main body of transition literature has a descriptive focus on historical completed transitions. For example the switch from horse to car and the transition from coal to gas have been studied (see appendix A of (Chappin, 2011) for an extensive overview of the body of literature). The transitions that have been studied typically span over several decades, which is as a result also the typical timeframe that is used by scholars to frame these processes (Chappin, 2011; Yücel, 2010). Concerning the things that change, the literature focusses on relatively large entities usually being sectors and organisations (Chappin, 2011). If we project this way of thinking to the CaPP case we arrive at the level of the transport- and energy system. If we use this perspective we would gain a focus on why these systems might or might not change over the upcoming decades and what role the CaPP concept *as a niche* can play in this transition. We are however interested in specifically this CaPP niche and its *internal working*. For the CaPP case the aim should not be to analyse the transport or the energy system over the next few decades. Instead the problem occurs at a level that is more detailed, lower and finer granulated aggregation level of niches. This level is different from the transition level which is used by the majority of the current body of transition literature.

The introduction of CaPP is however not a transition, but would rather be a contribution to a possible transition. The CaPP project founders foresee that an implementation of CaPP will lead to a dramatic change in the business models, assets, products, services and markets of the energy and transport sector (van Wijk & Verhoef, 2014). This makes CaPP a system innovation. Rotmans (2005) provides us with the link between these kind of innovations and transitions; "System innovations are organization-transcending innovations that drastically alter the relationship between the companies, organisations and individuals involved in the system. Transitions arise from a number of congregating system innovations." This requires some more explanation as no single widely accepted definition of an innovation exists (Twomey & Gaziulusoy, 2014). We adopt the view as presented by Klein and Sorra (1996, p. 1057); an innovation is a new product, service, technology or a practice. In this study we view 'an innovation' being a successful novel combination of elements, and not the process towards realising this combination.

1.2 Problem statements

From the context as presented in the previous section two problems can be distinguished; one from a practical perspective and one from a theoretical perspective.

1.2.1 Practical problem statement: Complex solution space

The complexity resulting from the large amount of environmental uncertainties and the distributed control of future CaPP systems, make it unclear what requirements are (to be) imposed on CaPP designs. A designer would currently face an enormous design space of which he does not know which parts are viable, making his job practically impossible. In order to make progress towards the goal of a deployable design, knowledge is required about how we can map the boundaries of the set of feasible CaPP designs.

1.2.2 Theoretical problem statement: High abstraction of body of transition literature

If we view CaPP as a system innovation we find ourselves at a uncovered part of the body of literature. Transition literature focusses on transitions processes, which are long term and large scale processes. System innovations, that are the building blocks of transitions, are processes that reside at a more detailed, lower and time-wise shorter aggregation level. The current body of transition literature provide us with a limited set of means to gain a systematic understanding of the workings of system innovations.

1.3 Research objectives

This research has two objectives. For the first objective we take the GreenVillage as problem owner and conduct an exploratory, diagnostic research concerning the operation of different CPPP designs. *The first research objective is to aid in the process of delineating the design space for CaPP, by providing an approach that is capable of identifying possible barriers for the successful operation of a CPPP when introduced in different forms.*

The first objective is embedded in and serves the theory-testing *second research objective: to contribute to the body of transition literature with regard to the formalisation of the operation of system innovations, by delivering a case study in which the Actor-Option Framework has successfully been applied on the Car as a Power Plant case.*

1.4 Research questions

As described in section 1.3, this research has two major objectives. Even though our objective is twofold, one central research question is formulated for one of these objectives for the sake of clarity. The practical objective is selected as leading and we pose ourselves the following central research question:

Which design elements or environmental factors could form barriers for the successful operation of an introduced Car Park Power Plant installation?

We formulate sub-questions 1 to 3 in order to divide and structure our answer for the central research question:

1. Which theory is able to guide the system identification of the operation of a system innovation?
2. What are important technical and institutional design choices that are expected to impact the operation of a CPPP and can be formalised with the current available knowledge?
3. What is a relevant system delineation to explore the environment and operation of a CPPP?

The main research question sets the end goal of this research. The insights that will fulfil our research objectives will however be generated during the journey towards this goal. By challenging ourselves to identify possible barriers, we are challenged to come up with a useful approach that fulfils is capable of doing so. If we are able to formulate an answer for the main research question, we can also state that we have fulfilled the objective of providing an approach that is capable of identifying barriers for the successful operation of a CPPP.

1.5 Scope

For this thesis we focus on the system design challenges as indicated by the GreenVillage (van Wijk & Verhoef, 2014). This leads to the assumption that required technology will become available and operate correctly. Furthermore we focus on substantial design choices that are still to be made. As a result design choices that do not lead to functional differences of the CPPP as a system fall outside the scope of thesis (such as designing the length of internal pipelines). Lastly, the scope of this project is limited to the possible operation of a CPPP in the Netherlands.

1.6 Research approach & relevance

The two different research objectives of this project give base to a split in the approach of this project. The theoretical and practical approaches are discussed below and schematically depicted in Figure 1-2.

1.6.1 Theoretical Framework: Transitions

For this thesis we take transition literature as guiding as it gives support for research concerning systems changes and innovations. Due to the missing coverage of system innovations in transition literature we cannot directly apply a theory on the CaPP case. Our approach to achieve the theoretical objective is as follows:

1. Conduct a literature review of the dominant transition theories, and select the theory that we expect to be most useful for the CaPP case (chapter 2).
2. Ex-ante determine how the theory is to be applied to the CaPP case (chapter 3).
3. Apply the theory to the CaPP case (chapters 5-8).
4. Ex-post reflect on the application of the theory on the CaPP case (chapter 9).

We use the CaPP case to experience the use of one of the current available theories in order to gain (prescriptive) knowledge about how this theory could be expanded. The *theoretical relevance* of this thesis is the addition of the case study to the body of transition literature. In this case study a system innovation is researched based on the guidelines of an explanatory transition literature theory.

1.6.2 Practical Research object: Possible futures of CaPP designs

In order to aid in the delineation of the solution space of the possible CaPP designs, we aim to create knowledge on the possible futures of these different CaPP designs. The dynamics of the context of CaPP is complex and is to be simplified in order to analyse the set of futures within an acceptable timeframe. For this purpose we use a theory from the body of literature to guide us in the system identification. This theory should act as a sort of lens that aids in the identification of the entities, actors and processes that are of importance. Once identified, our approach is to formalise these elements into a model in order to be able to experiment 'in silico' and gain insight into the possible future operation of a CPPP. The approach to achieve the practical objective is as follows:

1. Gain insight into the CPPP design space (chapter 4)
2. Formalise the CPPP designs and relevant surroundings (chapter 5 & 6)
3. Experiment with different CPPP designs and identify possible barriers for successful operation (chapter 7)
4. Interpret the results of the modelling study for the ongoing research efforts by the Green Village (chapter 8)

The *practical relevance* of this thesis lies in the identification of the system elements that are influencing the operation of a CPPP. By providing the first overview of these elements, their possible configurations, knowledge gaps and active mechanisms a better understanding of the boundaries of the CaPP design space should be obtained.

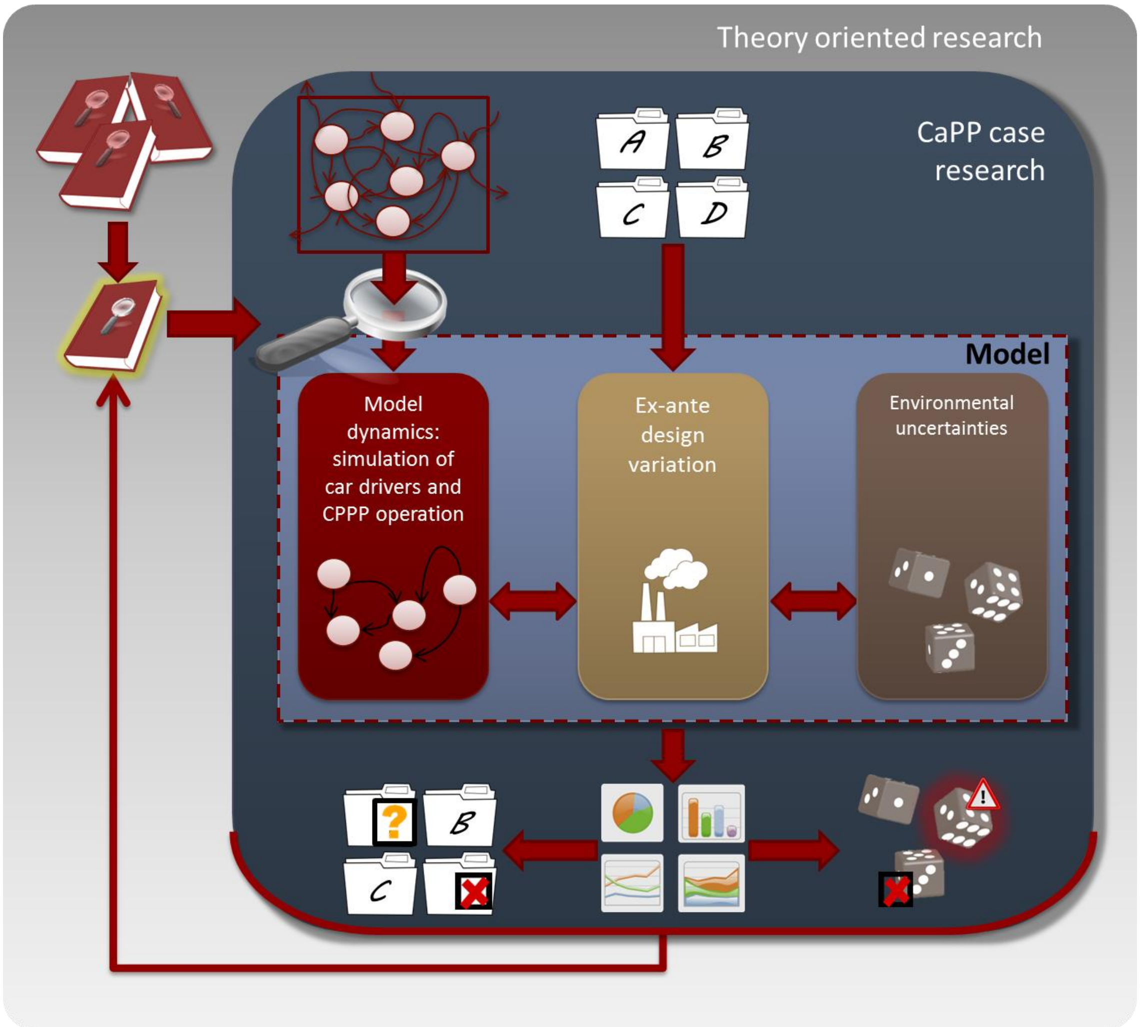

Figure 1-2: Theoretical and practical research approach

2. Transition literature

We turn to transition literature for finding a theory that we can use to guide our system identification and that can serve as the foundation for building the conceptual model. The theory should thus aid in deciding which dynamics are and are not to be included in our model. Furthermore we look for concrete structured identification steps that are relevant for processes at the lower aggregation level of system innovations. In this chapter we first discuss the concept transition. Subsequently the most dominant transition theories in the field are reviewed. It should be noted that the body of transition literature is broad and entangled, which makes classifying and structuring these theories a somewhat arbitrary activity.

2.1 Defining transitions and transition literature

One sound definition of transitions is not present in the body of transition literature. Chappin (2011, p. 26) and Yücel (2010, p. 3) both listed a number of definitions that are used by scholars. From the given definitions it becomes clear that transition is a specific type of change. How to distinguish a transition from other types of change is however problematic. Both the work of Chappin and Yücel was written at the TPM faculty and they have not surprisingly used a system perspective on this definition problem; the different definitions have been dissected in order to study their components. Through this approach (although both used a different categorisation of components) both came to a similar definition. We adopt the definition as given by Chappin[3]:

A system transition is substantial change in the state of a socio-technical system (Chappin, 2011, p. 16).

We find two challenges for using this definition. First of all the term substantial is freely interpretable; therefore no unambiguous threshold can be identified that delineates transitions from 'normal' changes. Secondly the term state is problematic as it is observer dependent. For person A, who is conducting an assessment of the current energy usage in his home, the relevant states of the coffee machine might be on or off. The relevant states of the machine for person B, who is about to do groceries, might be completely different; he will look at the level of the coffee beans in the machines' reservoir. If the machine is turned on, did the machine then change for both persons? If the system under analysis was not a private owned coffee machine but a socio-technical system (such as the road system), how can something be called a transition in *the* state of the system, if the definition of '*the* state' is dependent on the observer? Literature does not clearly give a solution for this problem. This highlights the importance of a clear system identification.

An unsuccessful transition does not exist (cf. (Chappin, 2011; de Haan, 2010; Geels & Kemp, 2007; Rotmans, 2005; Yücel, 2010)) either something did or did not change. A transition takes place when an innovation breaks through; if this is not the case we are not dealing with a transition but rather with a reproduction or transformation of the system (Geels & Kemp, 2007). Studying failed transition attempts is however also present in the body of literature (Loorbach & van Raak, 2006) and contributes to the understanding of the phenomena.

We view the body of transition as a set of theories and frameworks which contribute to the understanding of the emergence of the phenomena called transitions. The research object of the body of literature is in our view *transitions processes*. Later we will see that there are a number of theories within the body of transition literature that are not analysing or describing compete transition processes. Instead these theories focus on possible supportive actions for

[3] Yücel (2010, p. 5) uses: "transitions can in general be defined as a significant and permanent change in the way a societal system functions with respect to the fulfilment of a societal need." The definition of Chappin is preferred as (1) permanent change is equal to all change in the context of societal systems, given as example the existence of learning among humans; (2) societal systems is a broader term than socio-technical systems, however we see that all consulted literature is explicitly dealing with changes that are somehow related to technology, making this extension unused; (3) the "way a societal system functions with respect to the fulfilment of a societal need" is alike "the state" of a system, however we perceive a change in state to be more useful when distinguishing substantial or significant changes.

transition processes (e.g. strategic niche management theory) or mechanisms that could be present in transition processes (e.g. pillar theory).

The body of literature can be split in to two; theoretical transition studies which focus on the general understanding of transition processes and how they can be influenced; and applied transition studies which are using the theoretical transition studies to solve particular transition problems (Yücel, 2010). For our purpose of finding a basis for conceptualising the operation of CaPP review the group of theoretical studies. The subsequent review is presented in two parts. First we discuss the descriptive and prescriptive oriented set of theories. These theories are relatively old in the body of literature and focus on how the transition processes could be described and how their outcomes could be steered. The second part of this review discusses the explanatory theories that have the objective to formulate analytic approaches and to use them to expose the dynamics of transition processes.

2.2 Descriptive & prescriptive oriented theories

The descriptive theories are the relative older theories in the body of transition literature. These studies have first contributed to an understanding of *what* the phenomena of transitions characterise and how they are being managed.

2.2.1 Multi-level perspective

The dominant theory in the body of transition literature is the Multi-level perspective (MLP) (Yücel, 2010). The concept has been developed by Kemp (1994) and has later been expanded by Rip and Kemp (1998) who introduced the concept of multiple layers, and by Geels who applied the perspective in different cases and introduced more concepts (Geels & Schot, 2007).

The core of the MLP is the regime concept which is defined by among others Geels and Kemp (2007) as 'the rule-set or grammar embedded in a complex of engineering practices, production process technologies, product characteristics, skills and procedures, ways of handling relevant artefacts and persons, ways of defining problems'. In short, regimes define 'how things are done' (Chappin, 2011) and are positioned as the meso level of the framework. Technological niches are the places where innovations can emerge and are at the micro level of the framework. The macro level consists of the sociotechnical landscape and can exert pressure on the current regime. If the niche innovation has gained enough momentum, landscape pressure can lead to the adoption of the niche technology, resulting in a new sociotechnical regime (Geels & Schot, 2007). A regime shift could manifest itself following different identified types of pathways, depending on the actual state of the niches, regime, landscape, their interaction and the timing of an intervention. The different pathways are types of transition, reproduction or transformation of the regime.

The MLP relies on the power of aggregation in order to construct conceptual levels and to provide a useful guiding framework (Yücel, 2010). This aggregation is however sometimes problematic, as different actors and accompanying perspective on the reality will result in a different categorisation of forces and groups. This makes the distinction of the three levels non ontological (Raven, van den Bosch, & Weterings, 2010). The MLP has often been used for historical transition cases studies (Geels & Kemp, 2007) but provides little basis for insights into the mechanisms behind a transition. The MLP is a descriptive framework that is useful for conveying descriptions about transitions in the form of narratives (Yücel, 2010).

2.2.2 Transition management

Transition management (TM) can be divided into two parts; intra-organisational TM and inter-organisational TM (Chappin, 2011). The latter is relevant for our research, and will from this point on use the term TM for inter-organisational transition management. Many of the scholars who have contributed to the development of TM are colleagues of the developers of the MLP. As a result much of the TM literature uses the MLP as a mean to convey ideas and frame concepts (Twomey & Gaziulusoy, 2014). The starting point of TM is a certain societal problem for which a transition path is to be developed (Loorbach & van Raak, 2006). TM does not aim to control transitions or guide them to specific outcomes, instead the direction and speed of the transition is influenced through a bottom up approach using adaptive policies (Loorbach & Rotmans, 2006). The core of TM is a set nine governance tenets which first have been used in a descriptive framework, and later in a prescriptive framework. The descriptive framework is an 'analytical lens' that distinguishes four types of governance activities (strategic, tactical, operational and reflexive) in which the actions of society can be framed when dealing with complex societal issues (Loorbach, 2010). The operational framework has the form of a cyclical and iterative process. The so called Transition Management Cycle aims to connect the four different governance levels and provide systematic instruments on how activities within these levels can be influenced in specific directions (Loorbach, 2010).

Compared to other transition theories, TM has been developed to offer practical insights. It is however poorly backed with empirical documentation (Loorbach & van Raak, 2006). TM could be seen as a set of guiding strategy that the authors expect to be successful in managing transitions processes. It is a future oriented approach that prescribes how one could influence a current undergoing transition process by managing systems during different types of activities and on different levels. Some of the recommendations that could lead from an analysis based on TM would be to draft a common transition agenda (strategic), form new coalitions of actors (tactical) or initiate experiments (operational; overlap with SNM, discussed below). TM explains why such recommendations could be effective in driving a transition process by using the concepts from the MLP (Rotmans & Loorbach, 2009). In other words the aggregation concepts of the MLP (external landscape, regime and niches) are used as the main elements on which the narratives of TM are based. TM could lead to statements like "through the establishment of a transition agenda the external pressure on the regime will increase and a regime changes becomes more plausible." TM does not provide a description of the dynamics behind the expected effects.

2.2.3 Strategic niche management

A related theory to TM is Strategic Niche Management (SNM). Where TM starts from a societal problem, a certain technology (which has been selected by the researcher) is the starting point for SNM (Loorbach & van Raak, 2006). SNM focuses on the planned development of protected spaces for a new technology (Kemp, Rip, & Schot, 2001) through a process with the focus on experiments and learning. These experiments are settings in which the various innovation stakeholders are encouraged to collaborate and exchange information, knowledge and experience (Chappin, 2011). Through the experiments the involved actors should learn about the viability of the technology and be stimulated to build a supporting network around the product which all together should bring the technology from idea or prototype into real use (Kemp et al., 2001).

SNM focusses on the micro or niche level of the MLP. It deals with how different innovations could interact and eventually penetrate the socio-technical regime via an demand-supply dynamic (Loorbach & van Raak, 2006; Twomey & Gaziulusoy, 2014). Such a focus on internal niche processes goes at the expense of attention to external niche processes (Twomey & Gaziulusoy, 2014).

The work of Raven, Bosch, Fonk, Andringa, and Weterings (2008) is a prescriptive approach on how the core elements of SNM, experiments and learning, should be executed. The qualitative approach is laid down in a 'competence kit' and is scientifically discussed in (Raven et al., 2010). The kit guides 'transition professionals' to setup useful experiments optimally make use of the gained insights from these experiments. Much attention is given to the roles of the social network around the innovation and the vision of the transition professional. The competence kit is made for policy makers and managers and includes clear cut steps and example cases.

SNM might prove useful to the Green Village (if it hasn't already) in keeping the attention of the social network for CaPP and in providing methods for setting up new experiments in niches. For our purposes the SNM is of less value. Due to its qualitative approach and dependence on the social network, SNM gives little support to quantitative explorations. Social learning and cooperative strategy making are difficult to capture in a quantitative model and are outside the scope of this project due to time limitations.

2.2.4 Innovation systems

Unlike the previous discussed theories in this section, the theory of Innovation Systems (IS) is not based on the MLP. An IS consists of the participants or actors, their activities and interactions, as well as the socio-economic environment, which all together determine the innovative performance of the system (Eggink, 2012). Said differently, the main focus of IS is on how the different elements, the structure and the interactions within a system result in an innovation process, which in its turn results in technological development (Hekkert, Suurs, Negro, Kuhlmann, & Smits, 2007). In literature four analytical types of innovations systems are used. These types differ in the rationale on which the system under consideration is delineated. National innovation systems (NIS) and Regional innovation systems (RIS) are constructed on the basis of a geographical area; Sectorial innovation systems (SIS) are concerned with industrial sectors; and lastly Technological Innovation Systems (TIS) focus on technological development (Hekkert et al., 2007). TIS are for our research the most relevant and we will further discuss this type of IS analysis.

The main focus of a TIS approach is to understand the success or failure of a specific technology based on the functioning of the TIS (Twomey & Gaziulusoy, 2014). A TIS has four structural components; actors, institutions, networks and technological factors (Eggink, 2013; Hekkert, Negro, Heimerinks, & Harmsen, 2011). The interaction of these components results in the functioning of the innovation system with respect to the emergence or production of innovation (Hekkert et al., 2007). This functioning is then tested on the fulfilment of seven functions that are deemed to be indicative for successful system functioning. Depending on the phase the IS is in (pre-development, development, take off or acceleration) the lack of proper filling in a function may become a barrier for proper system development (Hekkert et al., 2011). By using the seven functions to evaluate the system during its different phases, policy recommendations can be made concerning the structural components.

IS provides some different insights with respect to the MLP based theories (although IS also bases some of its concepts on the MLP) (Chappin, 2011). The core of the theory is the set of the seven system functions which have a strong evaluative character. Further work on the theory of IS is suggested to focus on the dynamics of these systems (Hekkert et al., 2007).

2.3 Explanatory oriented theories

The explanatory oriented theories contribute to the body of transition literature by establishing the link between *what* transitions are and *how* they are being stimulated. The explanatory theories can be seen building upon the descriptive and prescriptive theories by identifying the mechanisms underlying the emergence of transitions.

2.3.1 Pillar theory

Building on the foundations of the MLP de Haan (2010) formulated the Pillar Theory (PT) during his PhD in the group of the main contributors of the MLP. PT could be seen as an additional theoretical layer surrounding the MLP. The main elements in the theory are constellations. Constellations are subsystems that are providing a certain societal need within a societal system. Examples of the public transport and the car based personal transport system are given by de Haan (2010). PT explains transitions as the interplay of conditions and patterns. Conditions are aspects of a societal system that make a system prone to change. Conditions lead to patterns which are ways a transitional change takes place. Patterns lead to new conditions and so the chain of events continues. Chains of patterns are called transition paths and they are the final deliverable of PT. In order to be able to focus analyses based on PT, de Haan describes and limits the theory to three types of conditions, three types of related patterns and four types of paths that could manifest themselves (de Haan, 2010).

We view PT as an additional theoretical layer of the MLP as it tries to add an explanatory dimension to the MLP; where the MLP describes what is happening, PT describes why it is happening through the use of conditions and patterns. PT resides at the abstraction level of the MLP and uses the concepts niches and regimes to build its narratives (Yücel, 2010). For the goal of PT, being to provide a generic explanation on transition dynamics (Yücel, 2010), it is sufficient to use the concept of niches and regimes as black boxes and study their dynamics. In the view of de Haan (2010) the dynamics and interactions of the constellations are by structuring them in conditions, patterns and paths explanatory for transitions. Yücel (2010) however questions if this is a full explanation. He considers PT as being more descriptive than explanatory due to the lack of postulation of behaviour rules of the conditions and patterns.

2.3.2 Matisse conceptual framework

The Matisse Conceptual Framework (MCF) originates out of the MATISSE project funded by the EU. It displays itself as a framework that is to address the challenge of modelling non-linear social dynamics of future transition to sustainability (Haxeltine et al., 2008). A main challenge for the MCF was to be able to reconstruct the transition pathways as defined by Geels and Schot (2007) (Yücel, 2010). For this challenge the MLP was adopted making niches and regimes the research objects in the MCF (Holtz, 2011). There are many similarities between MCF and PT (Holtz, 2011), which is likely caused by the fact they both originated from Geels and Schot (2007). However in the literature on MCF the link with PT and vice versa has not been discussed.

The idea behind the MCF is to model constellations (used in the same way as in PT) in a multidimensional grid called the practice space. Each dimension represents a different characteristic of the constellation under consideration, for instance carbon-intensity. Agents that reside in the practice space are regimes, niche-regimes (more power full niches), niches and consumers. The success of the non-consumers is determined by consumers who move within the practice space. If the location of a niche or regime overlaps with that of a consumer, this consumer is automatically supporting this actor, making it more successful (Haxeltine et al., 2008; Holtz, 2011; Köhler et al., 2009). Niches and regimes have different heuristics with respect to their actions. Niches move in the practice space as long as a certain direction is increasing their support. Regimes generally maintain their position (their 'practice') and will start to move if their dominant position is under threat. Interactions between different types of agents could take the form of niches being absorbed by the regime or the regime trying to move consumers in a new direction. Depending on the amount of support or through different activities niches may be transformed into regimes or vice versa (Haxeltine et al., 2008).

Criticism on the MCF mainly focuses on the lack of argumentation on the imposed dynamics. MCF is said to use many weakly core assumptions that are expected to be the result of the intuition of the researches themselves (Holtz, 2011). Also the question of providing a satisfactory explanation rises as did when we discussed PT. Some dynamics are reproduced based on certain conditions and mechanics on the niche/regime aggregation level. However the behavioural rules of these niches and regimes themselves have not been underpinned (Yücel, 2010).

2.3.3 Actor option framework

The Actor Option Framework (AOF) aims to provide a general conceptual framework for simulation supported transition analyses (Holtz, 2011) and was constructed by Yücel (2010) during his PhD research at the TU Delft. An analysis using the AOF has its starting point at a certain societal need that has to be fulfilled. When using the framework a researcher is to identify options that could fulfil this need. Options are defined as the means the selected societal need can be fulfilled, and constitute both out of the technology/technological artefact as well as the manner it is used (Yücel, 2010). Options have properties that differentiate them. The AOF distinguishes between embodied properties (those which can be observed when the option is studied in isolation) and disembodied properties (which are dependent on contextual factors) (Yücel, 2010). The options are the more passive entities within an AOF based study. Actors are the main drivers of the system and determine the behaviour of a system by the choices they make related to options; they *choose* which option to support (Yücel, 2010). The decision making of actors in the AOF is based on prospect theory of Kahneman and Tversky (1979) and is split up in a framing phase (projecting alternative courses of action based on available knowledge on these courses) and a valuation phase (make decisions as a consequence of valuing this framed information) (Yücel, 2010). Actors are heterogeneous based on their decision making rules and the impact of their decisions (Yücel, 2010). This leads to the identification of four main groups to which an actor could belong: practitioners, providers, opinion groups and government (Holtz, 2011).

The interplay between actors (social agents) and options (technical agents) results in the system behaviour. A distinction between the technological and social entities has also been used by Nikolic and Dijkema (2006) (using the term technological and social spheres) and is also used in the work of Chappin (2011). In the AOF actors influence the existence of options and their properties. Based on new sets of options or option properties, actors update their information and beliefs resulting in new actions taken by the actors. The technological and social elements in the system co-evolve and result in the dynamics of the system under consideration (Holtz, 2011). The coevolution occurs through different mechanisms which are specific instances of change processes and interactions between actors and options. Mechanisms could target the way options are used, the set of available options, the options' properties, the information possessed by the actor and the identity of an actor on which the actor bases its behaviour (Yücel, 2010). Yücel has formulated a set of relatively simple mechanisms that could be seen as the first building blocks that can be used to construct the so called web of the active mechanisms in the specific case. In different cases, different sets of mechanisms are expected to be active. The internal simultaneous interaction of the active mechanisms leads to the complex dynamics that can be observed during transitions processes (Holtz, 2011; Yücel, 2010). Yücel (2010) also formulated a roadmap consisting out of seven steps in order to guide the development of a model based on the AOF.

The AOF is different from the other explanatory theories given its more detailed scope of analysis. Where PT and MCF considered niches and regimes to be the active entities, the AOF explicitly opens up these concepts and bases its analysis on the elements of the socio-technical system, making it easier to link findings from the analysis to real-world policy making (Yücel, 2010). A downside of the scope of the AOF is the need of a large amount of information for model design, validation and robustness testing (Holtz, 2011).

2.4 Synthesis

In this paragraph we reflect on the gained knowledge from the literature review. A summarizing overview of the main elements of the discussed theories is given in Table 2-1. The structure of this chapter already used the distinction between descriptive, prescriptive and explanatory theories. We see a distinction between these types of theories, their origin and their age. The focus of the relatively older descriptive theories could be seen as trying to explain *what* is happening, and complementary the prescriptive theories focus on *how this could and/or should be influenced*. Only recently the link between *what* and *how to influence* is being made by the explanatory theories.

Table 2-1: Summarization of discussed theories

	MLP	TM	SNM	IS	PT	MCF	AOF
Authors of studied work	Rip, Kemp, Geels, Schot	Rotmans, Kemp, Loorbach	Loorbach, Rotmans, Kemp, Raven	Hekkert, Negro, Eggink	De Haan	Haxeltine, Bergman, Rotmans, Schilperoord	Yücel
Knowledge type	Descriptive	Prescriptive/ normative	Descriptive/ prescriptive	Evaluative/ prescriptive	Explanatory	Explanatory	Explanatory
Starting point	Observed transitions	Societal problem	Selected technology	Flaws in development and diffusion of innovation	Observed transitions	Observed transitions	Societal need
Building blocks	Niches & regimes	Niches & regimes	Experimenta-tion processes	Actors, institutions, networks & technologies	Niches & regimes	Niches & regimes	Actors & options
Core	Three levels of aggregation to develop transition narratives	Nine governance tenets	Expectation management, learning & niche experiments	Seven evaluative functions to analyse bottlenecks	Interplay of conditions & patterns resulting in transition paths	Simulation of movements of niches and regimes in the practice space	Simulation of interaction between actors and options
Mobility example	Description of transition from sailing ships to steam ships	Providing recommenda-tions to alter the person mobility system	Analysis of the breakthrough of the e-bike	Drafting policy recommenda-tions for zero emission cars	Adaptation of EV technology due to new oil prices and introduction of alternatives	Competition between hydrogen, electric and biofuel cars	Analysing the dynamics of the transition from sailing to steam ships

2.5 Theory selection for formalisation

The dominance of the MLP in the body of literature results in many of the theories applying the aggregation level of this perspective. Yücel (2010, p. 16) uses the term structuralist stance which is explained as "relying on a (social) structure that is autonomous from the individual elements (e.g. individual person), which constitute the structure, in explaining a (social) phenomenon." By aggregating the system into the three levels of the MLP the scholars are using this structuralist stance (in among others the PT and MCF). Subsequently they assign properties to, define actions on the basis of, and interpret results as the consequence of dynamics of the niches and regimes concepts. By using a structuralist stance the reality is aggregated and thus simplified. For the goals of the MLP, PT and MCF this is very useful in order to maintain a workable theory (Yücel, 2010).

The alternative would be not seeing niches and regimes as black boxes, but basing an analysis on the constituents within these black boxes. The regimes and niches are no longer the protagonists, but serve as "conceptual borders" (Yücel, 2010). Such an approach looks at the different elements in more detail and could be said to be finer granulated. The AOF uses this latter approach and is said to be able to capture more of the complexity. The price of using a more detailed scope is however the requirement of more input (Holtz, 2011).

The difference between the two stances can be illustrated by Figure 2-1. The upper illustrated regime change could be an example based on the MLP; the regime is a black box, and one black box will under certain conditions transform to a new one. The AOF is depicted at the second level where we are looking inside the regime and try to understand the changes of a system at a more fine grained level.

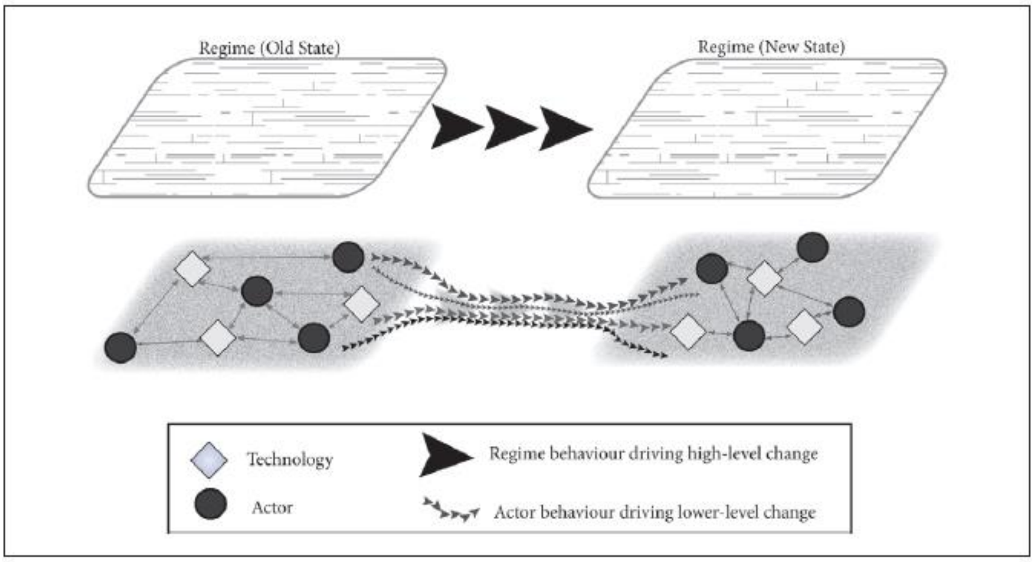

Figure 2-1: Micro- and macro-level changes in the structuralist stance (upper) and conceptual border approach (lower), by Yücel (2010).

Hekkert et al. (2007, pp. 428-429) suggested to depart from the 'macro' approach and analyses a restricted set of social phenomena to come to a more detailed understanding of transitions. The AOF is not following this advice and has the scope of studying full transitions. We however position this research more in line with the suggestion of Hekkert. We do not aim to understand the whole transition of the energy or transport system. Instead we aim to study a part of it; the possible operation of the CaPP concept. As transitions arise from a number of congregating system innovations (Rotmans, 2005), we hope to be able to contribute to the understanding of transitions by studying the dynamics behind the operation of a specific system innovation; CaPP. We have depicted our view on the position of our study in Figure 2-2. The white circle in this figure is the position of our study.

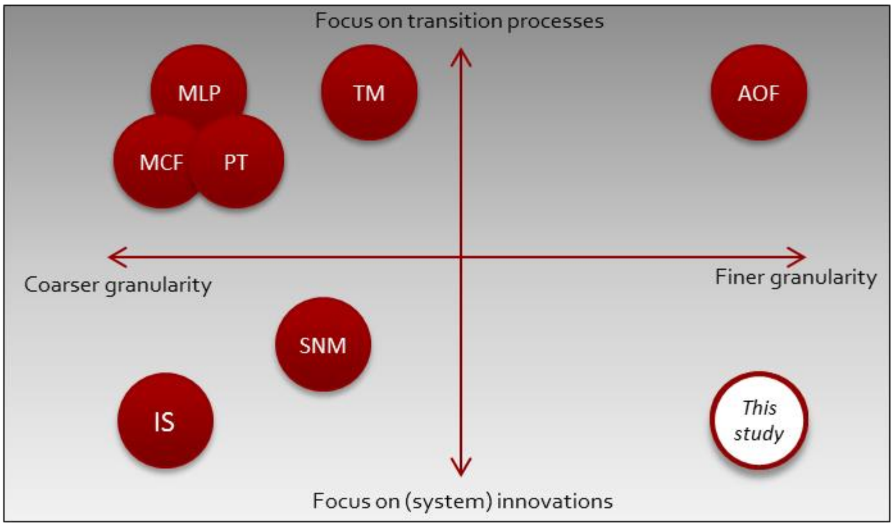

Figure 2-2: Perceived focus and stance of transition theories w.r.t. this thesis.

Based on the insights we have gained through the literature review chapter a selection of a theory on which we base our conceptual model was to be made. We selected the AOF as a leading theory for the rest of this thesis. The theory uses a focus that allows research to be conducted at the level of processes within the concepts of niches and regimes. Furthermore Yücel (2010) provides a clear step by step approach and the AOF fundamentals matches theories that we have considered to use for this project in an earlier stage such as work by Chappin (2011); Nikolic and Dijkema (2006) and Herder et al. (2008). Lastly the set of concepts of the AOF are flexible enough to be adjusted to a specific case, but allows for comparison between models and theory building (Holtz, 2011).

The AOF might not align with our interests as it is focussing on full transitions processes. By applying it nevertheless to the operation of system innovations we aim to contribute to the AOF theory in being also applicable for more low level processes.

3. Research approach for the CaPP case

In this chapter we describe our approach for studying the CaPP case. The chapter starts with a short summary of how the AOF will be used in this case study. The tools that we will use to translate the insights gained from applying the AOF into a model are discussed in the second section. The closing section of this chapter gives an overview of how the AOF and these tools are combined.

3.1 The lens: the Actor Option framework

We have characterised CaPP as a system innovation in section 1.1.3. Such technologies operate in complex systems. The complexity makes it difficult to identify which aspects, relations and dynamics are important to include in our research. As a solution we looked towards the body of transition literature. This body of literature was selected as we believe it gives the most support concerning adoptions of new technologies. In chapter 2 we selected the AOF to serve as the guiding framework for the system identification for this case study. The main reasons why the AOF was chosen are its focus on processes within niches and regimes and the suggested set of flexible concepts.

The AOF has a focus on allowing its users to study transition processes. Our scope is smaller with respect to the timeframe and system boundaries. We are aware that for the rest of this thesis we cannot solely rely on the guidelines of the AOF and that we will have to reflect on the fit of the AOF on the CaPP case.

3.2 The tools: ABM & Simulation

By conducting this research we aim to gain insight into the possible operation of a system innovation. Among others, Holtz (2011), Yücel (2010) and Chappin (2011) have discussed the fitness of simulations for studying transitions. Holtz (2011, p. 168) states; "[...] simulation models are, in principle, useful tools to facilitate the comprehension of emergent dynamics as they can be used to generate macro-level dynamics on the basis of multiple interactive micro-level mechanisms". For the exploration of the possible operation of a CPPP we want to be able to run numerous experiments without real-life consequences and within an acceptable timeframe. A simulation tool allows for such research. This is the main reason why we chose to conduct a modelling study to research the operation of CaPP over and the system it operates in, over a middle-long time frame.

The modelling paradigm that we have chosen for this study is the Agent Based Modelling (ABM) paradigm. In this paradigm much attention is given to bottom-up processes, complex systems and internal system interactions. Within the ABM paradigm, agents are entities that interact with other agents or the environment and have some degree of autonomy. Models made with the ABM paradigm are said to be specifically fit for modelling socio-technical systems in which the dynamics and structure of interactions within and between social and technical networks are to be analysed (Van Dam, Nikolic, & Lukszo, 2013). The overall characteristics of the paradigm match with our approach, considering among others the objectives and the way of decomposing as prescribed by the AOF. There are three aspects of our approach that specifically make the ABM paradigm fit for our purpose:

- The AOF prescribes the inclusion of social mechanisms in the analysis of transition dynamics. Such interaction between agents is easily formalised and captured in agent based models.
- Matching the operation of the CPPP and the aggregated fuel cell vehicle availability pattern is expected to be one of the largest challenges (cf. (Kempton & Tomić, 2005b) for a discussion of this challenge for vehicle to grid in general). The FCV availability pattern could be described in an emerging pattern from the actions of many autonomous agents. Such pattern formation can be well formalised using ABM.
- Agent based models are easily expanded or adjusted. Taking the limited time horizon of this project into account, the flexibility an ABM offers might prove valuable for future research efforts.

3.3 Overview

Together the lens and the tools as discussed above form our case study approach. The approach is illustrated in Figure 3-1.

The AOF will be used as a lens to filter the complex real world. The AOF guides us in which entities, relations and dynamics should be incorporated in our system identification and subsequent model formalisation. By combining these dynamics with the pre-defined interesting CPPP design options, we can study the dynamics that affect the operation of the CPPP. With the insights gained from this exploration we draw conclusions upon the effects and viability of including the considered design options and the possible effects that different environmental uncertainties could have on the operation of the CPPP. The focus of the AOF is however different from the focus of this study as noted before. The AOF is made to support the construction of conceptual models that allow transition dynamics to be analysed (Yücel, 2010). We intend to use it to support the construction of a model that allows exploration of dynamics that could affect the operation of a system innovation.

In chapter 4 we will define a set of interesting CPPP designs. The model is used to explore the operation of these designs under the given environmental uncertainties. With this exploration we aim to identify either design related or environment related factors that could form barriers for the successful exploitation of a CPPP.

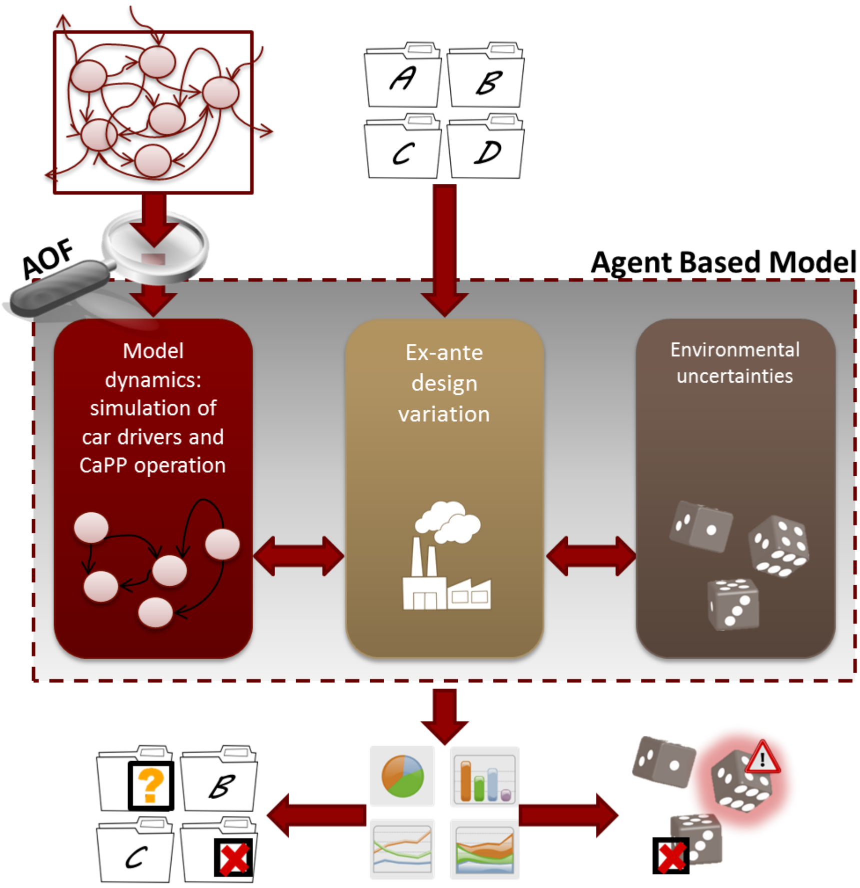

Figure 3-1: CaPP case study approach

4. CPPP design space

In this chapter we work towards the formalisation of our problem by discussing the major CaPP design choices. This chapter starts with presenting and explaining the selection criteria that are used to select the design choices that we will analyse in more detail. Secondly the technical and institutional design choices are discussed. The final section of this chapter summarises the findings and summarises the set of design choices that we will further investigate.

With the aid of a manuscript of the Process Energy group (Fernandes, Woudstra, Verhoef, & Aravind, 2015, In press), two prior MSc theses on CaPP (Palazzi, 2013; Spanjer, 2014), the CaPP booklet (van Wijk & Verhoef, 2014) and a brainstorm with a Esther Park Lee, a PhD researcher at the TPM Energy & Industry section, we have mapped the design choices that are seen as interesting for CaPP. A detailed overview of the considered technical and institutional elements can be found in respectively Appendix A and Appendix C.

4.1 Selection criteria for CPPP design options

To come to a feasible set of viable CaPP designs choices we need to select important design variations that could influence the functionality of a CPPP. Below we discuss the selection criteria that are used to determine whether certain design choices and their corresponding design options are considered in the rest of our research.

- The design choice must have multiple design options to choose from.
  It could be debatable if a choice without multiple options actually is a choice. For selecting design options for further research, it does not make sense to include elements that we do not vary. We did, however, include functionalities with currently only one design option in our overview. In this way a complete understanding of the state-of-the-art design efforts of CaPP is presented. Furthermore, we aim to signal that the list is most likely incomplete given that the research for the CaPP project is still in an early stage.

- The design choice must have a functional effect on the CPPPs as systems.
  Central in our analysis is the interaction between CPPPs and the other associated technical components and actors. In order to limit the complexity of the model we will formalize the CPPPs as black boxes, resulting in neglecting internal dynamics. Design choices that only affect internal dynamics and do not influence the behaviour of the black box (i.e. do cause functional difference) fall as a consequence outside the scope of this research.

- We must be able to correctly formalise the design option
  Some of the listed design options are theoretical, non-commercial or never tested. If a correct formalisation of these technical options requires an additional substantial amount research (e.g. an MSc thesis), it is not feasible to include them in this project.

4.2 Selected technical design components for analysis

The technical design of CaPP is with respect to the institutional aspects fairly well developed. Fernandes et al. (2015, In press) and Spanjer (2014) have reported on thermodynamics of CaPP, for which they included a description of the main technical components. An overview of these components complemented with other non-essential components as envisioned by van Wijk and Verhoef (2014) is presented in Appendix A. There is one technical design choice which fulfils our selection criteria; the technology is used to reform methane into hydrogen. This choice and why it is important to further investigate it, is discussed in the following section. A complete list of the discussed technical design choices and argumentation on why these are included or excluded for further research can be found in Table 4-2.

4.2.1 Methane reforming

The inclusion of methane reforming in the CaPP design allows for hydrogen production on-demand. Methane reforming might be needed when hydrogen demand is high (for filling the FCVs for driving or electricity production), but electrolysis is unattractive due to for instance high electricity prices or a limited capacity. A CPPP can during these times extract natural gas (being mostly methane) from the gas grid (van Wijk & Verhoef, 2014).

Steam reforming

The current dominant production method of hydrogen is by steam methane reforming (van Wijk & Verhoef, 2014). This reaction allows for the conversion of methane to hydrogen by bringing methane and steam into contact with a catalyst under high temperature and high pressure (Fernandes et al., 2015, In press). The high temperatures are typically achieved by burning some natural gas. The output of a steam reforming reaction is hydrogen and excess heat. The typical industrial installations could produce enough hydrogen to fill 20 to 200 fuel cell vehicles per hour (Palazzi, 2013).

The advantages of the steam reformer are its relatively high hydrogen yield per amount of methane and the maturity of the technology. A more detailed description of steam reforming can be found on page 96.

Solid oxide fuel cell

A new and promising technology for the production of hydrogen is the solid oxide fuel cell (SOFC). The SOFC combines the steam reforming reaction with a fuel cell. The steam reforming reaction takes place at the anode side of the fuel cell, where the anode itself fulfils the role of the catalyst for the reaction. The inclusion of a fuel cell allows for electricity generation during hydrogen production. Furthermore no external heat source is required due to the exothermic fuel cell reaction.

Where the steam reformer produces hydrogen and heat, the SOFC produces mainly hydrogen and electricity resulting in a higher exergy efficiency at the price of a lower hydrogen production per amount of methane. Other advantages of the SOFC are it being able to produce electricity without FCV's present in the CPPP and the possibility to substitute methane as feedstock with a wide range of hydrocarbons. The SOFC is discussed in more detail on page 97.

Comparison

Table 4-1 gives an indication of the differences between the two reforming technologies. It should be noted that this overview is the theoretical operation. The practical operation of the devices is due to the requirement of other devices (such as pumps) different, and is presented in Appendix E.

Table 4-1: Theoretical limits of reforming technologies based on (Spanjer, 2014)

	Steam reforming	SOFC[4]
Hydrogen yield per mole methane	3 moles hydrogen	2 moles hydrogen
Other energetic products	Heat	Electricity + heat
Energy in one mole methane (LHV)	803 kJ	803 kJ
Other required energy input per mole methane	225 kJ heat	0 kJ
Energy in produced hydrogen (LHV)	942 kJ	628 kJ
Energy in other energetic products per mole methane	86 kJ	197 kJ el.

4.2.2 Selection overview of technical design options

A full overview of all investigated technical components can be found in Appendix A. The components are listed and shortly discussed in Table 4-2. The table indicates whether the different technical design choices have or have not been included for the rest of this thesis, along with the underlying motivation. The exclusion of a certain design element does not by default mean that its functionality is not included in the rest of the thesis; it indicates that the way this functionality is provided is not altered in the experimentation phase.

[4] Table 4-1 presents maximum theoretical possible production capacities of all types of products. For the SOFC these maximums are achieved at different temperatures, making it impossible for these values to be achieved at the same time. This explains the possible implied violation of the energy balance (Spanjer, 2014).

Table 4-2: Selection of technical design options for experimentation

Design choices	Design options	Characteristics	Included for further research?	Motivation
Handling methane	Compression + desulphurization	Methane brought to suitable conditions for steam reformer or solid oxide fuel cell	Excluded	No other option to vary with
Reforming methane	Steam reforming	Mature technology, using nat. gas for process heat. Relative low efficiency.	Included	Including the possibility to produce electricity without FCVs allows for different business models and affects required availability of FCVs in the CPPP
	Solid Oxide Fuel Cell	New technology, producing electricity & hydrogen. High efficiency. Can run on any hydro-carbon	Included	
Producing H_2 with electricity	Electrolyser	Transformation from electricity and to hydrogen possible	Excluded	No other option to vary with
Handling H2	Pressure swing adsorption	Mature, energy intensive	Excluded	No significant functional difference than costs or energy efficiency
	Hydrogen membranes + CO-Prox	Less energy intensive, more vulnerable to poisoning	Excluded	
Storage of hydrogen	High pressure	Mature, difficult to store	Excluded	Besides ammonia no functional differences. Inclusion of ammonia would require inclusion of long term energy dynamics and the current ammonia system. Such inclusions are time intensive and fall outside the scope of this project.
	Liquid stage	Energy intensive. High energy density	Excluded	
	Chemical	Immature technology, non-commercial. Requires complex installation.	Excluded	
	Ammonia	Long term storage possible. Relative low efficiency	Excluded	
Convert H2 to electricity	50 FCVs capacity	High costs per kWh, high density of CPPPs in an area	Excluded	FCV capacity influences the spread of CPPPs over an area. Effects of this spread depended on city architecture consumer reactions to the distance between parking location and final destination. This knowledge is lacking and makes it unfeasible to study this effect in this project.
	200 FCVs capacity	Medium costs per kWh, medium density of CPPPs	Excluded	
	500 FCVs capacity	Low costs per kWh, low density of CPPPs in an area	Excluded	
Exchanging heat	Heat exchangers	Mature technology, allowing transfer of heat	Excluded	No other option to vary with
Parking FCV	Automated parking	High costs, spatial efficient	Excluded	No significant functional difference other than costs
	Manual parking	Spatial inefficient, known procedure for drivers	Excluded	
Connecting FCV	Automated	Requires connection standard for different FCV types	Excluded	No significant functional difference than costs
	Manual	Less complex CPPP technical system at the price of possible reduced support from drivers and accidents.	Excluded	
Purifying water	Purification unit	Preparation of waste water to be injected into network	Excluded	No other option to vary with
Controlling system	Automated IT system Manual	Allows management of FCVs to follow intended use case	Excluded	No significant functional difference
Interaction with owner	App Terminal in CPPP	If allowed, method to convey preferences concerning operation of FCV	Excluded	No significant functional difference

4.3 Selected institutional design components for analysis

In previously performed studies the technical aspects of CaPP have been studied in relative detail. This is not surprising given the origin of the concept being a technical university. The institutional design of the concept is, however, at least as important seeing the complex and dynamic environment CaPP is to operate in (cf. (Meadows, 2015)).

Since late 2014 Esther Park Lee is conducting a PhD research on the socio-technical system design of CaPP. Based on literature on vehicle to grid technology[5], and short actor analysis and a brainstorm with Esther Park an overview has

[5] Vehicle to grid (V2G) systems allow for an electricity flow from cars to the centralized grids. Cars that could provide such functionality are fuel cell, hybrid or battery cars when they are plugged in during parking. CaPP could be seen as a central organized V2G concept. The main author on V2G that has been consulted for this project is (Kempton & Tomić, 2005a).

been made of the expected important institutional design choices. The results from the actor analysis and the overview of all investigated institutional design options can be found in respectively Appendix B and Appendix C.

The following sections discuss the institutional design choices that are selected to be included in our modelling study. These choices are the CPPP location, CPPP use case and used driver parking incentives.

4.3.1 CPPP location

The actor analysis as described in Appendix B shows the large impact of the location of the CPPP on the set of actors that can play a role in the operation of a CPPP. Depending on the location the owner of the CPPP and consumers of heat, water and electricity can vary. The choice of the location of CPPPs furthermore is expected to a have a large influence on the times the FCVs will be parked in the CPPP. As a consequence the times at which the CPPP could produce electricity, heat and water depend on the location of the installation.

The CPPPs would benefit most of locations where FCVs are parked for longer time periods and their availability can be predicted with relative high certainty. This makes locations near homes and offices prime candidates. Locations near points of interest where drivers only stay for a limited time are less suitable, such as city centres or supermarkets.

4.3.2 Use case

The owner and/or operator of a CPPP will have the challenge to 'match the markets' in the words of Kempton and Tomić (2005a). Contracting clients to sell electricity to becomes problematic due the uncertain availability of the FCVs. In the Dutch electricity market there are several market segments a CaPP could produce for. We will below very briefly discuss the different market segments. More information on all the different segments can be found in Appendix C.

Wholesale production

Wholesale production is most likely the most well-known type of production. Generators produce for long term contracts or contracts sold via the spot market. In short we can divide the wholesale production into two:

1) Baseload demand, which needs to be fulfilled around-the-clock. Generators producing for this segment are designed to run for as many hours as possible and have high capital and low variable costs. These characteristics are directly opposing the principles of CaPP, leading us as labelling this design option as unviable for CaPP and thus excluding it.
2) Peak demand, which is in the Netherlands defined as the demand between 09:00 and 20:00. During these hours demand is high, which is met by firing up generators that can quickly ramp and have low capital costs.

Ancillary services

The Dutch Transmission System Operator (TSO) TenneT has the obligation to secure the stability of the electricity grid. Ancillary services are services that electricity producers can offer TenneT to maintain this balance. In the Netherlands three types of ancillary services are used:

1) Primary control: used for the fine tuning of the grid. This type of control is called about 400 times a day per contracted generator. Generators can bid on supplying their capacity and are reimbursed based on the time and amount of capacity they are available (capacity fee). In the Netherlands the contracting time of primary control is full weeks during which at each moment in time the capacity must be available. This requirement is in conflict with the dynamic availability of electricity production in the CPPP. Also, primary control requires production to be adjusted within very short time periods. Quickly ramping up and down of fuel cells is reported to have a negative effect on their lifetime (Palazzi, 2013). We deem it very unlikely that primary control in its current design will become a feasible business case for CaPP and therefor exclude it for further analysis.
2) Secondary control: used for matching supply and demand on a 15 minute basis. CaPP could both provide supply increasing services and demand increasing services (and get paid in both cases). Reimbursement is based on the actual additional produced or consumed electricity (production fee).
3) Tertiary control: in practice only used in cases of unexpected events. Contracted generators are obliged to be on standby during the full contracted periods of calendar-years and receive a capacity fee accordingly. In the current

institutional design of this service provision the contracted capacity is obliged to be available at any moment during the contracted year. This requirement (as in the case with primary control) makes providing this service with CaPP unfeasible and leads us to excluding this use-case for further analysis.

Local production

A special use case is selling the electricity services to local demanding parties. This could be production for local demand, but also offering ancillary services to balance smart-grids once widely uses. Advantages of selling electricity locally are possible cost reductions, better security of supply for users and a better relation between CaPP operator and FCV drivers. However, due to the local characteristics of this contract each contract will have different specifics making it very difficult to include such a strategy in our research. This leads to the exclusion of this strategy for this project.

Table 4-3 gives a summarization of the different market segments as discussed. Peak load production and secondary control are highlighted as they are included in the further analysis of this project.

Table 4-3: Possible market segments for CaPP production

Type of production market	Production times/ call times	Contract period[6]	Reimbursement type	Typical fees[7]
Baseload (excluded)	Around-the-clock	Long term	Production-fee	35 €/MWh
Peak hours	09:00 – 20:00	Day-ahead	Production-fee	45 €/MWh
Primary control	400 times a day per generator	Week	Capacity-fee	4500 €/MW-w
Secondary control	Every 15 minutes	Day-ahead	Production-fee	50-200 €/MWh (r. up) -150 to 30 €/MWh (r. down)
Tertiary control	20 times a year nation-wide	Year	Capacity-fee	3000 €/MW-w
Local (excluded)	Case specific	Case specific	Case specific	Case specific

The work of Palazzi (2013) is to be mentioned here, being an optimization study towards the different market segments under strict assumptions of the CaPP design. Palazzi concluded that CaPP can be profitable when operated under the peak hour, balancing services or local production strategy when the variable cost of producing hydrogen is less than €1/kg. At a variable cost of €2/kg a small profit can be made when selling locally and still a significant profit can be gained from selling as balancing services. The profit made from balancing services becomes questionable at a variable cost of €3/kg.

The work by Palazzi (2013) is for our purpose very interesting, although slightly different than this research. Where Palazzi studied the potential of one particular CaPP design under assumed FCV availability schemes over the time period of several weeks, we aim to include more design variations and also loosen the assumption on set FCV availability. In this sense this work could be seen as an extension of the work of Palazzi.

4.3.3 Driver parking incentives

The parking behaviour of the FCV drivers will have to match with the operating scheme of the CPPP. Different pursued use cases will require guarantees that the FCVs are available at certain times. Currently the car driver has full control over the times he parks his car. This might change when the CPPP gives certain incentives or obligations to the driver. We discuss three types of incentives that could be given, of which two will be included in the rest of the research.

No incentive

The easiest design option is not to give any incentive for the car drivers to park their cars at designated times in the CPPP. Although effortless and costless to implement, the accompanying uncertainty concerning FCV availability might

[6] Day-ahead: contracts are closed latest one day ahead of actual production. Duration of contract can vary from quarters of an hour to several hours.

[7] MWh: Megawatt hour, being one megawatt produced for the period of one hour. MW-w: Megawatt-week, being one megawatt of production capacity available for the duration of one week.

cause large problems for operating the CPPP. The location of the CPPPs will in this case gain in importance as it will have to be adapted to the driving scheme of the FCV drivers.

Obligation

Most convenient for the CPPP owner would be to eliminate all uncertainty concerning FCV availability and oblige the FCV drivers park their car at the location and times that suit the CPPP owners' goals. Although unthinkable in the current situation with respect to car ownership, new forms of car use such as more widely implemented car leasing and/or car sharing make such an obligation more plausible. Leasing cars is currently common between companies and employees, but in the future we might also see car drivers lease their car from electricity producers, CPPP owners or maybe the network operator. The argumentation for a company outside the traditional car sector to lease cars to users might be gaining a say in the parking locations and times of the car.

Car sharing seems to be a less plausible option. Car sharing is the subsequent use of one car by multiple users. This implies that the owner aims to minimize the parking hours of the car, which conflicts with the principles of CaPP.

Monetary incentive

A mid-way between no incentive and an obligation would be to implement a monetary incentive. Such an incentive gives the CPPP operator a tool to try to persuade FCV drivers to park their car at the CPPP at times of high electricity demand. Although allowing for flexibility this option would require some sort of (nearly) real time communication between FCVs and all CPPPs in the area.

To formalise a parking obligation or monetary incentives is quite challenging. Knowledge is lacking on how consumers will respond on the offer of obliged or compensated car parking. We would for instance need to know how much drivers value control over their parking times, what financial benefits they as a result would demand for certain freedom limitations or how they would take these constructions into account when planning trips.

Even though, we do find it important to include at least one variation on the 'business as usual' case. Kempton and Tomić (2005b, p. 282) highlight the importance of matching the "needs and desired functions" between the V2G operator (availability of FCVs at specific times) and car users (drive as desired). We expect that not studying the dynamics of the availability of FCVs would be excluding an important aspect of the problem, reducing the usability of this study. The problem of matching these needs and desired functions is for the CaPP case even more important due to the centralisation of the V2G locations in a CPPP.

Comparing the obligation option and monetary incentive, we expect to encounter less uncertainty surrounding the obligation. Assuming that the drivers adhere any obligation, the movements of the driver are both for the CPPP operator and the driver known in advance. When using a monetary incentive, the issuing of an incentive might come at unexpected times for both the drivers and the CPPP operator. As a result the behaviour of the FCV driver can no longer be known ex-ante. If an incentive is issued during a journey of the FCV driver, factors like the location of the FCV driver at that time, the availability of public transport and the time schedule of the driver then all come into play. Also when financial incentives are given for instance the day-ahead, uncertain factors like the agenda of the user, heterogeneity among drivers and no confirmation for the CPPP operator are at play. We view the monetary incentive to be more complex with respect to the obligation option due to among others the smaller time scale it operates on and the resulting limited time for drivers to come to a decision. Gathering the required knowledge to formalise this option requires additional research of substantial scale, and therefor falls outside the scope of this project.

Following the argumentation as given above, we will not attempt to include the monetary incentive in this project. In order to be able to experiment with influencing the parking behaviour of the FCV drivers we will however include the obligation option in the rest of this research. In order to deal with the lack of knowledge we will inverse the "design process" of such a driving obligation. A normal design process would first analyse the design problem, gather and analyse the different design options and come to one favourable design. Going through this design process for the obligation option falls outside the scope of this project. Instead of researching if certain forms of an obligation would be viable, we will study if the effects of such an obligation will have a large or determining effect on the operation of a CPPP.

4.3.4 Selection overview of institutional design options

Appendix C gives an overview of the investigated institutional design choices and related design options. Table 4-5 gives a summarising overview of this appendix. We expect the full list to be subject to change as research efforts on the institutional aspects of the CaPP design has only just begun. The exclusion of a design choice indicates it will not be used as a variable to experiment with later in the research. This does not imply that the provided functionality of the design element is completely excluded from the formalisation of the CPPP.

4.4 Formulating experimental designs

For the exploration of the effect of different CPPP designs on the operation of a CPPP we have assessed the design choices and accompanying options that are currently being considered for the CPPP. The selected design options that we will study in more detail have the characteristics of having functional effects on the operation of the CPPP and can be formalised with the currently available knowledge.

In the previous sections a total of four different design choices have been identified which are summarised in Table 4-4.

Table 4-4: CaPP morph chart to be used in formalisation phase

Functionalities	Design options	
Reformer	Steam reformer	SOFC
CaPP location	Near homes	Near offices
Use cases	Peak load	Secondary control
Parking incentive	No incentive	Obligation

Table 4-5: Selection of institutional design options for experimentation

Design choices	Design options	Characteristics	Included for further research?	Reason
CPPP owner	Traditional carpark owners	Different owners will set different goals for the usage of the CaPP. This results in different use cases.	Excluded	Use cases are discussed separately. Varying these and reflecting on viable strategies after the simulation effort provides the same insights with a simpler model.
	Offices			
	Electricity network operator			
	Electricity retailers			
	Housing cooperatives			
	New entrepreneur			
CPPP operator	Traditional carpark owners	Operators will adhere the wishes of the owner or will themselves adopt a certain use case.	Excluded	Use cases are discussed separately. Varying these and reflecting on viable strategies after the simulation effort provides the same insights with a simpler model.
	Offices			
	Electricity network operator			
	Electricity retailers			
	Housing cooperatives			
	New entrepreneur			
Use cases	Local demand	Contract dependant.	Excluded	Variation in contract details per location leads to high uncertainty concerning institutional design preventing correct formalisation
	Baseload hours	Around-the-clock production. Production fee	Excluded	Basic principles are opposed to those of CaPP, making this a unviable strategy for CaPP.
	Peak hours	Production during day hours. Production fee	Included	Different market segments require different types and times of production, affecting the demand for FCV availability, FCV use and remuneration
	Primary regulation	High call rate, week contracts. Capacity fee.	Included	
	Secondary regulation	High call rate, day-ahead contracts. Production fee	Included	
	Tertiary regulation	Low call rate, year contracts. Capacity fee.	Included	
CPPP location	Near homes	High and predictable FCV availability during night hours	Included	Times of FCV availability define the times during which the CPPP can operate and sell its products. Furthermore the set of involved actors is different per type of location.
	Near offices	High and predictable FCV availability during office hours	Included	
	Near points of interest	Possible short parking times and unpredictable FCV availability	Excluded	Uncertainty concerning availability makes closing contracting problematic and is at this stage expected to be too much of a challenge.
Car ownership	Private	High upfront investments. Full control over FCV availability by driver	Excluded	Including driver input (discussed separately) and after the simulation discussing car ownership results in the same insights with a simpler model.
	Aggregator: leasing	No need for long term investment of driver. More control over FCV availability	Excluded	
	Aggregator: car sharing	Sequential supply of mobility to consumers by a fleet of cars	Excluded	
Payment to car owner	Monetary	Incentive for owner to participate	Excluded	No significant functional difference. H_2 tanks too small to significantly affect operation conditions
	Full H_2 tank			
Driver input - parking	Monetary incentive	Providing monetary compensation to park FCVs in CPPPs when demand for FCVs is high	Excluded	Large uncertainty concerning communication of these incentives and consumer behaviour w.r.t these incentives
	Obligation from owner	Freedom of driver is limited as compensation for lower costs	Included	Largely determining FCV availability and causes different ownership constructions
	No incentive	Based on driving schedules the drivers are expected to use the CPPP	Included	
Driver input - operational	Driver preferences	Usage of FCV in CPPP could be limited. Allows in higher driver utility but may result in irrational behaviour and uncertainty for CPPP operation	Excluded	Driver limitations effectively are certain amounts of hydrogen to be present in the car at all times, resulting in a perceived insignificant effect on the implementation of CaPP
	Full control by CPPP operator	Full FCV potential is used in order to maximise CPPP profit	Excluded	

5. Modelling problem & system identification

The CPPP designs that we want to experiment with have been formulated in chapter 4 with the aid of the insights gained in Appendix A and Appendix C. This chapter reports on the translation of the relevant real world dynamics into a conceptual model. In this and the following chapter we apply the approach of Van Dam et al. (2013). Although this approach also includes the step 'system identification and decomposition', we will in 5.2 deviate as we substitute the activities as suggested by Van Dam et al. (2013) with the AOF. The AOF is, as discussed in chapter 2, specifically tailored to fulfil the requirements of system identification for transition studies.

5.1 Problem formulation and actor identification

As the model is a mean to an end, we could see it as a small research that should contribute to answering the research questions of this thesis. In this first step of the modelling process we introduce the problem formulation for the modelling effort. We define the modelling question, the problem owner and the other actors involved.

What is the problem? What is the exact lack of insight that we are addressing?
The addressed lack of insight is the missing knowledge on how different designs of CaPP would perform in reality. The *modelling question* is; which CPPP designs aspects (including both technological and institutional aspects) or environmental factors could form a barrier for viable CPPP exploitation?

We expect this question to come down to the question if the operating strategy and the incentives for car users to use the CPPP, are properly aligned in order to have an appropriate availability of FCVs during production times. The car drivers have to make the decision whether they find buying an FCV attractive and are subsequently interested in making use of the services of the CPPP. The CPPP owner has to offer rewards that are attractive for FCV drivers (monetary and acceptable freedom restriction) while profitably supplying electricity services to make up for the investment costs.

Whose problem are we addressing?
We view the GreenVillage as the problem owner of this modelling study. The study should contribute to a better understanding of the boundaries of the design space of CPPs. Furthermore the work should give insights for the researchers focusing on CaPP by suggesting providing a formalisation to study the operational side of the concept.

What are the outcomes of interest?
With this study we aim to gain a better understanding under what conditions the CaPP concept could be operated successfully. Although successful operation could be measured in different forms, we have chosen to focus on the financial viability of the concept. If the investment costs of building a CPPP cannot be recovered, a long term sustainable exploitation becomes problematic. For the rest of this project we label a situation as viable if the return on investment for the CaPP exploiter can be expected to be more than one on the middle long term of a couple of years.

Besides viability we are also interested in the effects of the introduction of a CPPP for the system as a whole. We will for this purpose also monitor the emissions of the whole systems in kg CO_2 equivalent and the adoption rate of the CaPP concept and FCV's among drivers.

Which other actors are involved?
Once the CPPPs are deployed the main actors are the car drivers and the CPPP operators. Furthermore electricity (and heat) demanders could have a passive role.

What is our role?
Through the modelling study we aim to provide the knowledge to fill the given knowledge gap. The model is in this aspect a tool that helps us to structure our thoughts and to compute the results of many but relatively simple actions. Once we obtain a workable model, we will have to test it how sensitive it is for our defined input and to the made assumptions.

5.2 System identification and decomposition

Identifying and structuring the system composition and boundaries is the second step of model construction in the approach as reported by Van Dam et al. (2013). This step is a complicated one as the complexity of the system under analysis should be understood and translated by the modeller. He has to understand and decide which components are important for mimicking the system dynamics and a way how these components should be represented. Precisely for this task we have searched in chapter 2 for a theory that could help us identify and structure important elements for studying system innovations. As described at the end of chapter 2 and later in chapter 3 we have found the Actor Option Framework to be the best fit for this purpose. Although the approach of Van Dam et al. (2013) would most likely also result in a useful model for the CaPP case, the AOF is preferred as it is expected to be of more value in specifically transition related processes. In this section we thus substitute the approach of Van Dam et al. (2013) by the system identifications steps as suggested in the AOF (Yücel, 2010, ch. 7).

The AOF guides system identification by having the user answering the following questions;

- What is the societal function/need of concern?
- Which aspects of the societal function characterize the transitional change?
- What are alternative means of fulfilling the societal function?
- Who are the major social actors in the system?
- How to formalize actors' decision-making?
- How are the options characterized in the model?
- Which mechanisms are 'active' in the analysis context?

The answers of each of the questions for the CaPP case are given in the subsequent sections.

5.2.1 What is the societal function/need of concern?

The societal function of concern acts as the 'anchor concept' of the AOF. It is the starting point from which all other relevant actors, options and processes are identified.

For our study the societal function that is to be fulfilled is the demand of mobility with car usage. This demand can be split into three; having a car available, driving the car at desired times and parking the car after usage. The spatial scope of the innovation is a fictional area in the Netherlands with enough car drivers to potentially fill at least one CPPP.

5.2.2 Which aspects of the societal function characterize the transitional change?

Not all aspects related to the societal function are of interest for our study. Defining which aspects of the societal function are of interest, allows for further narrowing the focus of the identification of relevant actors, options and interactions.

Our focus is on the profitable exploitation of the potential of parked FCV's. More specifically we aim to understand which factors could form barriers for achieving viable financial performance when operating the CPPP.

5.2.3 What are alternative means of fulfilling the societal function?

In this step we define the different options that are considered in our model. An option is the combination of a technological artefact with its accompanying mean of using.

For the car drivers we can list three types of variations in the options. The different variations of the options are discussed below and are illustrated in Figure 5-1.

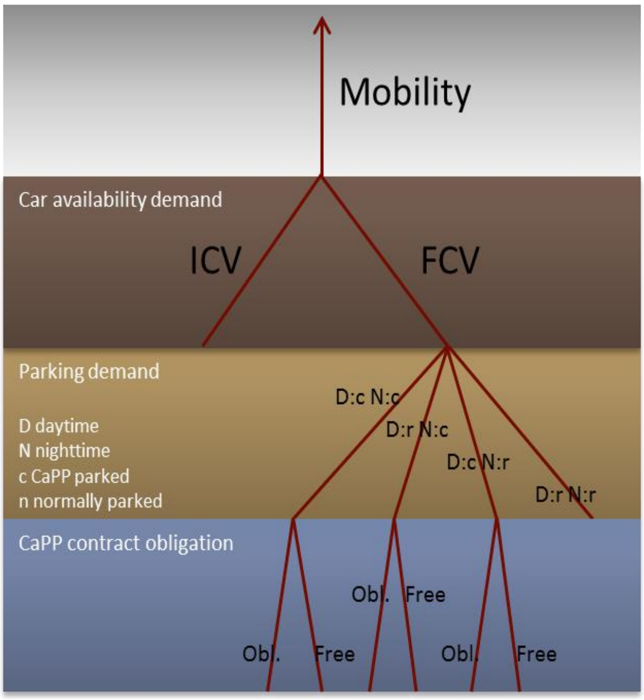

Figure 5-1: Considered options and underlying relations

Driver: Type of owned car

First of all the type of car that is available to the driver is of concern. In our analysis we will consider the internal combustion vehicles (ICVs) and the fuel cell vehicles. For the sake of simplicity we thus exclude future competing alternatives such as (hybrid) electric cars. We study a world in which fuel cell vehicles are widely available and used in daily life. This implies that in this world a hydrogen refilling infrastructure (parallel to CaPP) is available for users.

Driver: Parking behaviour

The second relevant variation is the location of parking the car during times it is not in use. We assume the majority of the trips to be between home and work, and subsequently the car is being parked at home or at work. During these times we are interested if the cars are being parked in a CPPP or not. This leaves us with four variations to explore.

Driver: CPPP contract specifics

Lastly the term on which the drivers agree to park their car in the CPPP can differ. For our project we will include one contract element; the times of obligatory parking.

5.2.4 Who are the major social actors in the system?

The actors are the major players in the AOF and have the largest influence on the system behaviour through their decisions with respect to the options. The AOF distinguishes four categories in which relevant actors could be sought. Below we discuss these groups separately for the case of CaPP.

Users/Practitioners

The group of actors that is utilising the options is the group of car drivers. In our case the key decisions that are being made by the users is the choice for a driving technology (ICV or FCV) and if the driver uses the services of the CPP under the offered conditions.

Suppliers

When related to the different types of options we distinguish two sets of suppliers of the options. First the cars are being provided by either car dealers or other suppliers such as leasing companies. For our purpose the origin of the cars is of little interest. This allows aggregating all the different car suppliers into one. For the sake of simplicity we make the environment selling the cars to the car drivers.

The second type of supplier is the company that is operating the CPPPs and offering the CaPP service. For our delineated world no more than one CPPP will be in place.

Regulators

Governmental aspects for the CaPP case are discussed on page 116 to 117 and have been concluded to be unknown external forces at this stage of the CaPP development process instead of being active forces within the system itself. For this reason we do not include an actor representing the government within the system.

A regulator that is of interest is the transmission grid operator who has a demand of various electricity system services. This demand can be fulfilled by CPPPs. Although we do not foresee an active role of the TSO in the model dynamics we will include this actor to be representing the electricity market as a whole and as a result be the entity that is demanding different electricity services (including electricity production during peak hours).

Opinion groups

There are concerns on the security on hydrogen. An opinion group trying to influence the public opinion on hydrogen would however rather influence the construction of CPPPs or the selling of FCVs, instead of the operation of the FCVs and the CPPPs once they are in place. As stated in Appendix B we assume that the municipality assures the safe operation of hydrogen, and that in any scenario in which CaPP is potentially viable the requirements from the municipality will have to be met. We do not foresee any influence of public opinion on the dynamics of the operation of the CPPP and therefore will not include an actor in the model that represents opinion groups.

5.2.5 How to formalize actors' decision-making?

Within the AOF a large role is given to the prospect theory of Tversky and Kahneman (1992) (Yücel, 2010, p. 65). The theory prescribes splitting decision making by actors into *framing* and *valuation*. Actors frame different options according to the information they possess. The possessed information represents the beliefs of the actor and can be incomplete or incorrect. The way the actors gain more or updated information is through different mechanisms discussed later in section 5.2.7.

General procedure

Valuation of different decision options is based on the preference structure of an actor. Such a preference structure represents the importance of different aspects of the possible consequences of the choice at hand. The preference structure contains different dimensions which should be attempted to limited to a maximum of six for the purposes of the AOF (Yücel, 2010). The preference structure of actors could change over the course of time and could be influenced by for instance commitment forming or the adjustment of the actors' references.

If the preference structure of an actor is determined, a value function based on the beliefs of the actor is to be calculated per decision option in order to allow the actor to compare the different options with one another. The actor then chooses the option which has the highest expected utility. The preference structure of the actors in our model and the construction of a value function are discussed below.

Value functions for car drivers

Ewing and Sarigöllü (2000); Hidrue, Parsons, Kempton, and Gardner (2011) and Koetse and Hoen (2014) report on consumer preference on different vehicle types (EV or clean fuel vehicles). The paper by Parsons, Hidrue, Kempton, and Gardner (2014) extends the approach of (Hidrue et al., 2011) by including vehicle to grid aspects to the experiments. We adopt the choice model as presented by Parsons et al. (2014, p. 318) for which 3029 North American participants were asked to choose between an ICV, an electric vehicle without V2G capabilities (conventional electric vehicle; C-EV) or an EV with V2G capabilities and the accompanying contract (V2G-EV). Using this choice model is not ideal as it does not fully match our needs. An alternative would have been the choice model as reported by Koetse and Hoen (2014) which is more applicable in the sense that it was executed among Dutch company drivers, but it only considers the purchase of alternative fuel vehicles for company drivers. As we value the fact that the models of Hidrue et al. (2011) and Parsons et al. (2014) as a combination both cover the choice of providing V2G services and the purchase of ICVs or EVs we have selected these models for our study. A discussion on this choice can be found in section 8.2.3.

The utility function based on Parsons et al. (2014, p. 318) has the following form;

$$U_{parson,i} = \beta_0 d + \beta_p \Delta p_i + \beta_\chi x_i + \beta_y y_i d + \varepsilon_i$$

Equation 5-1: RUM model by (Parsons et al., 2014) for choice modelling of consumers considering ICVs, EVs or V2G-EVs

Where;
i =0 for ICV, i =1 for C-EV, i =2 for V2G-EV.
β_0 is a constant that captures an average effect of V2G-EVs versus C- EVs.
d is a dummy variable that is 0 if a choice is being made between an ICV or C-EV, or 1 if the choice is to be made between an ICV or V2G-EV.
$\Delta \mathrm{p}_\mathrm{i}$ is the price difference between the ICV and the EV in question (C-EV or V2G-EV).
x_i is the vector containing conventional EV attributes: driving range, charging time, pollution reduction, performance and fuel cost savings.
y_i is a vector containing the V2G contract terms: minimum guaranteed driving range, required plug-in time and cashback payment
ε_i is the error term with a mean zero and standard deviation 1.

We here assume that we can substitute the FCV for the EV in these analyses. In the formula this would mean substituting *i*=1 with a C-FCV and *i*=2 for V2G-FCV. This for instance implies that if consumers value a price difference between ICS and EVs with a parameter of -0,007 per euro difference, the consumers also value a price difference between the ICS and FCV with -0,007 per euro difference.

For our purposes we calculate a value function for the car drivers in two separate cases;

1) Car drivers considering using the services of a CPPP

The car drivers that already have an FCV can make the decision to park their cars in CPPPs under the given contracts. For this case we assume that all FCVs on the market are compatible with CaPP. This assumption allows for the elimination of the terms in Equation 5-1 concerning the differences in price and differences in car attributes. A difference between supplying V2G by EVs and the CPPP is the fact that CPPPs are centralised locations and the destination and parking location of drivers might differ. We will use estimations of the monetary value of time of drivers to include this effect in the decision. Valuation of the average walking distance by foot between CPPP and final destination is dependent on the exact location of the CPPP and the relevant urban architecture. Knowledge on these aspects is lacking and obtaining this knowledge falls due to time reasons outside of the scope of this project. We assume that if the CPPP is located near homes the driver will be required to walk 5 minutes. If the CPPP is located near offices the drivers were already required to walk some distance and no additional disutility is experienced from parking at the CPPP. The specific value of time used is €18/hour based on (Small, Winston, & Yan, 2005). The value function for the choice to use the FCV for V2G becomes:

$$\mathrm{U}_{V2G,i} = \beta_0 + \beta_\mathrm{y} \mathrm{y}_\mathrm{i} - \beta_i z_i + \varepsilon_\mathrm{i}$$

Equation 5-2: RUM model for choice of facilitating V2G with an owned FCV

Where;
i =1 for C-EV, i =2 for V2G-EV.
β_0 is a constant that captures an average effect of V2G-FCVs versus C-FCVs.
y_i is a vector containing the V2G contract terms: required plug-in time and annual cashback payment
z_i the required traveling time by foot between CPPP and destination
ε_i is the error term with a mean zero and standard deviation 1.

We can simplify the preference vector y_i as some aspects of V2G for EVs do not apply for the V2G case of FCVs. In the model of Parsons et al. (2014) y_i included minimum guaranteed driving range, reflecting a certain threshold of the state of charge of the battery. Due the high energy density of hydrogen we assume that the FCVs can be refuelled to full capacity within minutes, and thus perform equally as good as ICVs on this aspect. This allows for the elimination of the minimum guaranteed driving range aspect from the vector y_i.

2) Car drivers considering buying an FCV or ICV

Unlike in the case of the experiments done by Parsons et al. (2014) we do not aim to force our virtual car driver to choose between adopting a CPPP parking behaviour or not at the time of buying the car. However the advantages of parking at a CPPP might play a role in the comparison between ICVs and FCVs. This influence is included by adjusting the beliefs of the fuel costs per car type. Drivers that park their car at CPPPs will incorporate the financial advantages in the fuel costs of their FCVs. As this information is diffused the average belief of fuel cost savings will include the role of the CPPP in the system. We then obtain a value function as below:

$$U_{cartype,i} = \beta_0 + \beta_p \Delta p_i + \beta_\chi x_i + \varepsilon_i$$

Equation 5-3: Adjusted RUM model for decision between buying FCV or ICS

Where;
i =0 for ICV, i =1 for FCV

β_0 is a constant that captures an average effect of ICVs versus FCVs.

Δp_i is the price difference between the ICV and the FCV.

x_i is the vector containing conventional the FCV attributes: pollution reduction and fuel cost savings.

ε_i is the error term with a mean zero and standard deviation 1.

The attributes of reduced driving range, performance difference and reduced charging time are found to be significant in the comparison between EVs and ICVs as made by Parsons et al. (2014). These factors are of much less importance when comparing ICVs and FCVs. We assume FCVs to have a driving range and refuelling time that is not significantly different to that of ICVs, allowing the elimination of these aspects from the vector x_i[8].

Value functions for TSO

The TSO is in our case a simple demanding entity that contracts a CPPP if it is financially offering the most attractive option. We here simplify the electricity market as being one party being the TSO. This simplification results in the TSO also being the party with a demand for peak load electricity. Formalising the actual contracting process would be to have the simulated CPPPs determining a bid price for supplying its services, have the TSO comparing this price with the other offers and make the TSO choose a bid. The process of determining bids by the CPPPs is however very complex due to the influences of factors such as uncertainty, past losses and future expectations.

By making the additional simplification that the TSO is a price taker we can inverse the actual decision making process and bypass the formalisation of the complex process of bid determining. In our case we can ex-ante already assign the specific contract to the CPPP at a fixed price scheme. This price scheme would be the current competitive price of the other bidding parties and is an external parameter. The freedom of using simulation allows us to have the virtual CPPP produce the contracted service for this price, even if it results in (excess) long term losses for the CPPP operator. We can then ex-post evaluate the profitability of operating the CPPPs under the specific contract and draw conclusions on the viability of the used CaPP design without the need of determining a value function for the TSO.

Value functions for CPPP operators

With respect to the design of the CPPPs as described in section 4.4 we implement an internal decision dynamic within our model. The technical part of the CaPP design is unlikely to be altered during a simulation run due to sunk costs. In reality the institution part of the design could however be altered within the time period of a year. We neglect this possibility for the sake of simplicity of our model and the ease the different designs can be compared after running the simulations. Once the CPPP has been introduced in the market, the CPPP operator will periodically be confronted with two operational choices:

1) *Determining capacity of upcoming contract*

Given the type of electricity service the CPPP is aiming to produce for, the requirements and basis for remuneration are different (see section 4.3.2). All use cases work with contracts that are closed at least one day ahead of the actual service provision. This requires the CPPP operator the estimate the availability of FCVs in his CPPP upfront. We assume

[8] This leads to the adjustment of the constant, as in the model of Parsons et al. (2014) the effects of driving range, charging time and performance difference are negative for the EV option.

that a CPPP operator will rely on its memory of the availability of FCVs in his installation. Based on this information he can estimate what the available production capacity can be for each quarter of an hour.

2) Determining hydrogen system operation

Hydrogen is required for the instant production of electricity with the available FCVs and to refuel the FCVs if they are about to depart. The CPPP will have to aim for appropriate hydrogen availability at all times as cheap as possible. The CPPP operator can chose between the production of hydrogen from natural gas and from electricity.

5.2.6 How are the options characterized in the model?

From all the different attributes a selection has to be made of the attributes that are relevant for the analysis and the model. The AOF suggests using two classes of attributes in order to structure the mapping of relevant attributes:

Option attributes related to the decision making of the actors

We defined different value functions in section 5.2.5. The calculations of the value functions are based on different aspects of the options, which as a result will need to be incorporated in the model. Derived from the value functions we can thus list a first set of attributes which we need to formalise within the model. Below we discuss the two different value functions and the option attributes related to them.

Car drivers considering using the services of a CPPP

Derived from (Parsons et al., 2014) with the addition of a centralisation effect of the CPPPs with respect to conventional V2G services the following attributes of the options of using CPPP services are to be considered:

- Required plugin time [hours per day]
- Cash back [€/yr]
- The time it takes to walk from the CPPP to the destination [minutes]

As discussed in 5.2.5. our list of attributes is shorter than that of Parsons et al. (2014). Parsons et al. (2014) included minimum guaranteed driving range for V2G EV's which can influence the drivers comfort as the charging time of EVs is significant. For the case of FCVs, the refuelling time is comparable to that of ICVs which allows adjusting the minimum driving range to a full fuel tank within minutes. As a result we do not expect any discomfort related to a minimum guaranteed driving range for V2G FCVs and thus exclude this attribute.

Car drivers considering buying an FCV or ICV

Derived from (Parsons et al., 2014) and under the assumption that we can substitute EVs with FCVs on attributes in which there are no functional differences, the following attributes of the two options are of importance:

- Price FCV [€]
- Fuel costs FCV [€/km]
- Pollution FCV [kg $CO_{2\text{-eq}}$/km]
- Price ICS [€]
- Fuel costs ICS [€/km]
- Pollution ICS [kg $CO_{2\text{-eq}}$/km]

Again we have excluded attributes from the list as presented by Parsons et al. (2014) due to the comparable energy density of hydrogen with respect to gasoline. Where there is a significant difference found by Parsons et al. (2014) between the perception of possible driving range, the acceleration rate and charging time between ICVs and EVs, we do not foresee these attributes to be significantly different when comparing ICVs and FCVs. This allows for the elimination of these attributes in our model.

CPPP operators operating their hydrogen system

For the CPPP operators to determine if they should be producing additional hydrogen and from what source this production should be based on we let the CPPP operators monitor the following attributes

- Available production capacity
- Available hydrogen in storage
- Expectation of required storage for the upcoming day

- Expectation of electricity prices for the upcoming day
- Expected FCV availability for the upcoming day

Option attributes related to the performance of the system.

Besides attributes related to the internal dynamics of the system, additional option attributes might be required to calculated important system variables that are to be analysed ex-post. For our purposes we require information on the financial performance of the CPPPs and will thus monitor the following attributes:

- Cumulative system pollution
- FCV ownership percentage
- CPPP service usage

5.2.7 Which mechanisms are 'active' in the analysis context?

The web of mechanisms is within the AOF expected to mimic the complex dynamics of socio-technical systems. A mechanism has three important aspects: a trigger, a time-scale and a specific consequence. Yücel (2010, ch. 5) has identified a set of ten types of mechanism that can be expected in socio-technical systems. Below we follow the categorisation of Yücel (2010) and very briefly discuss each mechanism for our case.

Mechanisms related to option properties

The properties of options might be dynamic over the time horizon of the analysis. Changes in the system might affect the properties of the options via the following types of mechanisms;

Experience driven change in option properties

Based on the knowledge gained by the actors as a consequence of accumulated historical (practical or provisional) experience, the option might be developed. Alternatively this mechanism is known as the "learning-by-doing" or "learning-by-using" phenomenon. For the case of CaPP the CPPP operators will gain knowledge on the past realised availabilities of the FCVs in his installation and is expected to accordingly estimate and determine an attractive operation plan for both electricity and hydrogen production. We do not foresee an influence of the car drivers on the different options based on gained experience in a simulation.

Scale-driven change in option properties

The scale of utilization or provision of the options could affect respectively the efficiency of the provision or the effectiveness of usage. In the CaPP case an example of scale-driving change would be a change in remuneration of the drivers parking at the CPPP. However in section 4.3.3 we have excluded this possibility for the remainder of this study, resulting in no scale-driven change is expected concerning this interaction. Also at the other elements and sub sections of our system identifications we do not foresee this mechanism to be active.

Resource-driven change in option properties

The provision of the options might change if the actors deploy resources they possess, such as financial, time or knowledge. Examples would be investing in the electricity grid, allowing for more water to be electrolysed per second. Seeing that we do not envision an active role of an actor with influences on the infrastructure, we do not foresee any resource driven mechanism to be active.

Exogenous change in option properties

Triggers coming from outside the system might influence how different options are offered within the system. For simplicity we neglect the possibilities of exogenous interference. For instance we will not include the possibility of automated driving during the studied timeframe.

Mechanisms related to actor perception

The choices by the actors are not based on the factual properties on the options, but on how the actor perceives these properties. This results in the possibility that the actor is basing decisions on incomplete or even incorrect information.

Furthermore the pace at which new information is taken in might play a role and result in internal delays in the system. Mechanisms that result in change in the perceived information of an actor are thus of importance as they can shapes the actors' behaviour. The mechanisms that relate to the actors' perception are intended to have effect similar to the 'gathering of new information' and correspond to single-loop (or first-order) learning (Yücel, 2010). More complex forms of learning, which result in the actor actually adjusting the way he makes decisions, are discussed later.

Individual learning

Actors can update their knowledge by direct observation or by experience. An actor can through this mechanism gain knowledge on the existence of options, learn about the properties of the options or gain knowledge about the state of the system. For our research the updating of the knowledge on the existence of CaPP is important, as we will only introduce the option after a short time simulation in order to give the model some start up time. Experience based learning for the drivers can occur after driving a particular car type for a while or use the services of the CPPP. If they have any incorrect information on these options, such as the remuneration offered by the CPPP or the fuel costs of an FCV, these will be corrected.

Social learning

Another source of information gathering is through information diffusion among agents. Information is then diffused from a 'source' group to a 'target' group. Yücel (2010) mentions the importance of acknowledging the heterogeneity of the source group. This is with our approach with an ABM well covered. Information diffusion in the CaPP case is likely to be present among the drivers. Experienced satisfaction on car and CaPP performance is expected to be exchanged on a regular basis.

Learning from external sources

Marketing campaigns, news or reports are also sources from which actors could gather new information. We do not foresee a learning role for external sources in the CaPP case.

Mechanisms related to actors' behavioural identity

Yücel (2010) defines the behavioural identity of an actor as the actors' references, commitments and preferences. If these change the decision making mechanism of the actor himself changes and thus how the actor behaves under certain conditions. Mechanisms that mimic such change can be categorised as double-loop (or second-order) learning. The formalisation of these mechanisms is somewhat problematic as they are social processes. What is the metric of the input, and what value can we give to the output? Yücel (2010) evaded these questions by referring to these processes as black boxes. Where with respect to the MLP the AOF opens more black boxes, this is the identified limit of including detail by Yücel. For the level of analyses as executed with the AOF, Yücel (2010, p. 83) states that "the regularity of the phenomena suffices, and it can be used as an atomic unit of analysis in the context of transitions."

Reference formation and change

Options are by actors evaluated with respect to a reference point. This point can be different from actor to actor. An option that is significant less attractive than the reference point, is not likely to be considered by an actor. Reference points can as a consequence result in long term lock-in situations, like the case where the EV is often depicted as non-satisfactory as the consumers are used to the driving range from the current gasoline vehicles.

We here see a clear difference between the original purposes of the AOF and our purpose. Reference change is said to be an important process that influences transitions. Our scope is however much more on a short time frame during which we and also Yücel (2010, p. 83) assumes the references of actors to be static.

Commitment formation

Commitment can result in resistance of an actor to a certain choice due to actions taken in the past, even if the other option is the rational thing to do. Commitment forming is related to (the perception of) gaining intangible or tangible assets with respect a certain option. The usage of a certain modelling programme might make the actor believe that he has gained useful know-how knowledge concerning this programme, or he has already purchased this programme.

Gaining either type of asset might result in a commitment for using this modelling programme next time, even if it might not fully suit the research in question.

In the CaPP case commitment formation occurs when drivers have bought a car. We find it unlikely that the drivers will replace their car when it is relatively new, signalling an expected commitment of drivers to the owned cars resulting from made investment.

Other forms of commitment that one might identify are the experience gained by drivers from using a certain energy carrier, and the commitment following from the made investments for the CPPP operator. We will however include neither of them. With respect to the type of energy carrier we assume the general perception and experience to be identical to that of gasoline. Inclusion of this effect would require more insight into the perception of drivers to hydrogen and subsequently the behaviour of drivers when confronted with the option. With respect to the investment made by the CPPP operator, formalising some sort of commitment to made investments would naturally result in formalising possible choices made with respect to this investment. Particularly for our research we do not want an endogenous influence on the CaPP design as we are interesting on its performance on the medium-term. If a commitment is not allowed to influence any decisions made within the model, it does not pay to formalise it accordingly.

Preference structure change

The preference structure has been discussed in section 5.2.5 and is essentially a construct that can be used to weight different aspects against others. A change in the preference structure would signal a shift in the perception of the actor with respect to the priority of aspects or issues. For our in 5.2.5 defined value functions a change in preference structure of the drivers would for instance meaning that due to a certain event, certain drivers will start valuing the costs of a vehicle more with respect to its environmental performance.

Similar to the argumentation as used above when discussing reference change, we see a difference between the application of the AOF for transitions and the application of the AOF for system innovations. The shorter timeframe allows for the assumption of a constant value function (Yücel, 2010, p. 86).

5.2.8 Addition: definition of time step

Although not explicitly dealt with in the AOF we here define our time step for our model. We find such a definition of a time step however of great importance seeing it has a high impact on how we conceptualise different dynamics.

For our purposes of testing different CaPP design options we require a model of the operational side of CaPP. For determining if certain designs are viable we have to simulate an economy in which CaPP has been implemented for several years. The main dynamic of interest is however whether the availability of the FCVs in the CPPP matches the use case of the CPPP. Whether and to which extend this match is achieved will be determined on a real time bases (in the order of seconds). Running a model with a time step of seconds for several years will however require a computational power that is beyond our limits. We therefor will have to simplify the FCV availability to a larger time step that does allow us to compute the effects. We have selected a time step of 15 minutes as this is the same timeframe which is used by TenneT to monitor their network and is subsequently also the smallest time scale for which electricity prices relative for our case differ.

5.2.9 Addition: time period of interest

Following from the focus on changes in societal systems, the time scale of the AOF is dependent on when the transition can be said to be complete. This could be one year or several decades. Our model with its focus on the operation of a technical installation does however not have a time scale dependent on the occurrence of a certain event. As such we are expected to define a run time of the model that matches a time period of interest. We have selected a time period of three years to be able to capture middle-long term effects but keep the run time of the model as short as possible.

5.2.10 Addition: "as is" dynamics

For our purpose the direct effects of the changes in driving behaviour are of large importance for the operation and subsequently the development of the CPPPs. As we now have gone through all steps we find ourselves lacking a description of the base dynamic of our model. The AOF relies heavy on the dynamics that are the result of choices made by the actors concerning options. However in our case the usage of the options, i.e. driving the cars is of large importance to determine the (possible) availability of the cars for a CPPP. Within the AOF we have not found a cause to define this behaviour that is not directly related to actors choosing between different options. For our scope we do define the dynamic here.

We are mainly interested in the availability of the cars and need to track whether the car is in use and when it is parked. We here assume that during the weekdays the cars are used to commute to and from work at set predetermined times. In the weekends also everyday one trip is made with the car to a random destination. This simplification of driving behaviour is an important one as it might have large influences on the car availability and as the success of the CPPP.

5.2.11 Addition: operational KPI's

The AOF suggests defining the aspects of the social need that would have changed after a transition to assess if a transition has taken place. For our purposes this measure is meaningless as we do not intend to specifically observe the change process. Instead we aim to gain a better understanding of the performance of the installation during the time period of three years. We have used different alternative key performance indicators of which the Return on Investment for the CPPP owner was chosen to be the major outcome of interest. For this purpose we have included additional attributes that are to be monitored. These attributes are the cumulative operational revenues and the cumulative operational cost made by the CPPP.

6. Formalisation

By using the AOF we have identified a system that we expect to be fit for this case study. This chapter reports on the steps of formalisation as intended in Van Dam et al. (2013). These steps result in a model definition that we can code in a modelling language. The concept formalisation is discussed in the first section of this chapter. For this step the entities of the system as we intend to model it are made explicit. The second step of formalisation defines how and when the entities act and interact and is described in the second section. An overview of the assumptions that are used in the formalisation and preceding steps is presented in 6.3. The last three sections of this chapter describe the steps of actually constructing the model and the verification and validation of the model. For all these sections we again adopt the approach of Van Dam et al. (2013). The descriptions as given below are the results of various iteration steps.

6.1 Concept formalisation

The phase of concept formalisation forces the modeller to precisely define the different aspects of the model with the result that the model is computer-understandable but also some formalisations choices and simplifications are explicitly reported.

Types of agents

In section 5.2.4 we identified three important agents: Drivers, CPPP operators and TSO's. The role of the TSO is a simple buyer of services for which we do not need a separate agent class. The TSO is for our study not an entity with its own behavioural rules.

For the ease of programming we have chosen to add two other agents besides the CPPP and the drivers. These are the households (homes of the drivers) and the offices (the most used destination of the drivers). Besides existing in the world and serving as regular destination for the drivers the office and household agents do not have any functions.

The model is thus to include four types of agents; Drivers, CPPPs, households and offices. Of these agents only the Drivers and CPPPs have behavioural rules and act and interact. An overview of the different agents and their relations is given in Figure 6-1.

Variables and attributes

Within the model, numerous variables are used of which many are derived from the description as given in 5.2. The different attributes and others that were found to be useful or required during several iteration steps are included in Figure 6-1. Additional information in the form of a software data structure concerning the variables can be found in Appendix D. The software data structure gives insight into the unit and the range of allowed values for each variable.

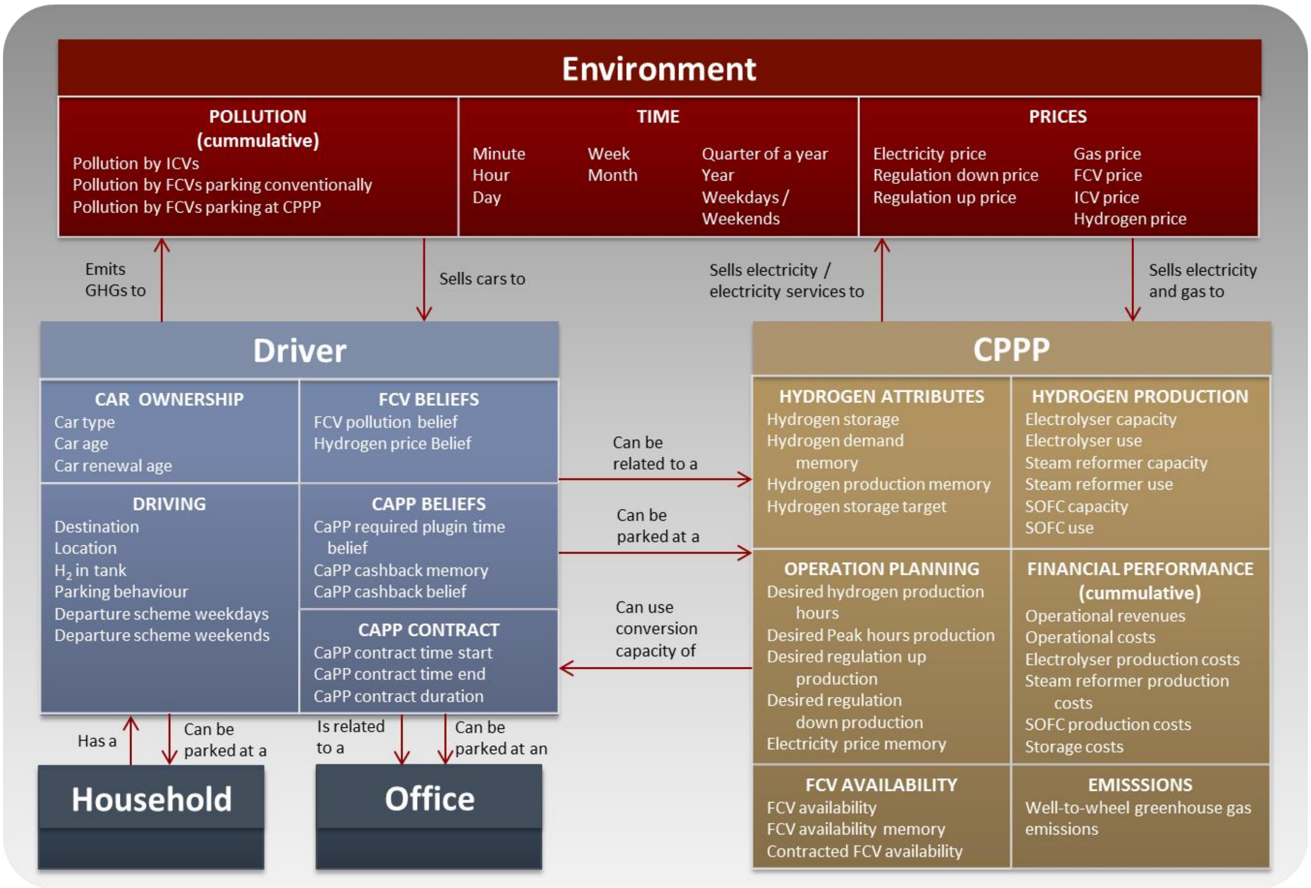

Figure 6-1: Model elements, attributes and relations

6.2 Model formalisation

This section focusses on the interactions between the elements as defined in 6.1. With the guidance of the AOF we have established the dynamics of interest for our studyThis chapter links the dynamics as identified with the elements 6.1 of by establishing when which agent does something with potentially someone or something else.

There are two types of agents that are actively making decisions in the model; the car drivers and the CPPP operator. The time step of our model is 15 minutes, while the time period of interest is several years. In order to build a model that can run experiments within feasible time limits, we have to carefully design the logic of our model. The logic should be such that irrelevant computations (or even the checks if these computations are required) for the current time step are brought to a minimum. This is a particular hazard in our case as there are different mechanisms operating at different time scales.

We have setup a control logic that calls mechanisms only when the time dimension that matches the time scale of the mechanisms is advancing. To give an example, the electricity price is changing every hour in our model. Thus only when a new hour starts (and not when the clock goes from a quarter past to half past the hour), the mechanism to update the electricity price is called. We base our narrative on this control logic and will use it as the structure for this section. A full overview of the control logic and the mechanisms called per time dimension is given in Figure 6-2. Subsequently the mechanisms for each time dimension are discussed separately.

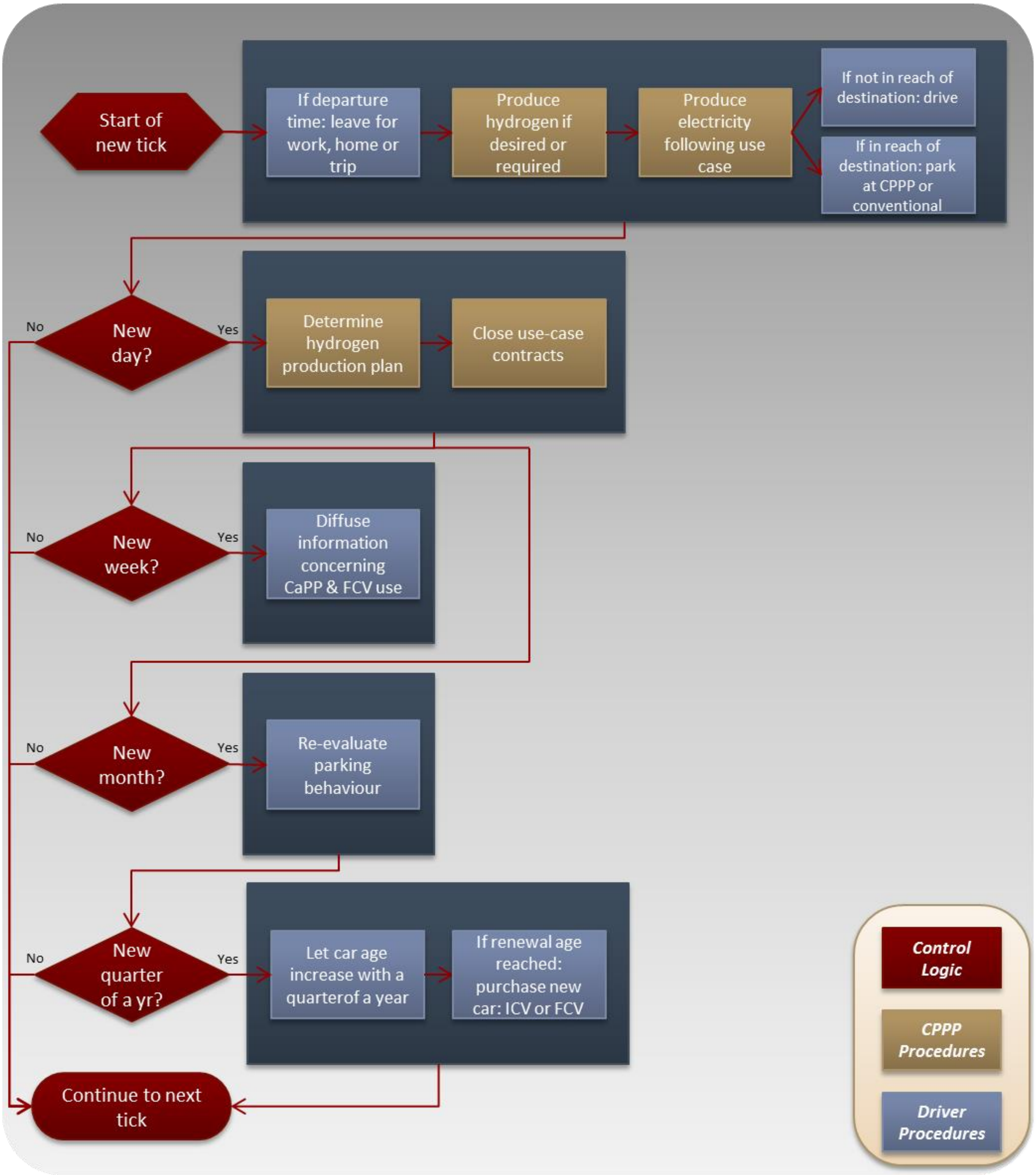

Figure 6-2: Model sequencing.

6.2.1 15 minutes procedures

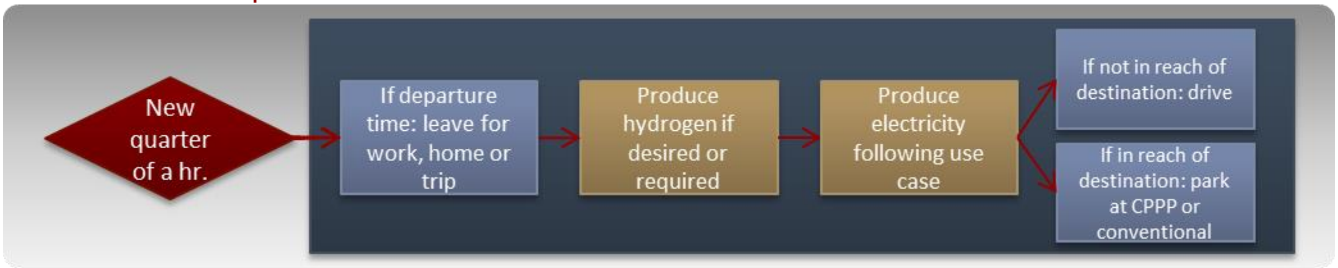

Figure 6-3: 15 minutes procedures

Driver: daily movements

For the daily operations activities that influence the state of the car (driving or parked at certain locations) are of interest to us. This leads us to limit our model to the activities that involve car movements. We assume that the driving patterns of the drivers are constant over the different types of days. Although not made explicit in the overview as presented above, the control logic is to signal the drivers if the current day is a weekday or part of the weekend.

Weekday movements

If the current day is a weekday, we assume that the drivers will commute to work and back to home. The movement from home to work is assumed to be somewhere between 04:00 and 12:45. All drivers at work leave for home again somewhere between 13:00 and 23:45. The distribution of departure times among the agents is based on data of the Dutch Central bureau of Statistics (CBS, 2014b) for commuting traffic for persons over 12 years of age.

If the driver departs from a CPPP, he has to tell the CPPP the car is leaving and extract a full tank of hydrogen from the reserves of the CPPP. We assume that the refuelling time of FCVs by the CPPP is negligible.

Weekend movements

To prevent the illusion of complete availability of the FCVs during the weekend we will movements of the drivers during these days. We assume that each driver will depart for a trip at each day of the weekend. The departure times of these trips are assumed to be between 09:00 and 15:00 so that no driver will depart for a trip if night is about to fall. The duration of the trips is between one and eight hours. If the driver has a parking obligation due to his contract with the CPPP, the departure times and duration of the trips are adjusted to comply with this obligation.

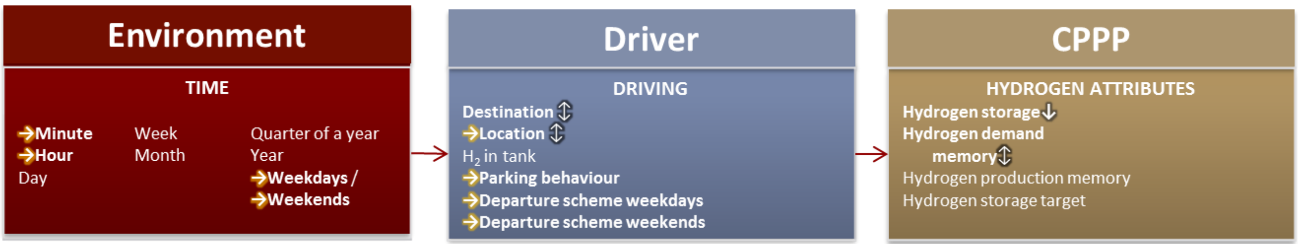

Figure 6-4: States used (yellow arrows) and states possibly affected (black arrows) by the daily movements procedure.

CPPP: produce hydrogen

At 00:00 each day a new hydrogen production plan is determined (see 6.2.2). This plan includes the hours during which the CPPP would like to produce hydrogen. If the current hour is part of the production plan and/or if the hydrogen reserves of the CPPP are below acceptable levels, the CPPP will produce hydrogen these fifteen minutes. We use a conservative assumption for determining the acceptable storage level for the CPPP: it will always pursue to have enough hydrogen in storage to be able to refuel the maximum amount of cars that it can house. For a CPPP with 500 parking spots this means a storage target of 2500 kg. Although this target is high, it is expected to have little effect on the direct operation of the CPPP as storage costs are only calculated when a kilogram of hydrogen is to be stored, and we have assumed an unlimited large hydrogen storage capacity. Furthermore, as we will see below, the amount of hydrogen that can be used to produce the electricity services is the excess hydrogen that is available on top of the target level. In other words only the refuelling of the FCVs can result in the hydrogen storage of the CPPP to drop below the target level.

As the CPPP is in our model an entity pursuing maximum profits, it will assess the hydrogen production methods it possesses and the current production costs. It will consequently select the cheapest method to use. Here the case of the SOFC will be special, as the CPPP will have to decide what to do with the possible produced electricity. We assume that if there is an electricity demand that can be fulfilled the electricity is used to (partially) fulfil this demand. If no electricity demand is present or if there is residual electricity, we assume that this electricity will be fed to the electrolyser to mitigate the need to purchase electricity from the market. In both cases the costs of production with the SOFC will be adjusted to incorporate these possibilities.

Once the cheapest production methods are determined, the amount of hydrogen that will be produced is limited to either the desired amount or the capacities of the production methods. The costs (and possible electricity sales revenues) are calculated and added to the balance of the CPPP.

We assume that not all hydrogen has to be stored, and that on average only storage is required if hydrogen demand and supply of the current hour do not match. So if the hydrogen was produced at 05:10 but used at 05:50 we assume no compressed storage was needed.

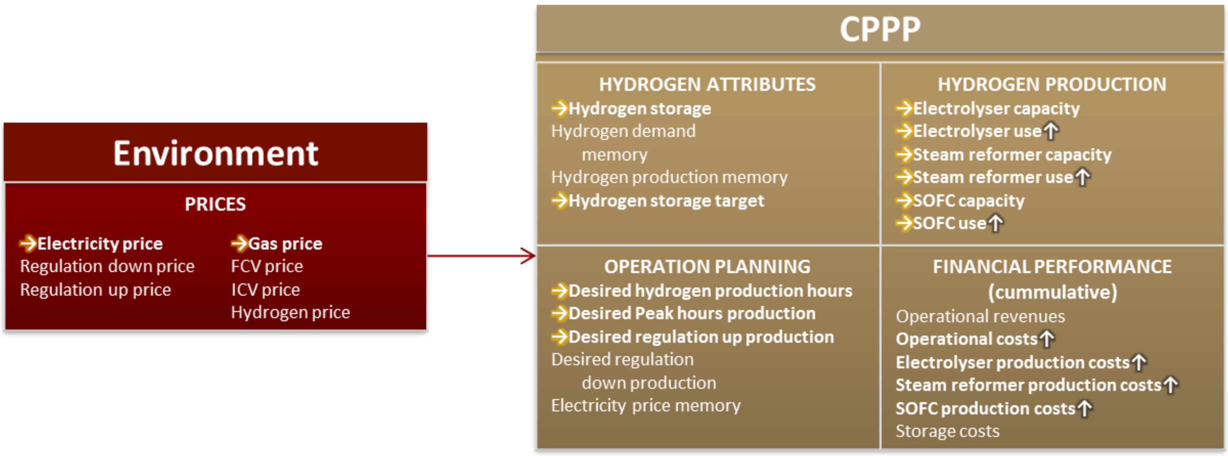

Figure 6-5: States used (yellow arrows) and states possibly affected (black arrows) by the produce hydrogen procedure.

CPPP: Execute Use case

Depending on the type of use case present, the operation of the CPPP will differ.

Peak load production

During the night the CPPP will construct a list for which quarters of hours it intends to produce electricity. If the CPPP desires to produce electricity this hour, it will assess the amount of FCVs that are available for production and the amount of hydrogen that it can use. This amount of hydrogen is limited such that the amount let in storage will be at least at the target level as discussed above. The amount of electricity produced will be the desired amount of production limited by possibly the amount of conversion capacity available (parked FCVs) or the amount of hydrogen in storage. The sales revenues will subsequently added to the balance of the CPPP.

Secondary control: regulation up

The times during which the CPPP desires to produce electricity for this purpose will also be determined during the night; however the price for regulation up services at this quarter of an hour must be positive (i.e. TenneT gives a regulation up signal). If the CPPP desires to produce electricity at this time step and there is a regulation signal coming from TenneT, the CPPP will produce electricity identical as how it would for the peak load production as described above.

Secondary control: regulation down

Also the production plan of regulation down is established during the night. If the plan includes the current quarter of an hour and if there is a negative regulation down signal (i.e. TenneT pays contracted parties if they increase demand) the CPPP will use the available electrolyser capacity to produce the hydrogen. The hydrogen is added to the storage and the revenues are added to the balance of the CPPP.

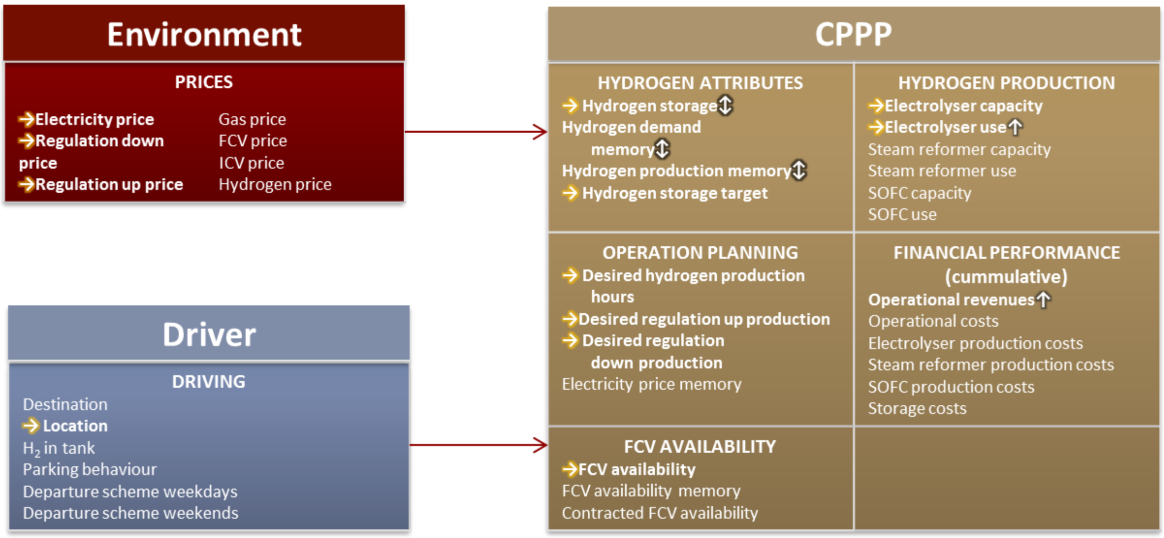

Figure 6-6: States used (yellow arrows) and states possibly affected (black arrows) by the execute use case procedure.

Drivers: Drive

If the drivers have departed from home or work, they will take a while to reach their destination. The duration of commuting movements is on average roughly 30 minutes (CBS, 2014b). This means that in two time steps the average driver can travel from home to work and vice versa. If a driver can reach his destination in the upcoming time step, we assume that he arrives at the end of this time step. Based on his parking behaviour (discussed below) he will park his car in the adjacent CPPP or on a normal parking spot. If the car is parked in a CPPP the hydrogen in the tank is given to the CPPP for use, and the FCV can be exploited for the use case of the CPPP.

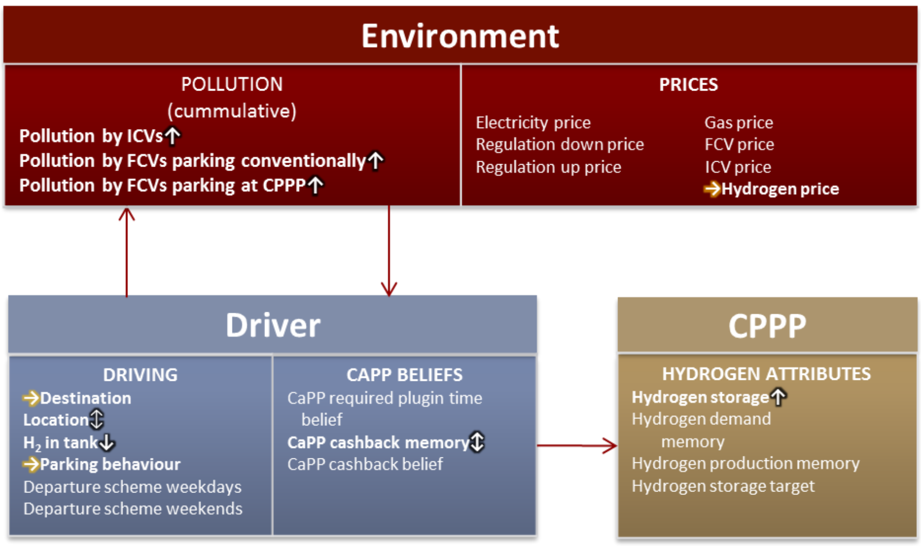

Figure 6-7: States used (yellow arrows) and states possibly affected (black arrows) by the drive procedure.

6.2.2 New day procedures

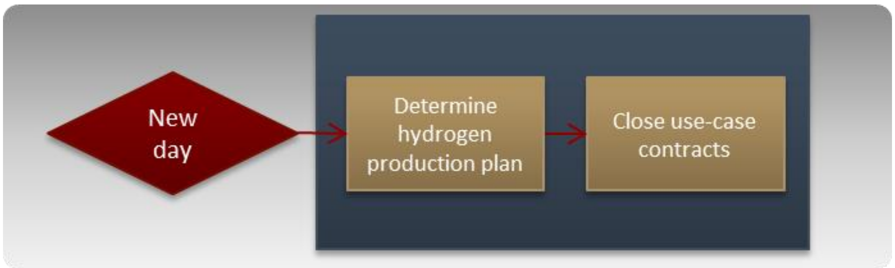

Figure 6-8: new day procedures

CPPP: Determine hydrogen production plan

In the hydrogen production plan the CPPP lists the hours for which it desires to produce electricity. It will calculate the desired production of the upcoming day based on his memory which we assumed to last for 30 days. For the hydrogen production plan, the CPPP determines the average hydrogen demand of the last 30 days. The amount of hydrogen the CPPP wants to produce is then the expected demand minus the available amount of hydrogen that is in storage at this moment. The available amount of hydrogen is the total stored hydrogen minus the target level (discussed above).

The hours that are selected during which the CPPP aims to produce hydrogen is again based on its memory. The CPPP will determine the average electricity price per hour of the last month, and will select the cheapest hours for the production of electricity. Note that this is not an advanced control strategy, and more effective but complicated strategies should be constructed. A reflection upon the used control strategy is presented in 8.2.3.

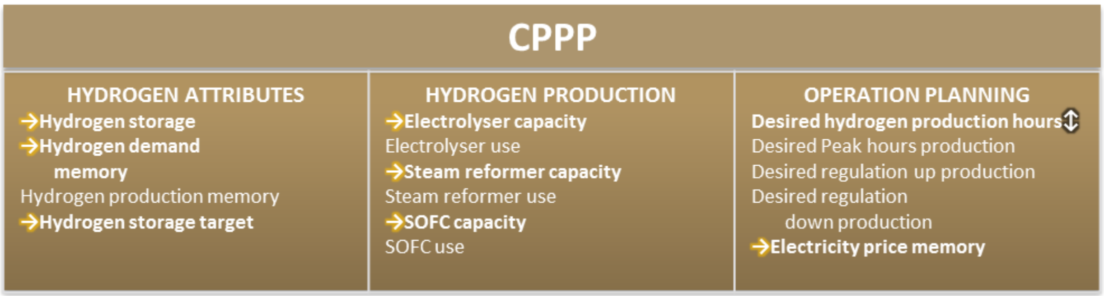

Figure 6-9: States used (yellow arrows) and states possibly affected (black arrows) by the determine hydrogen production plan procedure.

CPPP: close use-case contracts

For both use cases the CPPP has to close day-ahead contracts. We assume that the CPPP can close these contracts at midnight. Furthermore we assume that CaPP can close contracts and will not get fined if it does not meet the contract obligation (i.e. it cannot produce the electricity at the contracted times).

Peak load contracting

Based on its 30 days memory, the CPPP will determine the average amount of FCVs parked in the installation for each quarter of an hour for the peak hours. The desired production per quarter of an hour of these peak hours is the amount of FCVs parked times the production capacity of the FCVs, which is 25 kWh per 15 minutes (see Appendix E). The peak hours are the hours between 09:00 and 20:00 following the definition of the APX group (2015). If a parking obligation is in place, the CPPP does not have to rely on its memory but can simply base its plan on the amount of contracted cars per quarter of an hour.

Secondary control contracting: regulation up

Besides the times for which the production plan is constructed, the estimation of the desired production is identical to the peak load contracting process. As regulation signals can come at any time of the day, the plan is not restricted to the peak hours.

Secondary control contracting: regulation down

The available capacity for regulation down is at all times the maximum amount of electricity the electrolyser could process. As we assumed that the CPPP will only react to negative secondary control prices (prices for which the CPPP gets paid to use electricity), the CPPP will desire to respond to all secondary control signals independent of time. Exceptions for these times are the hours for which the CPPP has planned hydrogen production. Again this is a relative simple algorithm which can be improved.

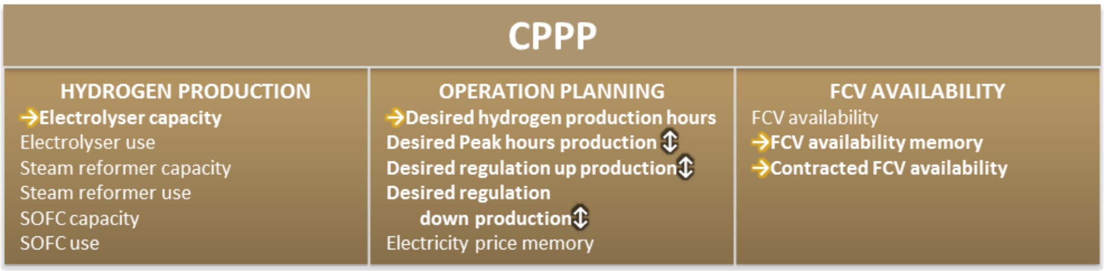

Figure 6-10: States used (yellow arrows) and states possibly affected (black arrows) by the close use case contracts procedure.

6.2.3 New week procedures

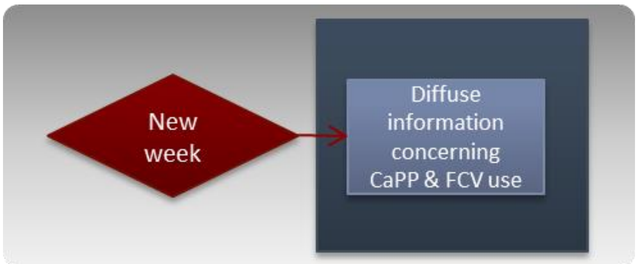

Figure 6-11: new week procedures

Driver: Diffuse information

In the model we have included a social mechanism to mimic the information diffusion among agents. Agents are expected to influence each other's beliefs. The beliefs that are of interest for our study concern the beliefs used by the agents on which they base their choice for a type of car and the choice of adopting a CaPP parking behaviour.

The time scale of the social mechanism is assumed to be weekly. The mechanism that is used is based on the explorative model as used by Yücel and van Daalen (2009). This model assumes that a group of source agents and target agents interact with one another on a regular basis. During this interaction information from the source agents is conveyed to the target agents. The target agents will adopt this information based on the word of mouth ('how often they hear the information'; mimicked by the share of source agents in the total population), a learning delay and an information gap (the 'strength of the message').

For our purposes we assume that information diffusion occurs between colleagues of the same offices once a week. Information concerning CaPP or FCVs is then diffused by drivers which respectively currently park at the CPPP or drive an FCV. The value of the learning delay is adopted from (Yücel & van Daalen, 2009) and is 5, resulting in only 20% of the difference in information being processed.

To illustrate the working of the social mechanism the following example can help. A target driver believes that the hydrogen price for FCVs is €10/kg and a source driver knows this price to be €4,75/kg. Furthermore the learning delay is 5, and the share of the source group in the total population is 40%. If the source agent then diffuses his knowledge to the target driver, he will be confronted with an information gap of €6,25/kg. The learning delay and the strength of the word to mouth results in the target driver to adjusts his belief with 6,25*0,40*0,2 = 0,5. The resulting belief of the target driver becomes €9,50/kg.

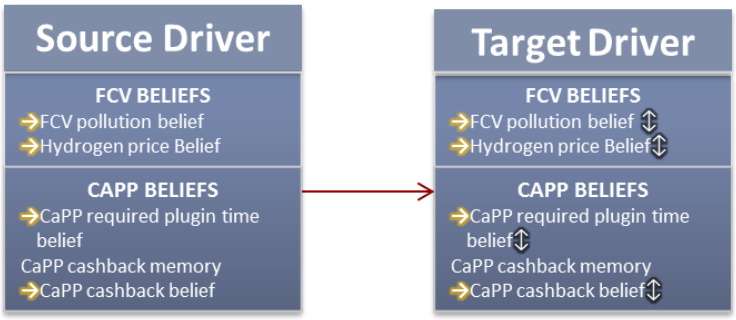

Figure 6-12: States used (yellow arrows) and states possibly affected (black arrows) by the diffuse information procedure.

6.2.4 New month procedures

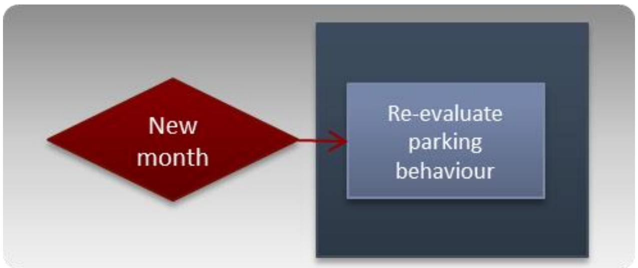

Figure 6-13: new month procedure

Drivers: re-evaluate parking behaviour

At the beginning each month, drivers will rethink their current parking behaviour. Based on the value function as discussed in 5.2.5 and possessed information of the driver at that moment in time he will either chose to use the CPPPs for parking or the normal parking spots. We here thus assume that a reconsideration of once a month will be adequate to mimic the reality. In reality the timing of this assessment is likely continuously.

If a parking obligation is in place drivers who will newly adopt the CaPP parking behaviour will have to determine the contracting times of the obligation. We assume that these times are dependent on the commuting behaviour of the driver and that the driver will demand thirty minutes of flexibility at both the starting time and end time of the obligation (i.e. he can arrive thirty minutes after his usual arrival time, and can depart thirty minutes early). Furthermore drivers who no longer park at the CPPP will have to tell the CPPP to adjust its list of contracted drivers.

When drivers adopt a CaPP parking behaviour they will learn through experience how long they are required to make their car available to the CPPP (required plugin time), how much they in the future will play for hydrogen (which is zero as they receive it from the CPPP for free) and how much pollution their FCV will produce with the hydrogen as produced by the CPPP.

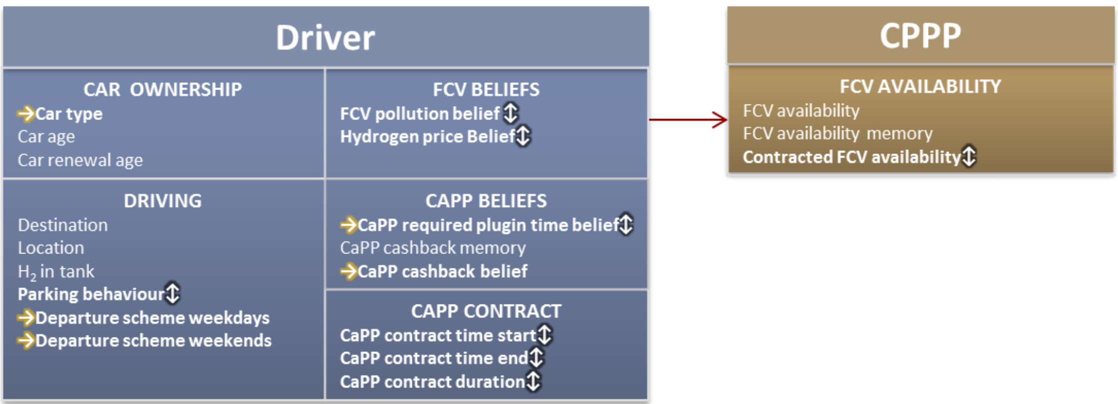

Figure 6-14: States used (yellow arrows) and states possibly affected (black arrows) by the re-evaluate parking behaviour procedure.

6.2.5 New quarter of a year procedures

Figure 6-15: new quarter of a year procedures

Drivers: Let car age increase

We will measure car age in quarters of years. When a new quarter of a year starts the drivers are adding a new quarter to the age of their car.

Figure 6-16: States used (yellow arrows) and states possibly affected (black arrows) by the age car procedure.

Drivers: Renew car if renewal age is reached

If the age of the age of the car exceeds the 'car renewal age' of the car the car driver will renew his car. When the car is renewed the driver assesses ICV and FCV type cars based on his current beliefs and the value function as described in 5.2.5.

We assume that on average drivers renew their car on average once each three years based on data on the car population (CBS, 2014c) and car sales (CBS, 2015b). The car renewal age is assumed to be normally distributed with a mean of 3 years and a standard deviation of a quarter of a year. This results roughly in the renewal of 99,7% of the cars when they reach an age of 2,25 to 3,75 years. For computational time considerations we let the model determine the age at which the driver will renew its car directly when the new car is put in use. The alternative would be drawing a random distribution over all car drivers each quarter.

Figure 6-17: States used (yellow arrows) and states possibly affected (black arrows) by the renew car procedure.

6.2.6 Costs & Environment

The environment of the model supplies the agents with different types of information, such as the electricity prices and the price of FCVs. In this paragraph the formalisation of these elements and their sources is presented. The estimations on which these values are based can all be found in Appendix F.

Electricity prices

Due to different reasons we were unable to use complete historical data for the electricity price. Instead we have constructed our own data set. How this set was constructed is discussed in Appendix F.

Gas price
The gas price has been estimated following data from the CBS (2015a). We assume that the middle large user price of 39 cent per m^3 is applicable for CaPP. This would however require about twelve installations to operate under the same company. A more detailed discussion concerning the height of the gas price can be found in Appendix F.

Hydrogen price
Different governments have set targets for hydrogen production costs to fall below €5/kg (Pollet, Staffell, & Shang, 2012). Our simulation assumes that FCVs have penetrated the market, and we thus subsequently assume that the target production costs have been met. We assume a price of €5/kg for our simulation.

Gasoline prices
The gasoline prices have been very volatile at the time of writing. We assume a gasoline price of €1,70 to be of effect in our simulation.

FCV and ICV prices
A middle class car in the Netherlands was priced around €40.000 in 2014 (Bovag-Rai, 2014). FCVs are expected to cost a factor 1,2 to 1,3 more than conventional vehicles (Veziroglu & Macário, 2013), leading us to assume an FCV price of €50.000.

Pollution
The perception of pollution of drivers is assumed to depend on the WTW efficiencies of the used fuels. We base our estimations on the work of Edwards et al. (2014). The exact estimations per fuel type are presented in Appendix F.

6.3 Overview of used assumptions

At this point we know what, who and how we want to formalise the relevant dynamics. In the past sections we have made several assumptions which we list below for the sake of clarity. The numbers behind the assumptions refer to the section(s) of this report where the respective assumptions originate from.

6.3.1 Technical assumptions

- FCVs are widely available at the starting time of the simulation (1.5).
- A hydrogen infrastructure that is satisfactory for large scale FCV use is in place (5.2.1).
- All FCVs in the simulation are compatible with the CPPP (5.2.5).
- The refuelling time of an FCV is negligible (5.2.5).
- FCVs perform equally as good as ICVs in terms of driving range, refuelling time, and minimum guaranteed driving range when used for V2G services (5.2.5).
- CPPPs operators will not alter their installation during the simulation (5.2.5).

6.3.2 Institutional assumptions

- Issues with respect to permits or the perception of safety among drivers or residents has been resolved when the simulation starts (5.2.4; Appendix B).
- Electricity services are widely available at pre-determined prices, resulting in an endless availability for the CPPPs if desired (6.2.1).
- Peak hours are the hours between 09:00 and 20:00 (Appendix C).
- Day-ahead contracts can be closed at midnight for the upcoming day (6.2.2).

6.3.3 Driver behavioural assumptions

- The consumer choice of Dutch drivers when choosing for ICV or FCVs and when considering providing V2G services can be modelled and described by the data as presented by Parsons et al. (2014) concerning the choice of providing V2G services with EVs by North-American car drivers (5.2.5).
- Drivers who park their FCV at a CPPP near households are required to walk an additional five minutes to their final destination. If the CPPP is located near offices no additional distance is to be travelled by the drivers. The value of time is €18/hour (5.2.5).
- When confronted with a parking obligation, car drivers always adhere this obligation (4.3.3).
- During working days the car is only used for two commuting trips; one from home to work and one vice versa (5.2.3; 5.2.10).
- The departure times of the drivers are the same for each working day (6.2.1).
- Drivers depart from home to work during working days is between 04:00 and 12:45; distributed among the drivers following the data of the CBS concerning commuting traffic of persons over 12 years of age (6.2.1).
- Drivers depart from work to home during working days is between 13:00 and 23:45; distributed among the drivers following the data of the CBS concerning commuting traffic of persons over 12 years of age (6.2.1).
- During weekends the car is used for one trip each day, with a random departure time and length (5.2.10; 6.2.1).
- Reference formation of the actors is static over the simulated time period (5.2.7).
- The perception of drivers towards the usage of gasoline and hydrogen as an energy carrier for driving purposes is equal (5.2.7).
- Information concerning FCV use and CaPP experiences is shared among colleagues of the same office once every week following the mechanism as used by Yücel and van Daalen (2009) (6.2.3).
- Drivers will once every month re-evaluate their parking behaviour (6.2.4).
- If a parking obligation is in place, drivers will demand thirty minutes of contract flexibility at both the start and end times of the contract (6.2.4).
- Parking behaviour is reconsidered once every month (6.2.4).
- When drivers adopt a CaPP parking behaviour they will gain perfect knowledge on how the hydrogen of the CPPP was produced and will be able to perfectly determine the well to wheel pollution by their FCV (6.2.4).
- The renewal age of a car is normally distributed over the drivers with a mean of three years and a standard deviation of a quarter of a year (6.2.5).
- The car age is only assessed when a new quarter of the year commences (6.2.5).
- The drivers have perfect information on the gasoline price (6.2.5).
- Perception of car pollution is based on the WTW emissions of the used fuel (Appendix F).

6.3.4 CPPP behavioural assumptions

- CPPPs will not alter their strategy during a simulation (5.2.e).
- Hydrogen from the arriving cars can be freely used by the CPPP (6.2.1).
- CPPPs will always pursue to have enough hydrogen in storage to be able to refuel the maximum amount of cars that it can house (6.2.1).
- CPPPs can store an unlimited amount of hydrogen (6.2.1).
- CPPPs have a memory of one month concerning hydrogen demand per hour, electricity prices per hour and FCV availability per quarter of an hour (5.2.e, 6.2.2).
- Storage of hydrogen is only required if the hydrogen demand and supply of the current hour do not match (6.2.1).

6.3.5 Other assumptions

- Exogenous events are outside the scope of this research, such as the implementation of autonomous driving (5.2.7).
- The only types of cars in the simulation are ICVs and FCVs (5.2.3).
- The sales of residual heat and clean water do not significantly influence the (financial) viability of the CaPP concept (Appendix C).

- The capacity of the CPPPs is such that they will be required to offer services like centralised power plants do, i.e. CPPPs do not gain an preferred feed-in status like decentralised electricity production (Appendix C).
- We neglect the fines that a CPPP would get if its production at any given time does not match the contract as offered 6.2.2.
- Electricity prices are based on data from 2014 (Appendix F).
- CaPP is excluded from paying excises on electricity (Appendix F).
- CaPP is part of a larger cooperation that can buy gas at the price of 39 cents per m^3. (Appendix F).
- Hydrogen prices for consumers is €5/kg (Appendix F).
- Gasoline prices are €1,70 / litre (Appendix F).
- ICVs and FCVs respectively cost €40.000 and €50.000 (Appendix F).
- WTW emissions are based on the work of Edwards et al. (2014) (Appendix F).

6.4 Software implementation

The model is coded into Netlogo 5.1.0 (Wilensky, 1999). We chose for Netlogo as we had prior experiences with the programme, it has a low entry barrier and a detailed functions dictionary. The model simplicity however results in limitations when complex algorithms are to be used. With future uses of the model in mind, the model has been coded such that it follows the description as given in 6.2.

6.5 Model verification

A model verification step is executed to check if the conceptual model has correctly been translated into the programme. The step consists out of different types of tests that are designed to expose possible mismatches between our modelling intentions and modelling efforts. The model verification has been executed following the approach of Van Dam et al. (2013). We execute the following tests:

- Recording and tracing agent behaviour
- Minimal model testing: sanity checks
- Breaking the agent in a multi-agent setup
- Full model observing

A complete recording of the execution of the tests can be found in Appendix G. The tests have exposed different flaws in the model that have been corrected. The tests that exposed flaws were executed again after the correction. The model passed the test if no new flaws were exposed. At this stage the model passes all tests and we have verified the model.

6.6 Model validation

The approach of Van Dam et al. (2013) includes a validation step after the analysis of the experimentations with the model. Model validation has the goal to assure the modeller and reader that the model as constructed is the artefact that was needed to answer the research questions. We have executed a validation before the experimentation for two reasons:

1) If we find validation issues, we can solve them before the time consuming step of running experimentations.
2) The validation step can already give us some insight into how the model behaves

The validation step has the main purpose of assuring that the model represents a world which we needed to answer our questions. In Van Dam et al. (2013) four suggestions of model validation methods are mentioned:

- Historic replay
- Literature validation
- Face validation through expert consultations
- Model replication

The latter method of model replication is a very strong but intensive effort. It requires the modeller or, even better, someone else to construct a second model of the same system. This allows for a test if the beliefs of the modeller of the first model concerning the system at hand are valid. The time requirement for constructing a secondary model focused on the identical system is too large to be considered for this project. Fortunately Titiaan Palazzi (2013) wrote his MSc thesis in 2013 using a model to study the operation of CaPP. Instead of replicating our effort, we can cross validate our model with the model Palazzi made. The execution of cross validating our model is described in 6.6.1.

The methods of historic replay and literature validation have in common that they reflect on the model based on documented knowledge. Due to the objectives of our study and subsequently our model there are fundamental problems if one would try to use one of these methods. We elaborate on these problems in 6.6.2.

Although expert knowledge on the whole operation of CPPP is not yet available, we would be able to validate parts of our model with the aid of experts. For instance our understanding the working of FCVs or the hydrogen system can be scrutinised by the experts of the green village. Unfortunately we have not been able to use this method of validation due to time limitations.

6.6.1 Model comparison

For his study Renewable Energy Technologies, Palazzi has studied the value V2G concepts can offer for FCV owners. His approach was to use a linear optimisation model to determine the value of the electricity produced by parked FCV cars in CPPPs. The work of Palazzi is similar to ours as its main outcomes of interests are also financial performance, and the operation of a CPPP is simulated on a 15 minute basis. The differences of the two models are on the other hand also significant and are summarised in Table 6-1.

Table 6-1: Overview of most important differences between model as constructed by Palazzi (2013) and our model

	Palazzi	Our work
Method	Linear optimisation	ABM
Time scale	One month	Several years
CaPP technical design	Steam reformer, Electrolyser, FCV's	Based on Spanjer (2014); including secondary devices such as pumps and storage. Also option of using SOFC is explored.
CaPP institutional design	Three different use cases: peak load production, local production & ancillary services	Two different use cases: peak load production & ancillary services. Furthermore driver contracts with obligations are explored
FCV driving behaviour	Three scenarios assuming pre-determined parking times	Dynamic, including choice modelling of car purchase by drivers and determination of preferred parking locations

In comparing calculations as reported in Appendix E we have also found that some fundamental assumptions about the operation of the CaPP differ between the model of Palazzi and our model (based on the efforts of Spanjer (2014)). In particular the natural gas requirement for the production of one kilogram of hydrogen is in the work of Palazzi half the value we used[9]. Furthermore we note that the work of Palazzi does not include verification and validation steps. As a result the scientific value of this step of cross validation is questionable.

Comparing the model of Palazzi with ours should be done with some care due to the differences in system boundaries and some assumptions about the operation of the installation. A validation of comparing model results one on one does not seem appropriate. However we can test if the general conclusions of Palazzi concerning the operation of CaPP are in line with the behaviour of our model. Palazzi (2013, p. 60) concludes that the profitability of using CaPP depends on the costs of hydrogen. If the variable hydrogen production costs are below 1€/kg, all three use-cases can be

[9] The difference between these values is believed to origin from the more comprehensive system demarcation used by Spanjer (2014). For more information see page 85.

profitable. At variable costs of €2/kg the uses cases of local production and ancillary services is still profitable. At variable costs of €3/kg only the provision of ancillary services might be profitable.

Due to the differences in calculations and model scope, we do not attempt to match these exact conclusions to our model. However we can reduce the conclusions of Palazzi to the statement that it can be expected that the provision of ancillary services will be more profitable than the production of electricity during peak hours. The ancillary services as used by Palazzi concern only the secondary regulation up services, where we also included secondary regulation down services. We have tested these conclusions under different scenarios. To be able to compare the runs we have forced our model to ignore the possibility of offering regulation down services.

Our model indeed showed a more profitable financial situation of the CPPPs when using the use case of providing secondary regulation up services than in the case of peak load production. We conclude that our model passes this test on validity by comparing the model to that of Palazzi, and that this test does not suggests adjustments to be made to our model. We should however keep in mind that we have not examined our model under all settings and that no sensitivity analysis has been executed so far. Also no verification and validation steps were reported by Palazzi, questioning the scientific strength of this validation step.

6.6.2 Problems with validation for Explorative Complex Adaptive models

Next to model replication and expert validation Van Dam et al. (2013) suggest two other methods to use for model validation using existing historical, or other documented knowledge. For our purposes using these kind of validation methods have fundamental problems. Due to the innovative characteristic of our research object, research object, there is no historical data, expert insight or literature available to validate our model with. This knowledge is still to be discovered to which this thesis hopefully can contribute. Said differently, if the information with which we could validate the model existed, there would never have been the need to initiate this explorative modelling study.

6.6.3 Fit for purpose validation of modelling process

The alternative to validation with data is to validate if the model as constructed is fit for purpose (Chappin, 2011, p. 149). Fit for purpose validation is an often used method for validating ABMs. Due to its characteristics, an ABM model of a socio-technical system will include a translation of human behaviour to behaviour rules. Such a translation will always be different from reality resulting in data validation to be problematic. We acknowledge that this problem is also present in our study, however this does not exclude that the effort was useless.

Our model is an exploratory model. Such models are characterised by the fact that they focus on problems on which there are numerous knowledge gaps. The exploratory models are used to gain a general overview of these problems and to identify areas for future detailed research (Davis & Tolk, 2007). Our model is in the words of Davis and Tolk (2007, p. 863) a low resolution model on the complex system of CaPP. Given the fact that we have now used assumptions and simplifications concerning a highly complex system, we can say with high certainty that the outcomes of our model will not match with the outcomes of the future system.

However, constructing a computer model has the advantage of forcing the modeller to present the information in a computer understandable format. Saying that CaPP could follow a peak load production use-case is not enough. We have to specify which hours are the peak hours, what is the expected electricity price at this hours, what kind of contracts need to be closed for this use case and when, etc. By forcefully having to consider and formalize all aspects that fall in the scope of the model, the modelling *process* is the main generator of knowledge for this study. The model itself then becomes a tool that can compute the effects of the (inter-)actions of the different elements as considered much faster than the human brain.

Purpose of the model

To test if our model is fit for purpose, we compare the results of the model and the model requirements. Below we list the required functionalities of our model and discuss to which extend the model supplies these functionalities.

1. Allow variation of different designs of CaPP.
   In chapter 4 we have selected four design choices which were expected to have the largest influences on the operation of CaPP. We have formalised these options and they can be varied at the start-up of the model. The model is fit for this purpose.
2. Reflect on the financial operation of the CaPP under the different designs.
   Within the model we did not include upfront investments, as they can as easily be made after the model experiments have run. The model does keep track of operational costs and revenues. The model is fit for this purpose.
3. Include social interaction between drivers concerning CaPP relevant information
   Following the AOF we have implemented a mechanism that allows information diffusion among the agents. The mechanism chosen was suggested by Yücel and van Daalen (2009). Although there are many different possible information diffusion mechanisms to be considered choosing one and implementing this mechanism makes the model fit for this purpose. A reflection upon this choice is presented in 8.2.3.
4. Allow simulation of relevant consumer choice modelling
   Based on the literature by Hidrue et al. (2011) and Parsons et al. (2014) we have translated two consumer choice model concerning the choice between EVs and internal combustion vehicles, and the choice for consumers to offer V2G services or not. The translation relies on some assumptions that are the subject of reflection and further exploration (see chapter 7). The model is fit for this purpose.
5. Allow simulation of interactions between CPPPs and FCV drivers
   Resulting from the used choice models the driver closes a contract with the CPPP. This contract can include an agreement on obliged parking times, depending on the selected design to experiment with. Interaction furthermore takes place during days of operation when drivers arrive or depart from the CPPP. We did not include interactions between drivers and CPPPs outside the operational behaviour, such as negotiations concerning the contract. These elements could be added to the model to further improve it. For now we find the model fit for this purpose, but acknowledge that improvements are possible.

We conclude that the model is fit for our purpose. Together with the gained knowledge from the modelling process which forced us to specify our beliefs about every element in the considered system, the model gives us the tools required for this project, and is thus considered to be valid.

7. Experimentation

The model is at this stage a computer tool that takes the input that we feed it and transforms it to the defined KPI's. To explore the full range of dynamics the model can generate, the model should be investigated under every possible setting. This would require lengthy simulations that would require more time than available for this project. Therefore we adopt a different approach which is discussed in section 7.1. The execution of this approach is presented in the subsequent sections. In this chapter we study, describe and gain insight into the behaviour of the model. What these insights mean for our research question and the efforts of the Green Village is discussed later in chapter 8 and 9.

7.1 Approach

Figure 7-1 provides a schematic overview of the approach for the experimental phase of this project. For the given limited amount of time we have decided to execute two experiments which are discussed below together with the method used to structure the simulation data. A discussion on the choice for two and specifically these two experiments is presented later in section 8.1.1.

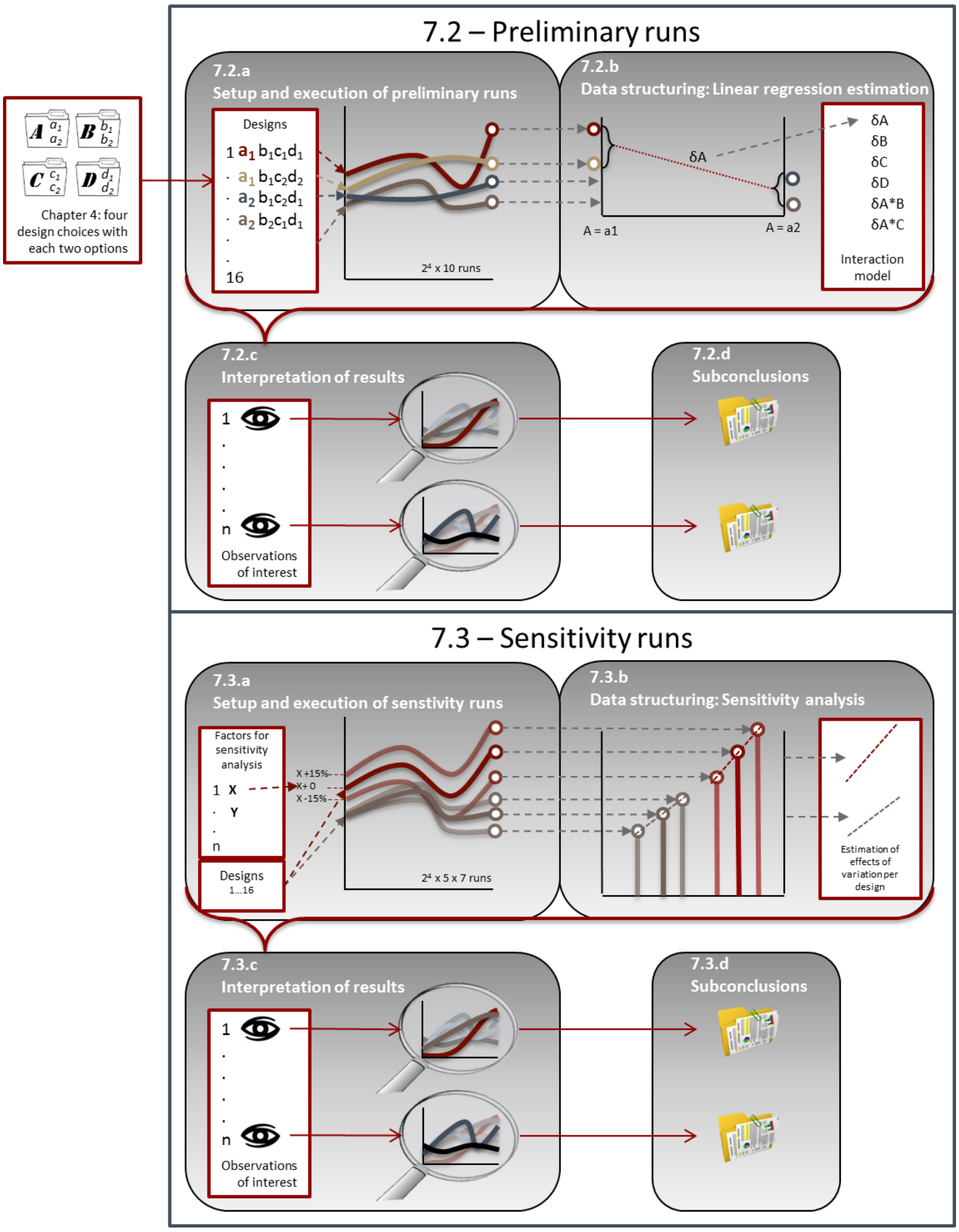

Figure 7-1: Approach of experimentation phase.

Preliminary runs

The preliminary runs are executed to provide a first insight into the behaviour of the model. The runs are executed over the sixteen design variation as defined in section 4.4. The settings of the other variables, the environmental variables, are set to estimated values based on literature wherever possible. As we use a pre-defined set of environmental variables, the focus of this experiment is on gaining a feeling of the effect of the used design on the behaviour of the model.

Data structuring with a regression model

Simulating a number of replications for each design leads to a large amount of data. We chose to use the linear regression approach to gain insights into the relations between the design choices and our main performance indicator; the return on investment (ROI) for the CPPP owner. Furthermore these runs should give base to the identification of behaviour worth further investigating. The fit of a regression model based on the linear regression method on data coming from an ABM model that is built to generate complex and dynamic behaviour is expected to be limited. As a consequence we will refrain from drawing conclusions directly upon the regression model.

Sensitivity runs

The preliminary runs are executed over a pre-defined set of environmental variables. This will give some insight into the model behaviour, but only executing the preliminary runs would provide little knowledge on how the CPPPs might perform under a different set of environmental variables. By running and analysing sensitivity runs we gain some feeling for the effect of certain factors on the behaviour of the model. We will select factors to vary that are related to the observations of interest as found in the previous experiment.

Data structuring based on visual interpretation

The sensitivity analysis is executed by varying selected factors with a margin for each CPPP design. We include other key performance indicators related to the model operation besides the ROI for the CPPP. A consequence of including extra factors that are being varied and are being monitored, is that the data set is larger compared to the data sets of the preliminary runs. Using linear regression for this experiment was expected to results in a regression model that would be difficult to interpret due to the relative large number of dependant variables (the different KPI's) and independent variables (the different CPPP designs and the factors being varied). Taking this into account, we have chosen to structure the data from the sensitivity runs in a set of plots and interpret the results visually.

7.2 Preliminary runs

7.2.1 Setup and execution

Setup

Control variables

The setup of the preliminary runs includes all possible CPPP design variations resulting in the following variation of the control variables:

- Parking times obligation for drivers: Obligation included, No obligation
- CPPP use case: Peak hour production, Secondary control
- CPPP methane reforming technology: Steam reformer, SOFC
- CPPP location: Near households, Near offices

The inclusion of all four design choices results in a set of sixteen CPPP designs that will be varied.

Environmental variables

In this section we discuss the used settings of the environmental variables for the preliminary runs. We have based the settings as much as possible on literature or other sources.

Initial share of FCVs in the simulation: 50%

For CaPP to be effective a significant fleet of FCVs should be available. Different outlooks or scenarios use estimations of 50% penetration (Pollet et al., 2012) to 60% in 2050 (Ogden & Rubin, 2009). For the preliminary runs we have selected an initial percentage of FCVs of 50%[10].

Share of wind electricity in the electricity mix for CaPP: 75%

As discussed in Appendix F, the mix of electricity supply for the CPPP has large influences on the WTW pollution of the hydrogen supplied by the CPPP. We have assumed that the WTW emissions are used by the drivers when they assess the expected pollution of ICVs and FCVs. Seeing the objectives of van Wijk and Verhoef (2014) a large share of wind energy in the used electricity mix of the future CPPP seems plausible. The CPPP might however also be forced to purchase electricity from other sources when instant hydrogen production is required due to an unacceptable low level of hydrogen in storage, and wind energy is unavailable. We have selected a share of wind energy of 75% as the value to be used for the preliminary runs. This value reflects the desires of van Wijk and Verhoef (2014) but also takes the possible mismatch between the times of electricity demand and wind availability into account.

Learning diffusion delay: 20%

The social mechanism that is of effect for CaPP could have easily been the subject of a whole thesis. For our purposes we have selected the mechanism as used by Yücel and van Daalen (2009). In this mechanism an information delay is included. This delay represents the mechanism that if an agent is confronted with new information, only a part of this information is processed into the new beliefs of the target agent (see 6.2.3 for a more detailed discussion of the working of the used social mechanism). For our model we have used the initial value with which Yücel has experimented, which is 20%.

CPPP size: 500 parking spots

The size of 500 parking spots for a CPPP has been suggested by van Wijk and Verhoef (2014). A variation in the size of CPPPs would have advantages and disadvantages (see p. 100). Studying the effects of the variation would require more knowledge on the value drivers would give to CPPPs closer to their destination and depend on the city architecture. Gaining such knowledge is time intensive and falls outside the scope of our project. As a consequence we will use the value as suggested by van Wijk and Verhoef (2014).

Gasoline price : €1,70/L

The gasoline price at the pump is at the time of writing around €1,70/L for gasoline and €1,35/L for diesel. The prices have lately been very volatile. Different scenarios exist and depending on the year of interest the price might be in a wide range of possibilities. For our settings we have chosen a relatively high gasoline price of €1,70/L.

Hydrogen price: €5/kg

For the hydrogen price we use the target prices of many European governments of €5/kg. A short discussion of the hydrogen price can be found in Appendix F.

Number of drivers in simulation: 10.000

From the experiences we had with the model so far a CaPP adoption rate of two to five percent over the total simulation population was expected. We assume that the specific locations of CPPPs will be chosen such that the expected use by drivers matches its capacity (otherwise a different location or CPPP size should be chosen). For our CPPP with 500 parking spots to be fully used, a pool of possible adopters of 10.000 is required.

[10] Note that we so far have not defined a year in which our model operates. This is due to the fact that the sources of our study also concern different years (e.g. the choice models of 2014) bus some of our required assumptions concern future situations (as this initial amount of FCVs). Please see section 9.5.2.2 for short discussion on this point.

Execution

The computational resources were limited for our purposes. The model is computational intensive as it simulates the movement of 10.000 drivers for each quarter of an hour, for multiple years. We have reduced the computational demand of our model by taking the following actions;

- We have limited the run time of the model to three years. This runtime is equal to the longest time frame used in the model; the average car is expected to be renewed every three years (CBS, 2014b, 2015b).
- Each driver agent in our model represents ten drivers. This has been achieved by multiplying different variables in the model with a factor ten, such as pollution per driver agent, hydrogen use per driver agent and FCVs parked at the CPPP per driver agent. The multiplication was necessary to reduce the amount of repetitions of driver procedures, such as the driving procedure, from ten thousand to one thousand per time step. The decision rules and such are unaltered, but as a result the behaviour model is more turbulent than intended; if one agent under this setting decides to purchase an FCV, the amount of FCV drivers will increase with ten instead of one.
- The KPI's were logged only at the end of the runs. The usual practice of logging all KPI's at each run demanded more internal memory than available. This limitation was caused by the available hardware for this project and possibly the limitations of Netlogo as discussed in section 6.4.

The logged KPI's were the following:

- Cumulative profit of the CPPP. With the aid of the cost estimations as in Appendix F we have calculated the Return on Investment (ROI) for the CPPP operator after the simulated three years.
- Pollution of the total system
- Share of drivers who adopted FCVs
- Share of drivers who adopted CaPP

In order to prevent unrepresentative simulation outliers to influence our results we have executed ten replications for each of the sixteen possible design setting. The experiment as executed consisted out of 160 runs which each took about four minutes to simulate. We ran the experiment on a computer with a quad core processor allowing four runs to be simulated simultaneously.

The simulation data is a set of sixteen different settings of the control variables, for each of which the model has run ten replications with different random seeds. We have checked the different runs for outliers and variability. For none of the runs did the cumulative profit deviate more than 5% from the mean of the ten runs with equal CPPP design settings. The small variation does not give rise to increasing the amount of replications.

7.2.2 Data structuring

We have used linear regression to estimate a regression model for the relations between the CPPP design options and the simulated ROI after three years. We have estimated an interaction model which takes into account that the influence of two design choices might not be unrelated from one another. The execution of this estimation can be found in Appendix H. Below we summarise the execution and discuss the results.

The first regression model included all first order (obligation, use case, reformer technology and location) and second order ([obligation * use case]; [obligation * reformer technology] etc.) terms. The model indicated that several of these terms had an insignificant relation with the return on investment after three years. Following from this observation several iteration steps are executed until the model only contained significant terms on a 5% significance level. During each iteration step a new regression model is estimated, but the term that showed the highest p-value in the previous estimation is excluded from the set of terms. The final regression model with only significant terms is shown below.

The resulting regression model has high R-square values, indicating that the variation in the dependant variable (the ROI) can be very well explained by the regression model. In Appendix H we have checked and confirmed that the assumptions underlying linear regression have been satisfied, that the regression model fits the simulation data and is adequate.

Factorial Regression: ROI versus Obligation; Use Case; ReformerTech; Location

Analysis of Variance

Source	DF	Adj SS	Adj MS	F-Value	P-Value
Model	6	0,054133	0,009022	23,70	0,000
Linear	4	0,044123	0,011031	28,98	0,000
Obligation	1	0,015837	0,015837	41,61	0,000
Use Case	1	0,007799	0,007799	20,49	0,001
ReformerTech	1	0,015941	0,015941	41,88	0,000
Location	1	0,004545	0,004545	11,94	0,007
2-Way Interactions	2	0,010010	0,005005	13,15	0,002
Obligation*Location	1	0,004080	0,004080	10,72	0,010
ReformerTech*Location	1	0,005929	0,005929	15,58	0,003
Error	9	0,003425	0,000381		
Total	15	0,057558			

Model Summary

S	R-sq	R-sq(adj)	R-sq(pred)
0,0195092	94,05%	90,08%	81,19%

Coded Coefficients

Term	Effect	Coef	SE Coef	T-Value	P-Value	VIF
Constant		-0,32578	0,00488	-66,79	0,000	
Obligation	0,06292	0,03146	0,00488	6,45	0,000	1,00
Use Case	-0,04416	-0,02208	0,00488	-4,53	0,001	1,00
ReformerTech	0,06313	0,03156	0,00488	6,47	0,000	1,00
Location	-0,03371	-0,01685	0,00488	-3,46	0,007	1,00
Obligation*Location	-0,03194	-0,01597	0,00488	-3,27	0,010	1,00
ReformerTech*Location	0,03850	0,01925	0,00488	3,95	0,003	1,00

Regression Equation in Uncoded Units

ROI = -0,32578 + 0,03146 Obligation - 0,02208 Use Case + 0,03156 ReformerTech
- 0,01685 Location - 0,01597 Obligation*Location + 0,01925 ReformerTech*Location

A representation of the model that is easier to interpret is shown in Figure 7-2. This figure shows the fitted mean of the return on investment after three years per design choice. These fitted means are the resulting average value of the dependent variable (ROI in our case) of all the runs that use designs that include the particular design choice[11]. Please note that the fitted means are negative, and a lower bar indicates a more favourable financial position of the CPPP. Figure 7-2 for instance indicates that if in the simulation a design with a SOFC was used, the return on investment was on average more favourable than when a SMR was used.

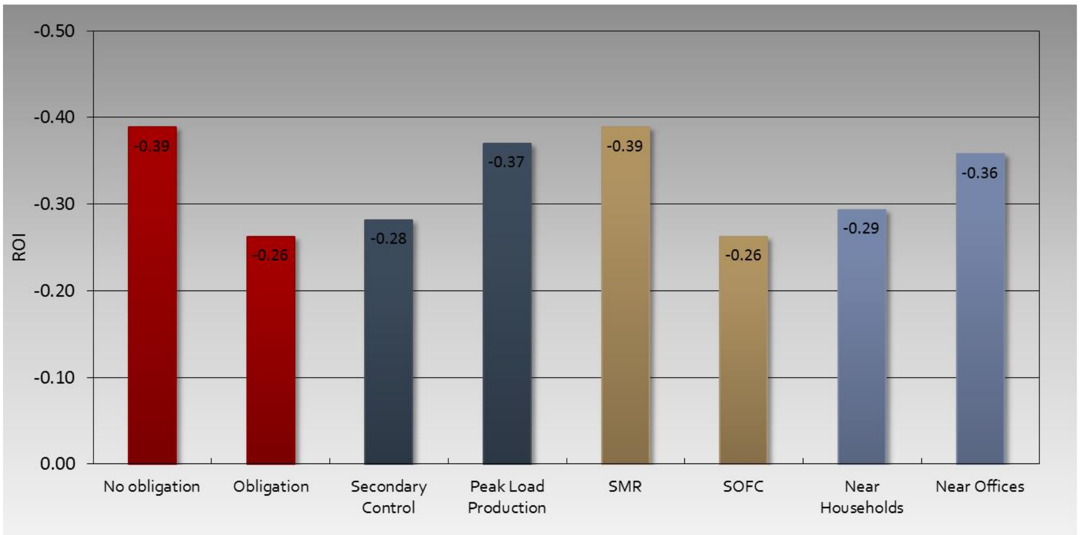

Figure 7-2: Fitted means per design option based on the preliminary runs.

[11] For instance, the fitted mean of the design choice SOFC is the mean of the ROI of all the runs that were set up with a design including a SOFC. The fitted mean of a particular design option is the mean of the values of the ROI based on the 80 (1*2*2*2*10) runs with this particular design option.

7.2.3 Interpretation of results

In this section we first list a number of observations that we have found to be of interest for our purposes. Subsequently we investigate multiple runs in detail to gain an understanding of what causes these observations of interest.

From the results of the regression analysis we observe the following:

- The R-square, R-square-adjusted and R-square-predicted are very high and the regression model fits the simulation data very well. This indicates that the regression model has a high explanatory value and we can quite accurately predict the performance of the CPPP with respect to the financial position of the CPPP once the design of the CPPP is known. This is an unexpected observation as we will discuss in the following section.
- The ROI after three years is in all cases negative. On average the simulated CPPP makes a loss between € 3,5M and € 5,5M in the first three years on top of its initial investments.

Below we will discuss both observations separately. Due to the fact that these observations were not expected we deem them to be more interesting than for instance the estimated effect of the different design choices on the ROI as shown in Figure 7-2.

7.2.3.1 Predictable behaviour

Although we intended the use of linear regression as a quick method to reduce the amount of interesting runs, the very high explanatory value is remarkable. It hints that with respect to ROI the ABM model behaves very predictable. The predictable behaviour was unexpected given the complex nature of transitions, the complex mechanisms that were considered following the AOF and the characteristics of socio-technical systems.

To gain a better understanding of the causes of this behaviour we examine a number of runs in more detail. In the model we included and added some plots that visualise chosen KPI's during the simulation run. The following plots are from runs with different CPPP design settings. Figure 7-3 illustrates the financial position of the CPPP when the model is run for half a year. Figure 7-4 shows the same indicators when the model is run for two weeks. Runs with different settings show identical behaviour, but are for the sake of overview not presented here.

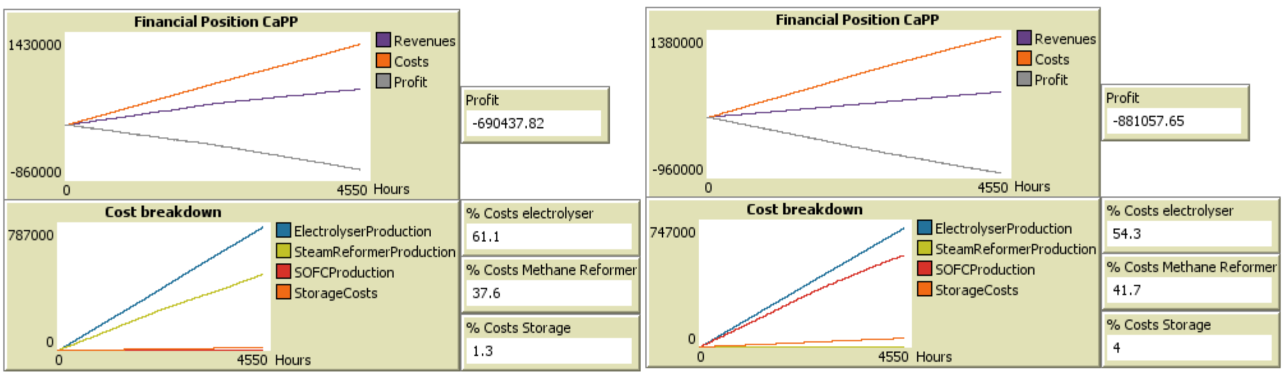

Figure 7-3: CPPP financial position after 183 days. On the left a CPPP with the design set to: secondary control, steam reformer, obligation and near homes (random seed 1042923022). On the right peak load production, SOFC, no obligation and near offices (random seed -1218486453)

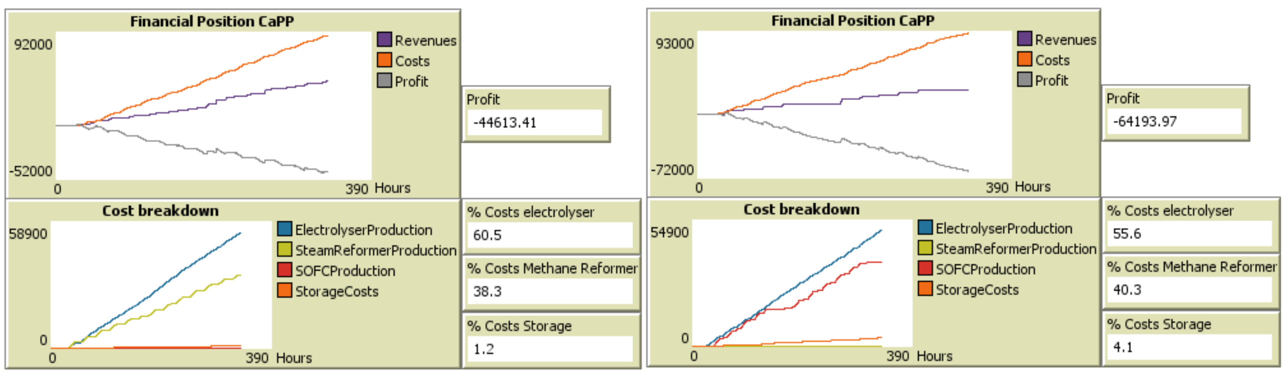

Figure 7-4: CPPP financial position after 14 days. On the left a CPPP with the design set to: secondary control, steam reformer, obligation and near homes (random seed 612779874). On the right peak load production, SOFC, no obligation and near offices (random seed -295613507)

We see that the CPPP revenues, costs and profit are behaving close to linearly over time. We find the constant increase in costs most surprisingly. Costs increase due to the production and storage of hydrogen (as discussed in 6.2.1). We can see in the cost breakdown plots that the costs are mainly resulting from the production of hydrogen and more specifically the constant increase of production costs of hydrogen with the electrolyser.

A constant increase in operational costs of the electrolyser would mean a constant use of the electrolyser. This is unexpected as the CPPP are designed to have a peak shaving function; buy energy when the price is low (mostly during the night) and sell energy when the price is high (during the day). If the CPPP would actually provide the peak shaving function the electrolyser would not be used during the day, and we would not see a constant increase of the operational costs of the electrolyser. To investigate why the CPPP shows this unexpected behaviour we take a closer look at the hydrogen system in the model, as it incorporates the operation of the electrolyser. In Figure 7-5 and Figure 7-6 the hydrogen system is depicted for an operation of two weeks.

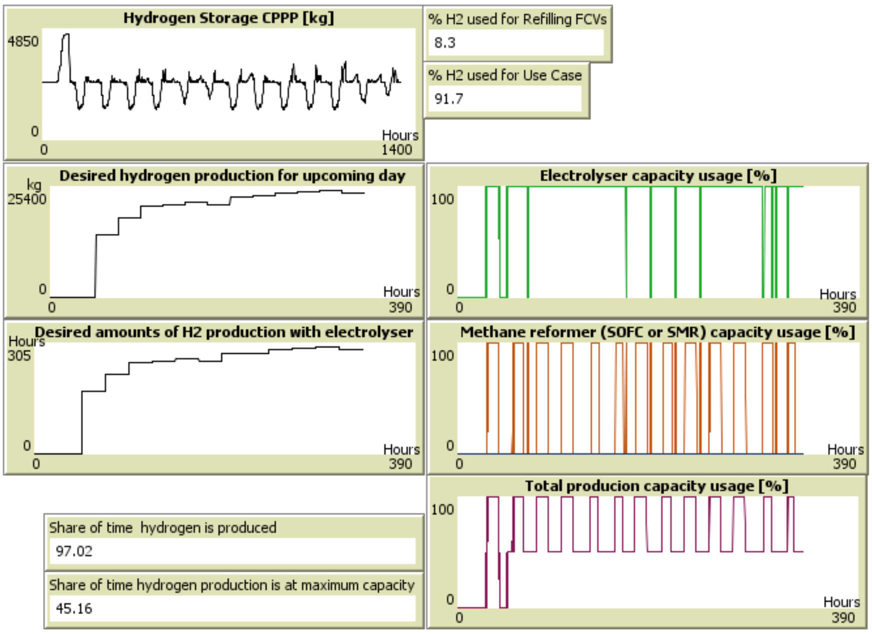

Figure 7-5: Hydrogen system operation after 14 days for a CPPP with the design: secondary control, steam reformer, obligation and near homes (random seed 2066958791)

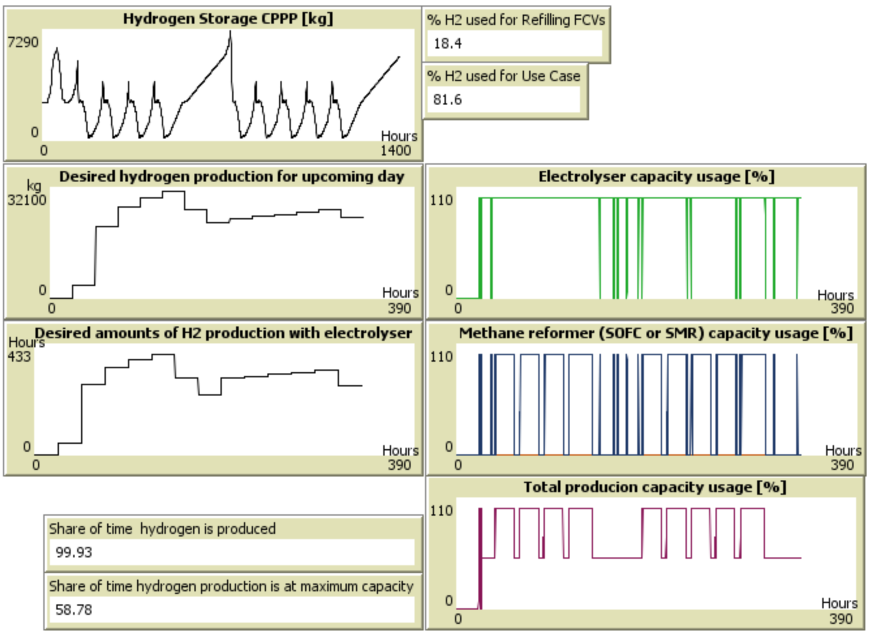

Figure 7-6: Hydrogen system operation after 14 days for a CPPP with the design: peak load production, SOFC, no obligation and near offices (random seed 1987029131)

These plots show that indeed the electrolyser is used almost constantly. Furthermore we see that during more than 97% of the time the CPPP is producing hydrogen of which about half of the time the full production capacity is used.

By looking at the plots of desired amounts of hydrogen and the resulting desired amount of hours of production we find the cause of the continuous usage of the electrolyser. The amount of hours of desired production per day is in the order of several hundred hours per day; the desired hydrogen production is much larger than the installed capacity. The desired amount of hydrogen production for the upcoming day is based on the memory of the CPPP in which it records the amount of hydrogen it would had like to have had during the past days (as discussed in 6.2.2). The figures indicate that the largest part of the hydrogen is used for the use case, i.e. the usage of the hydrogen for electricity production.

If we consider the used conversion rates for our model as discussed in Appendix E we can investigate the hydrogen demand in more detail. Based on the work of Spanjer (2014), the FCVs in our model convert one kilogram of hydrogen into roughly 16 kWh. In the same appendix we discuss the usage of 100 kW as the conversion capacity of an FCV (based on (van Wijk & Verhoef, 2014)). If we compare these numbers we see that for one car to produce one hour we require 6,25 kg of hydrogen; that is more than one of the hydrogen production units produces in one day per parking spot which is 4 kg/day/parking spot (as discussed in also the same appendix) or 2000 kg/day/hydrogen-production-device.

SYNOPSIS

The different plots and comparisons as presented above are providing us with an explanatory narrative for the observed behaviour of interest. Figure 7-7 is a visual interpretation of the mechanisms causing the linear behaviour.

The CPPP in our model is programmed to use the maximum amount of electricity it can produce with the available FCVs as its desired electricity production (discussed in 6.2.2). Due to the given limited FCV conversion efficiencies the amount of desired hydrogen becomes much larger than the CPPP can produce, resulting in the CPPP producing hydrogen around the clock and a constant and linear increase in the operational costs of the CPPP.

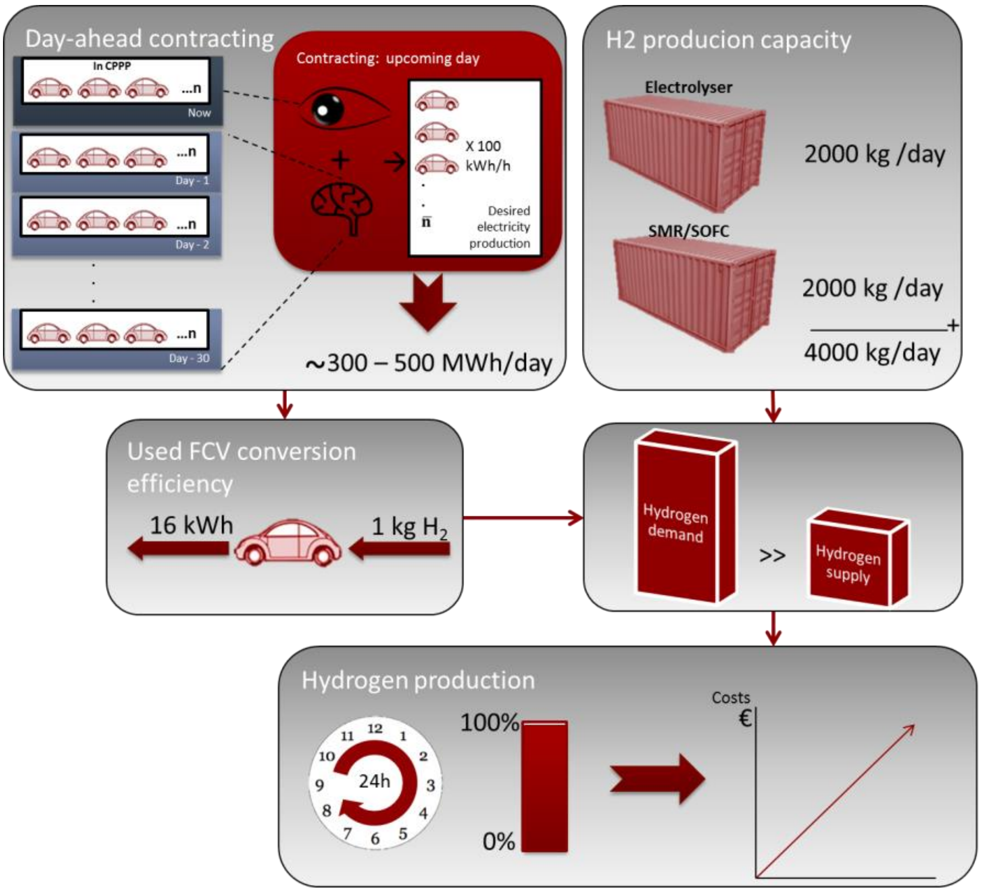

Figure 7-7: Schematic overview of mechanisms causing linear behaviour.

We note that we already took a large hydrogen production capacity for the hydrogen production devices being two devices with a capacity of 2000 kg/day. The current on-site devices have capacities in the order of 150 kg per hour (HyFleet, sd.). Scaling the hydrogen production capacity to values of today's on-site production modules would strengthen the set of mechanisms as depicted above. On the other hand we also note that the conversion efficiency of the FCV module used by Spanjer (2014) and subsequently also the conversion efficiency in our model is based on FCV models that are no longer state-of-the-art, let alone representative for future fuel cells. Furthermore, the used control operation logic of the CPPP in our model is simple and would be more advanced and sophisticated in reality. A more elaborate discussion on the used assumptions can be found in section 8.2.

7.2.3.2 Negative ROI

Besides the predictable behaviour of the model we find it remarkable that for each CPPP design the return on investment after three years are negative. For a sustainable business case this ROI should at least be positive to indicate that a profit can be made with the concept. Furthermore the positive ROI should be above some threshold to allow the investment to be earned back after an acceptable amount of years.

The return on investment is calculated as the cumulative profit of the CPPP over three years divided by the initial investments. The latter are not calculated within the model but are discussed in Appendix F. To understand the resulting ROI we find it useful to study the marginal profit of a kilogram of hydrogen. Using a kilogram of hydrogen as unit allows for comparison between the different energy flows resulting in operational revenues and costs. We have illustrated the different methods to produce a kilogram of hydrogen and the possible yield with the same kilogram in Figure 7-8.

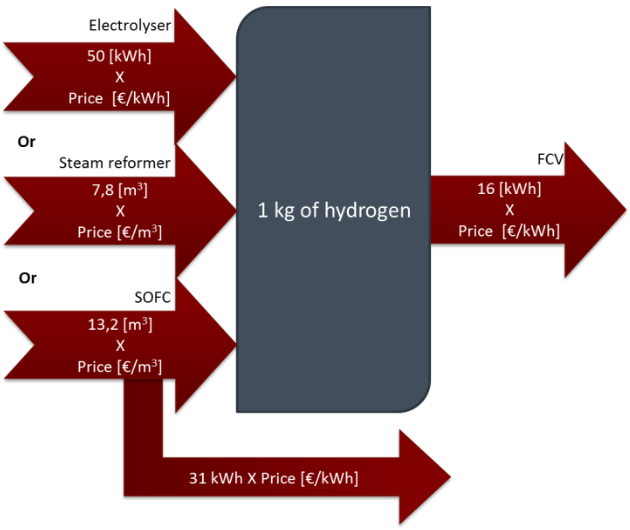

Figure 7-8: Diagram of production costs and revenue yield of one kg of hydrogen

Electrolyser

Based on Palazzi (2013) the model coded to require 50 kWh of electricity for the production of one kilogram of hydrogen with the electrolyser (see Appendix E). The price of production depends on the times the electrolyser is used. However we have seen that in our preliminary runs the electrolyser was used for more than 97% of the time. We have monitored several runs and found an average electricity price of 4,3 cents/kWh. On average the production of a kilogram of hydrogen with the electrolyser costs €2,15.

Steam reformer

The steam reformer module as used by Spanjer (2014) requires roughly 7,77 m^3 natural gas. The price of natural gas is discussed in Appendix F. In the model a gas price of 39 cents per m^3 is used. The production of a kilogram of hydrogen with the steam reformer thus costs €3,03.

SOFC

The SOFC also produces electricity when it converts methane into hydrogen. For each kilogram of produced hydrogen the SOFC requires roughly 13,2 m^3 but also produces roughly 31 kWh of electricity. The operation costs of the SOFC are given the gas price of 39 cents per m^3 €5,14. If we assume that the SOFC is used at random moments of the day we can value the side produced electricity by using the average electricity price of 4,3 cents/kWh, resulting in a revenue stream of €1,33. The net costs of the production of one kilogram hydrogen with the SOFC are €3,81.

Electricity production with FCV

The FCVs in the model convert a kilogram of hydrogen into roughly 16 kWh, based on the work Spanjer (2014). The times during which the electricity is sold depends on the selected use case of the CPPP. The peak load hours have been assumed to be between 09:00 and 20:00. The mean price during these hours is around 4,9 cents per kWh following from different simulation runs. The regulation up signals that are relevant when the secondary control use case is in use can be issued during any time of the day. From the data as used for this study we observe an average price of 7,8 cents/kWh. One kilogram of hydrogen can thus be used to generate a revenue stream in the range of €0,78 to €1,25.

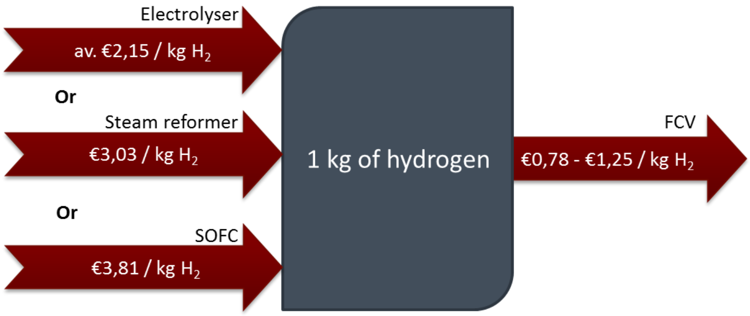

Figure 7-9: Production costs and possible generation of revenues per kilogram of hydrogen in the simulations

A simplified overview of the production costs and yield per kilogram of hydrogen is presented in Figure 7-9. Comparing both sides of the overview shows that the CPPP in our simulation is confronted with a negative marginal profit on each kilogram of hydrogen. This overview assumes that each kilogram of hydrogen can be used without storage for the use case of the CPPP. I.e. storage costs and hydrogen used to refuel FCVs are not included in this overview, making it somewhat optimistic. On the other hand the possible paid production of hydrogen with regulation down signals in the secondary control use case is also not included.

SYNOPSIS

After studying the costs of producing a kilogram of hydrogen and the possible revenues that can be generated with a kilogram of hydrogen, we see that the profit margin on hydrogen is negative in our simulations. The low profit margin is on the one hand caused by the conversion losses and on the other hand by the small difference between electricity prices that the CPPP has to pay when demanding electricity and the electricity prices received by the CPPP when supplying electricity. The difference between buying and selling price of electricity is among others low due to the continuous operation of the electrolyser as discussed in section 7.2.3.1, preventing the CPPP to produce its hydrogen during the hours of cheap electricity.

Some of the important assumptions that influence this behaviour are the following; first of all, the used prices of electricity and gas in the model might not reflect the prices that are of effect for the future CPPP. In this study the prices of today have been used, sometimes based on a limited amount of data (see Appendix F). The variance of the electricity prices are expected to increase in the future due to the introduction of more and more renewables. Furthermore, we have not considered taxes or other additional costs. Secondly, the used FCV conversion efficiency is not based on the current day's state of the art fuel cells as discussed earlier and by Spanjer (2014). An improvement of this efficiency will lower conversion losses and allow for more electricity to be produced from the same amount of hydrogen. Thirdly, the control logic of the modelled CPPP is very simple. In the simulations the CPPP will produce electricity when the environmental conditions satisfy the use-case. In reality one can expect a more advanced control strategy that will only allow for electricity production when there is a marginal profit to be made. Lastly our calculation of the revenue of the CPPP is based on only the revenues resulting from executing the use cases. It can be expected that also additional revenues can be made from the grid balancing function of the CPPP, the sales of heat and water, parking tickets etc. A more elaborate discussion on the used assumptions can be found in section 8.2.

7.2.4 Sub conclusions

The hydrogen demand of FCVs for hydrogen production is much larger than the production capacity of current commercial available on-site hydrogen production units. As a consequence the limited hydrogen production capacity is used around the clock. This operation contributes to the CPPP being unable execute the peak shaving behaviour as intended; buy electricity when demand is low, store the energy in hydrogen and produce electricity again when demand is high. The usage of a relative simple control logic of the CPPP and the usage of today's electricity prices, gas prices and FCV conversion efficiencies lead to the generation of operational losses by the simulated CPPPs.

7.3 Sensitivity runs

In section 7.2 we have observed and studied two interesting behaviours of the model: the predictable behaviour of the model and the negative return on investment. In this section we perform a sensitivity analysis to gain more insight into the causes of the negative return on investment and to explore for other behaviour of interest.

We have chosen not to further study the causes of the predictable behaviour as described and studied in section 7.2.3.1. This behaviour is caused by among others a limited hydrogen production capacity of the devices in the CPPP. Studying a scenario in which the hydrogen production capacities of the CPPP is increased seems logical, but would also have large negative financial impacts. We conclude after several test runs that a profit margin is only present if the capacity of the devices is increased with a factor of roughly thirty. Increasing the installations with such factor would raise investments to several hundreds of millions for a single parking garage. We deem such investments to be highly unlikely and as a consequence chose not to further study this behaviour with a sensitivity analysis. Other methods to mitigate the linear behaviour would be altering the modelling code with respect to the contracting procedures or hydrogen management procedures of the CPPP. Such alterations fall outside the scope and objective of a sensitivity analysis.

By varying factor that are expected to influence the ROI with certain percentages we aim to test if our findings and understanding of the causes of the negative ROI are robust. In order to increase the financial position of CaPP one could consider factors related to either the incomes or the expenses. For the incomes of the CPPP the electricity prices play a large role. Furthermore increasing the amount of electricity an FCV produces from one kg of hydrogen would benefit the financial position of CaPP. Expenses are related to the prices of the two feedstocks for CPPP; the gas price and the electricity price. For the sensitivity analysis we vary the following factors:

- FCV electricity production per kg of hydrogen
- Gas price
- Electricity price

Each factor will be varied with -15%, -7,5%, +7,5% and 15% from the values as defined in section 7.2.1. This results in the analysis still being based on the values from the base runs. With this analysis we do not explore substantial different (future) pathways such as a strong increase of the FCV electric efficiency from the value we used (roughly 45%) to the values as envisioned by van Wijk and Verhoef (2014, p. 60) (60%).

7.3.1 Setup and execution

Setup

Control variables

The sensitivity analysis is in the ideal case executed over all sixteen design variations for which the three selected factors are varied between four levels. Executing this analysis and incorporating the base values of the KPI's (resulting from preliminary runs) would result in 240 data points. We expect this amount of data points to be difficult to interpret and as a consequence chose to delineate the sensitivity analysis. The analysis is intended to give insight into the generic behaviour of the CPPPs, independent of the used design. As we do not focus on gaining insight into the relations between the used CPPP design and the chosen KPI's, we chose to limit the amount of studied CPPP designs in this analysis and exclude one design choice. Based on the results of the regression model as presented in section 7.2.2 we exclude the use case design choice. This design choice has the lowest impact on the ROI of the CPPP after three years[12]. The following CPPP design choices are still included:

- CPPP methane reforming technology: steam reformer, SOFC
- CPPP location: near households, near offices
- CPPP contract obligation: obligation, no obligation

This leaves eight interesting designs. The setting of the "use case" design option was set to "peak load production". This use case was chosen as it is less complex than the "secondary control" use case, possibly making it easier to understand the simulation results and study underlying causes.

Environmental variables

We will conduct a ceritis paribus sensitivity analysis, meaning that only one of the identified variables is varied at a time. The settings of the other environmental variables are unchanged from the values as reported in section 7.2.1.

Execution

We have constructed three different experiments for the sensitivity analysis. Each experiment varies one of the defined variables over the eight possible CPPP designs. With the variables being varied over four levels, 32 base runs were constructed for each experiment. In order to limit the computational time and seeing the limited variation we encountered with the preliminary runs we have reduced the number of replications from ten to seven. This resulted in 224 runs of approximately four minutes each. The experiments were once again run on a quad core computer, allowing four runs to be simulated simultaneously.

7.3.2 Data structuring

The results from the sensitivity runs have been structured in several plots. The complete set of plots can be found Appendix I and are not presented here for the sake of readability. In the following sections we discuss a number of interesting observations that we have made based on these set of plots. Before discussing each observation we will present the relevant plots here in the main body of the thesis. Figure 7-10 presents an example sensitivity plot and is followed by a description how these plots should be interpreted.

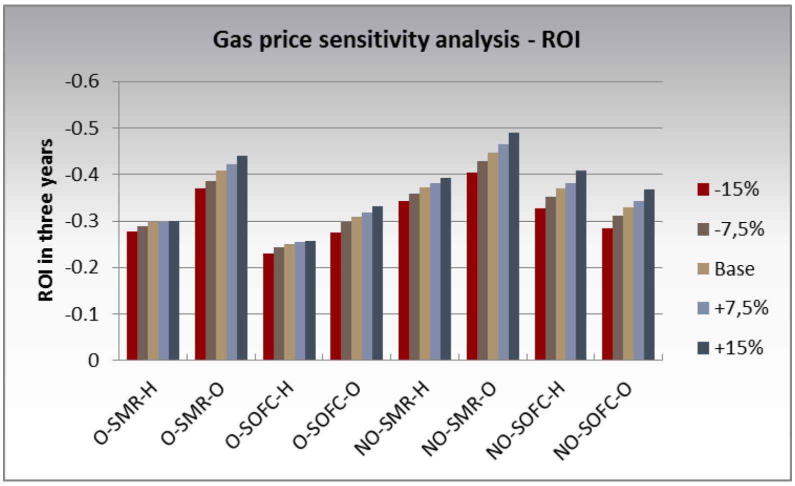

Figure 7-10: Example sensitivity plot

[12] Although the design choice of "location" has the highest p-value for the first order predictor, the significant second order predictors both depend on the "location" design choice.

Each sensitivity plot depicts one KPI when one factor has been varied over a set of CPPP designs and factor variations. The relevant varied factor and KPI are presented in the title of the plot. On the x-axes the different CPPP designs are listed. For the sake of readability we use abbreviations for each design. The key to these abbreviations is as follows;

Obligation:	[O] for obligation, [NO] for no obligation.
Methane reforming technology:	[SMR] for steam methane reformer, [SOFC] for SOFC.
Location:	[H] for near households, [O] for near offices.

The bars in the plots represent the average value of the KPI after a simulation time of three years based on seven simulation replications. The replications have been executed to prevent drawing conclusions upon unrepresentative outliers.

7.3.3 Interpretation of results

From visually interpreting the sensitivity plots as presented in Appendix I we make the following observations that we find interesting to further investigate:

- The relation between the variation of the selected factors and the resulting simulated ROI of the CPPP are nearly linear and in anticipated directions.
- The CaPP adoption at the end of year three is less than 4% in all runs.
- The FCV adoption decreases from 50% to less than 20% in three years.

Below we present the relevant sensitivity plots for each listed observation and discuss the causes of the behaviours.

7.3.3.1 Linear and anticipated relations between varied factors and ROI

The goal of executing the sensitivity runs was to gain more insight into the causes of the simulated negative return on investment. The analysis is especially suited to test if the found explanatory mechanisms as discussed in section 7.2.3.2 are still valid when we vary the exact values of some parameter in our model. In section 7.2.3.2 we found that the negative return on investment are caused the on average negative profit margins on each kilogram of hydrogen. To illustrate this profit margin we used the figure below. In this depiction we marked the factors that we have varied in the sensitivity runs in yellow.

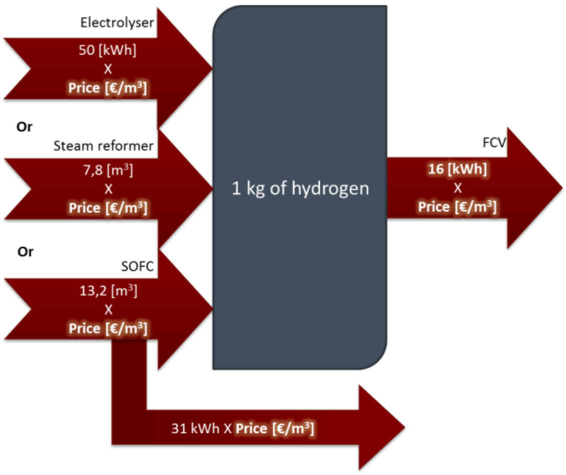

Figure 7-11: Diagram of profit margin per kg of hydrogen, with factors varied in the sensitivity runs highlighted in yellow.

Figure 7-12 shows the relevant sensitivity plots for studying the return on investment. The plots are identical to the plots in Appendix I where they are presented with some more background information and in a larger format.

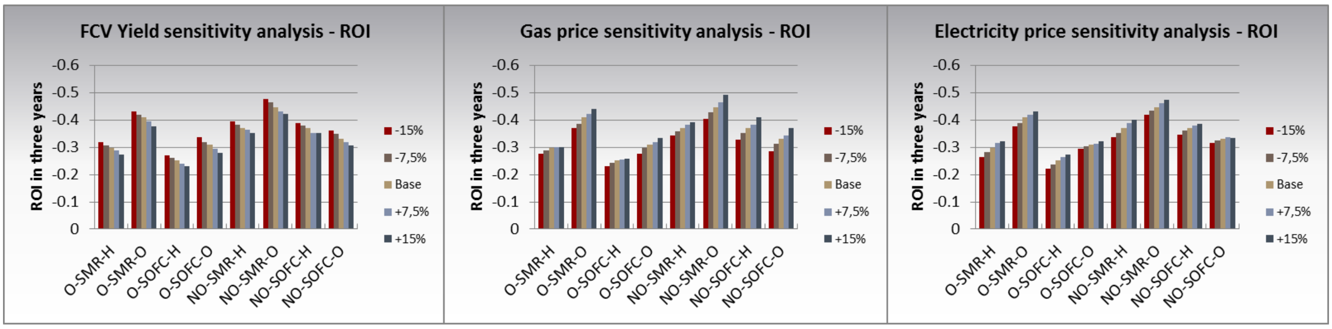

Figure 7-12: Effect of factor variations on ROI.

We find a near linear relation between the variation of the chosen factor and the resulting ROI for all the three factors that we have varied in the sensitivity runs. As anticipated, increasing electricity yield per fed kilogram of hydrogen of an FCV results in a more favourable financial position. An increase in gas and electricity prices results in a higher loss over the course of three years.

The results are in line with our explanation from section 7.2.3.2 (the occurrence of marginal losses per kilogram of hydrogen causing negative return on investments). Varying the factors that constitute the profit margin per kilogram of hydrogen influences the return on investment for the CPPP. The observed near linear relations do not lead to suspecting if the explanation from section 7.2.3.2 might not be valid if the values of the selected factor are varied from the base values. Said differently, the sensitivity runs do not give reason to suspect that different mechanisms are dominant with respect to the simulated ROI when the FCV yield, gas price or electricity price is varied over the used range.

SYNOPSIS

A set of factors that influence the profit margin per kilogram of hydrogen have been varied in the sensitivity runs. These variations all had the anticipated effect on the ROI and therefore do not give base to question the explanation from section 7.2.3.2. Furthermore based on the sensitivity runs we do not suspect changes in mechanisms and mutual mechanism interaction underlying the simulated ROI when the selected factors are varied. In section 7.2.3.2 we discussed that the negative return on investment are caused by the existence of an on average negative profit margin per kilogram of hydrogen in the simulation. We conclude that this explanation is robust over the used variations.

7.3.3.2 Low CaPP adoption share

The relevant sensitivity plots that illustrate the low CaPP adoption share can be found in Figure 7-13 . The plots are identical to the plots in Appendix I where they are presented with some more background information and in a larger format.

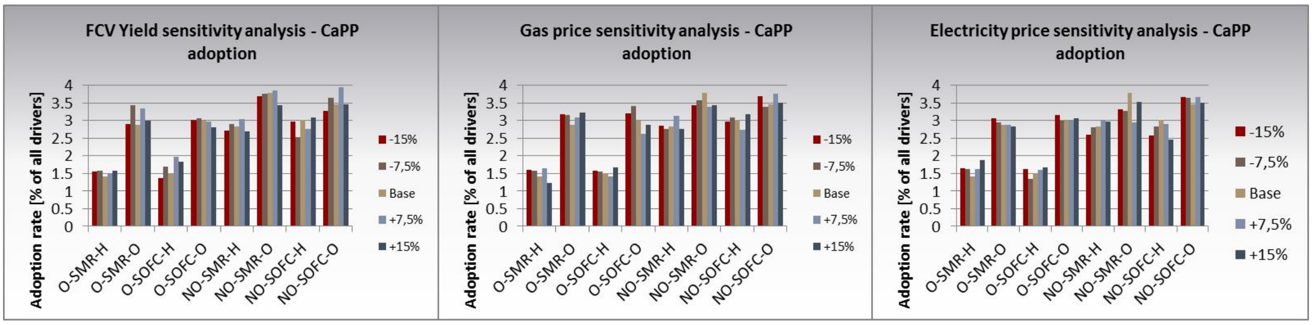

Figure 7-13: Effect of factor variations on CaPP adoption.

The KPI's monitoring CaPP adoption should be interpreted with some care. The KPI is a recording of a value at a specific moment in time. More specifically the KPI represents the share of drivers that adopted a CaPP parking behaviour of all drivers at the end of year three. The CaPP adoption share influences the amount of drivers that visit the CPPP but can also be used to reflect upon the feasibility of a CPPP.

A CaPP adoption of below 5% of all drivers would require a driver base of at least 10.000 drivers for the CPPP to possibly be filled to full capacity. To illustrate, such a driver base for CPPPs located near households is equal to roughly four times the driver population of downtown Delft (CBS, 2014a). If the CPPP is based at offices this would require office districts with 10.000 employees that arrive by car. This is more than twice the total amount of employees of the TU Delft (TU Delft, 2013). These populations are large and subsequently would require CaPP parking drivers to walk large distances once they have parked their car. In section 5.2.5 we assumed that if the CPPP is located near households drivers will have to walk an additional five minutes. If the CPPP is located near offices no additional walking was assumed. A required driver's base of 10.000 cars challenges this assumption. If the walking distances for drivers are larger than assumed one could expect drivers to experience more disutility from parking at a CPPP and an even lower CaPP adoption rate.

To study the adoption rate we let Netlogo visualise the CaPP adoption share in a plot during the simulation. The plots below are the result of two separate simulation runs using different CPPP designs. The other design combinations display similar behaviour and are for the sake of overview not presented here.

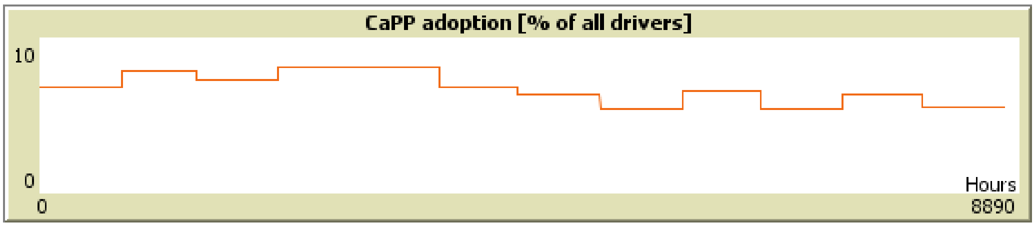

Figure 7-14: CaPP adoption share after one year. Design set to: peak load production, steam reformer, no obligation and near homes (random seed -411488838).

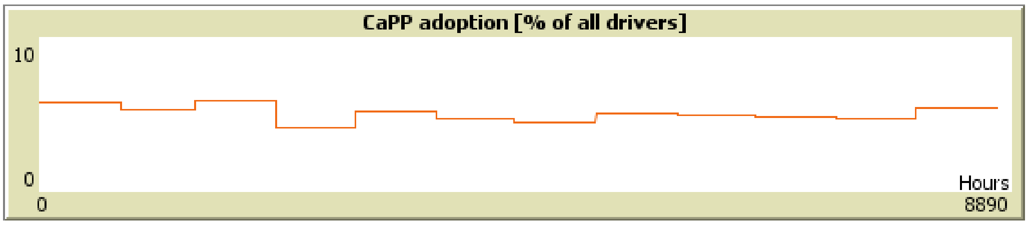

Figure 7-15: CaPP adoption share after one year. Design set to: peak load production, SOFC, obligation and near offices (random seed 315488479).

In Figure 7-14 and Figure 7-15 and we can see that the CaPP adoption rate is varying over time around roughly the same value. A periodic change in the CaPP adoption can be observed caused by the monthly procedure during which the FCV drivers re-evaluate their parking behaviour.

The observation that the CaPP adoption rate is not structurally increasing or decreasing is somewhat surprising. CaPP offers drivers a free tank of hydrogen when they depart. The first few drivers that park at the CPPP experience this benefit and are expected to pass it through to other drivers through the social mechanism in place (see 6.2.3 for the description of the used social mechanism). The diffusion of information concerning the benefit was expected to convince an increasing number of drivers over time to park at the CPPP. On the other hand if an obligation is in place the information on the obliged times the FCV is to be parked in the CPPP is diffused among drivers, negatively influencing the calculated value function. Also the diffusion of this information among drivers was expected to influence the adoption rate over time.

To study the decisions of the drivers concerning their parking behaviour we have added monitors to our model that track the calculation of the value function that drivers use to determine if they adopt CaPP or conventional parking. The value function is calculated based on the beliefs of the driver in combination with a normal distributed random error with a mean of zero and a standard deviation of one. If the calculated value function is above zero the driver is programmed to adopt a CaPP parking behaviour. The monitors as added to our model depict what the value function for an average FCV driver looks like if the error term is removed. This gives insight into which values of the error term will lead to a positive value function and subsequently what roughly the chances are for an average driver to come to a calculation of a positive value function.

Table 7-1: Selection of recorded CaPP value function terms

	Constant	Required plugin time	Cash back
120 days	-1,1	0	0,185
240 days	-1,1	0	0,158
360 days	-1,1	0	0,140

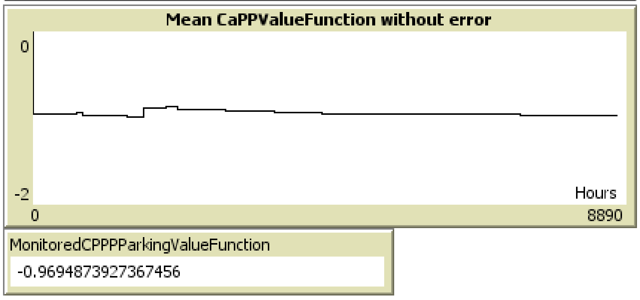

Figure 7-16: Mean CaPP value function without error term. Design set to: peak load production, steam reformer, no obligation and near homes (random seed -411488838).

Table 7-2: Selection of recorded CaPP value function terms

	Constant	Required plugin time	Cash back
120 days	-1,1	-0,11	0,305
240 days	-1,1	-0,11	0,285
360 days	-1,1	-0,11	0,276

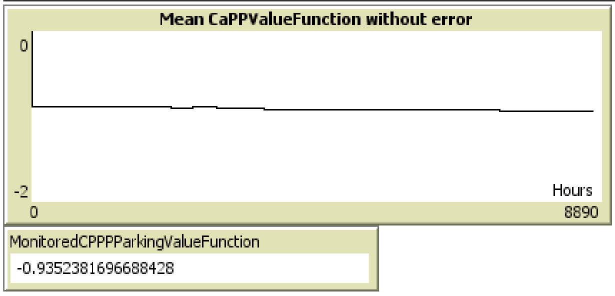

Figure 7-17: Mean CaPP value function without error term. Design set to: peak load production, SOFC, obligation and near offices (random seed 315488479).

From the figures and plots above we indeed see that the average value function for CaPP driving is negative and almost constant. The information that is diffused among drivers concerning the required plugin time and the possible cashback from CaPP has little influence on the calculation on the value function. In both cases the random error term must be roughly one or larger to result in a positive value function and the adoption of the CaPP parking behaviour by the driver. From the three elements from which the value function is calculated the remuneration for the drivers is a parameter that can be influenced by the CPPP.

In the model the drivers that park their car in the CPPP is guaranteed to receive a full tank of hydrogen when he departs. The FCVs have a hydrogen consumption of about one kilogram per 100 kilometres and are estimated to drive about sixty kilometres per day. As a result the remuneration exists of about 0,6 kilograms of hydrogen per day which equals to about €1500 on a yearly basis. The values that are used by Hidrue et al. (2011) to indicate the average desired annual remuneration for EV adopters are, however, in the range of €3000 to €4000.

Synopsis

In this study we have used a full hydrogen tank as a reward for the drivers that park their car at the CPPP. Due to the low daily hydrogen consumption by FCVs and the relatively low hydrogen price this benefit is valued as roughly a yearly remuneration of about €1500. Compared to the values used in literature this reward is insufficient to have a significant positive impact on FCV owners to adopt a CaPP parking behaviour.

This behaviour is first and foremost affected by the used decision models to calculate the value functions. These models are based on (Hidrue et al., 2011) and (Parsons et al., 2014). The original models were constructed for choices between conventional cars and EVs, and the choice of supplying V2G services with these EVs. We assumed these models to be applicable for the CaPP case with some adaptations, but this assumption is unlikely to be sufficient for further detailed studies. Another assumption is the used hydrogen price of €5/kg for drivers in the model. A more elaborate discussion on the influences of the used assumptions on this study can be found in section 8.2.

7.3.3.3 Decreasing FCV adoption

The effects of the variation of the selected factors on the FCV adoption share are illustrated in Figure 7-18. The plots are identical to the plots in Appendix I where they are presented with some more background information and in a larger format.

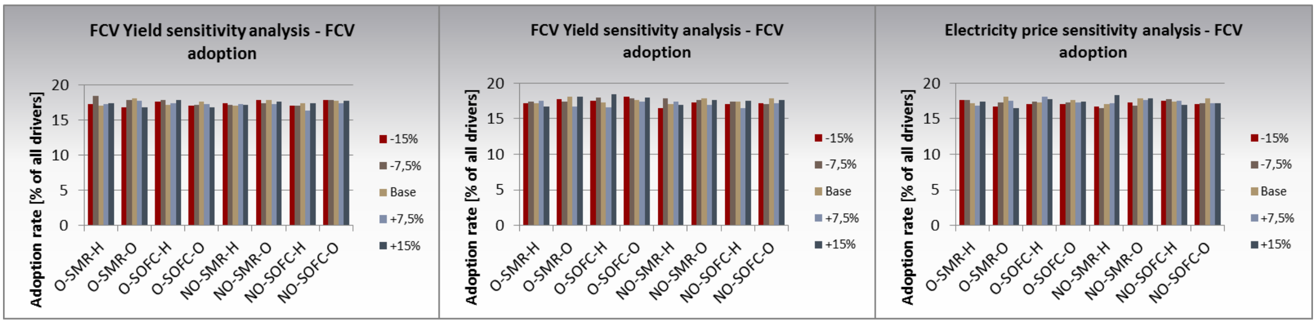

Figure 7-18: Effect of factor variations on FCV adoption.

The used metric to monitor the FCV adoption should similar to the CaPP adoption be interpreted with some care as it is a recording of the share of drivers owning a FCV at a specific time in the simulation.

The CaPP adoption is dependent on the amount of drivers that own an FCV. Only these drivers will possibly adopt a CaPP parking behaviour. Besides influencing the amount of cars at the CPPP, the amount of FCVs also influences the performance of the system with respect to pollution (discussed in Appendix F). One could expect the introduction of CaPP to lead to a higher FCV adoption; parking at a CPPP has the benefit of receiving a free refill of the hydrogen tank, and subsequently a lower yearly cost of use for FCVs. Mainly this latter influence of the CPPP on the FCV adoption share is interesting for this project.

Following the same approach as in 7.3.3.2 we first study the visualisation of the FCV adoption rate in specific runs over time. We have used Netlogo to plot the FCV adoption for a large number of runs for which each run a different CPPP design was used. The general shape of the plots was similar for all runs. This leads us to present only two of the plots for the sake of readability.

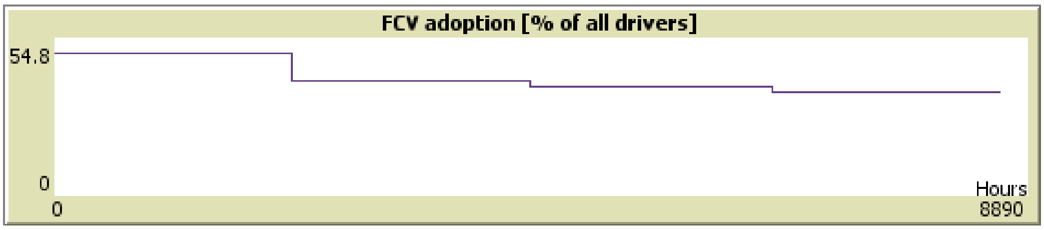

Figure 7-19: FCV share after one year. Design set to: peak load production, steam reformer, no obligation and near homes (random seed 1440832116).

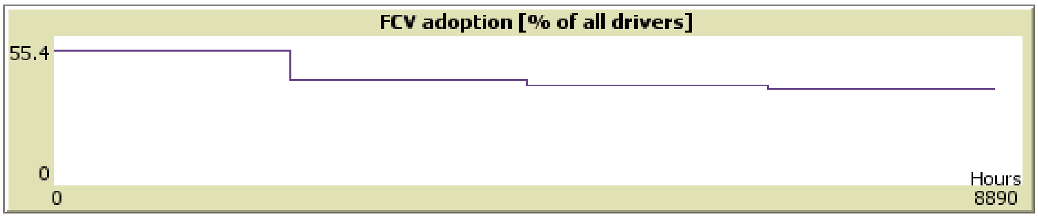

Figure 7-20: FCV share after one year. Design set to: peak load production, SOFC, obligation and near offices (random seed -125178597).

Figure 7-19 and Figure 7-20 confirm the decreasing share of FCVs in the simulation over the course of time. In the model drivers assess once every quarter of a year if their car should be renewed. In each of the plots above we see the effects of this mechanism in the form of four changes in the FCV share.

The model is initialised with 50% of the drivers owning an FCV. The observed consequent decrease in the figures above and the final values of less than 20% resulting from the sensitivity runs (Figure I-1, Figure I-2 and Figure I-3) challenge the initialisation with 50%. Also the decrease in FCV share in the simulation is in conflict with the earlier formulated expectation that the introduction of CaPP could result in higher FCV shares.

To understand why during each passing of a quarter of a year the amount of FCV decreases we let Netlogo monitor and plot the FCV value function without the error. The value function is calculated based upon the beliefs of the driver, certain global variables and a standard error normally distributed with a mean of 0 and a standard deviation of one. If the result of the calculated value function is a positive number, the driver will purchase an FCV. The figures below depict the resulting value functions if the average beliefs of the drivers are used and the error term is excluded. From the terms used in the determination of the value function, the terms fuel cost difference and the term pollution are based by the beliefs of the driver and subsequently subject to the influence of information diffusion among drivers.

Table 7-3: Selection of recorded FCV value function terms

	Constant	Car price difference	Price difference * car worth	Fuel cost difference	Pollution
120 days	-0,575	-0,899	0,279	0,059	0,1
240 days	-0,575	-0,899	0,279	0,062	0,1
360 days	-0,575	-0,899	0,279	0,064	0,1

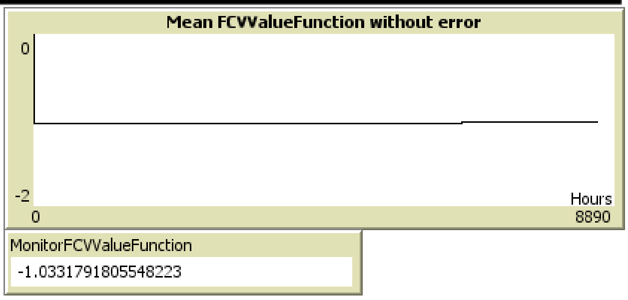

Figure 7-21: Mean FCV value function without error term. Design set to: peak load production, steam reformer, no obligation and near homes (random seed 1440832116).

Table 7-4: Selection of recorded value function terms

	Constant	Car price difference	Price difference * car worth	Fuel cost difference	Pollution
120 days	-0,575	-0,899	0,279	0,056	0,1
240 days	-0,575	-0,899	0,279	0,059	0,1
360 days	-0,575	-0,899	0,279	0,062	0,1

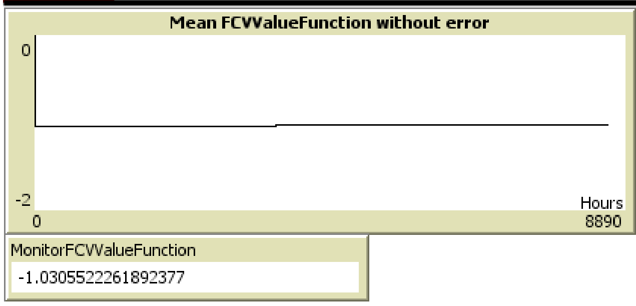

Figure 7-22: Mean CaPP value function without error term. Design set to: peak load production, SOFC, obligation and near offices (random seed -125178597).

The observed value functions are surprisingly constant over time. We would have expected these values to vary over time due to the influence of the information diffusion on the beliefs of the drivers. We indeed see that the term of fuel costs difference is changing over time, but it itself has only a marginal influence on the value of the value function. Also the benefits of pollution reduction are slim compared to the constant and the effects of the purchase price of FCVs. In both cases the weighting factor of the elements (i.e. the β's in the choice model) are responsible for the low influence of the terms on the value function. In line with the conclusions by Hidrue et al. (2011), we find that the purchase price of the vehicles dominate the car choice. We however did not foresee the influence of other factors such as fuel cost savings or pollution benefits to have a very small influence as found in the simulation runs.

SYNOPSIS

The existence of CaPP was expected to contribute to a larger share of FCVs. CaPP offers free fuel for FCV owners parking at the installation. CaPP also reduces the well to wheel emissions of fuel cell vehicles as a larger share of the hydrogen can be produced with renewable energy sources. By simulating the model we are however confronted with the fact that the difference in purchase price between an ICV and an FCV is by far the most influential parameter in the decision making of the driver. The factors that could be influenced by the existence of a CPPP are only valued to a limited extend by the drivers. Subsequently the existence of a CPPP has little effect on the share of FCVs in the simulation.

This behaviour heavily relies on the used choice models for our model. Besides originally being constructed for the choice between ICVs and EVs, the choice models are based on consumer perceptions of North-American drivers. One could expect that the valuation of fuel cost savings is different for European drivers than for North-American drivers.

The model as used in this project would greatly gain in strength if choice models would be available that give insight into the choice of Dutch drivers between ICVs and FCVs and the possibility to park at a CPPP with an FCV. A more elaborate discussion on the used assumptions and choice models can be found in section 8.2.

7.3.4 Sub conclusions

Varying the electricity yield per kilogram of hydrogen of an FCV, the gas price or the electricity price over a limited range does not result in structural different model behaviour. The operational losses made by the CPPP are caused by the existence of an on average negative profit margin per kilogram of hydrogen. The sensitivity analyses show that this mechanism is robust over the variations of the selected factors and used variation range.

Furthermore we have encountered a low adoption share of drivers willing to park at the CPPP. The cause can be found in the used reward for drivers. We have assumed that drivers that park their FCV at the CPPP are rewarded by a free tank of hydrogen. Due to the low consumption of hydrogen per driven kilometre by FCVs, a free hydrogen refill has a monetary value that is insufficient to convince drivers to park at the CPPP.

Lastly also the adoption of FCVs in the model was observed to be low. The existence of a CPPP provides additional benefits for FCVs with respect to ICVs (namely a reduction in fuel costs and improved environmental performance). These benefits only play a small role within the used car purchase choice models of Hidrue et al. (2011) and as a consequence do not significantly impact the valuation of FCVs by the simulated drivers.

8. Discussion of results

In this chapter we zoom out from the detailed modelling process and experimentation. We have used numerous assumptions and simplifications whose implications will be the topic of the subsequent sections. First we discuss the used set of analyses from chapter 7 which is followed by the discussion of the analyses separately. The chapter continues with a reflection upon the used assumptions and a reflection upon the modelling study itself. Lastly an interpretation of the results for the Green Village is given in the last section of this chapter.

8.1 Discussion of analyses

Due to the use of a time step of fifteen minutes and a run time of three years the model is computational intensive which limits the types of experiments that we can conduct in the set boundaries for this project. For our intentions of exploring the possible futures of CaPP methods such as the exploratory modelling analysis approach (EMA) would be fit (cf. (Hamarat, Kwakkel, & Pruyt, 2013)). However this approach requires several thousands of runs which would require considerable computational power. Due to time and computational limitations the EMA approach was not applied in this project.

8.1.1 Discussion of experimental approach

The analyses executed for this project are a fraction of the amount of analyses that we could execute with the model, as depicted in Figure 8-1. We note that the possibilities with the model are still large and numerous different experiments and analyses could have been executed. These analyses could focus on further deepening the knowledge gained from the analyses we have conducted, or could focus on fundamental different elements of our model. The goal of the modelling study was, however, not to understand the operation of the model under all the possible settings of the control and environmental variables. The model serves as a tool that is to aid us in gaining a better understanding of the possible barriers for the successful exploitation of a CPPP.

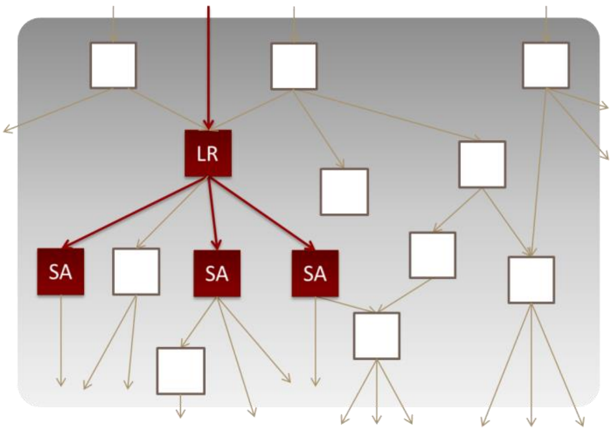

Figure 8-1: Used explorative analyses. The Linear Regression method (LR) gave base to a total of three Sensitivity Analyses (SA).

In chapter 7 we have identified several barriers by studying simulation runs and model behaviour that have been highlighted or were made visible by the executing the analyses. The used set of analyses that have been used in this project is fit for our purposes. This does not mean that the same or similar insights as obtained in the previous chapter could have only been found with the approach that we used.

In the studied runs the major barriers for successful exploitation have been exposed. The fact that specifically these barriers are exposed leads us to concluding that these barriers are dominant in the model simulations as studied. Although we intended to find these kinds of barriers, their dominance in our results also prevents the identification of other significant but less dominant barriers. To illustrate this with an example; hypothetically both the low electricity price and the structural shortage of hydrogen could prevent a profitable CPPP exploitation. If we would investigate this situation we would likely see that no electricity is produced due to the shortage of hydrogen and will identify the latter as the dominant barrier. As no electricity is sold due to the hydrogen shortage, we would not be able to observe the effect of the low electricity price and will not identify it as barrier.

A complete set of possible barriers could be obtained by identifying the current dominant barrier, remove it from the system and search for the following dominant barrier. This approach would however when executed with a modelling study require model adjustments and new experiments to be run for each iterations. Due to the time limits of this project we are not able to execute such iterations.

8.1.2 Discussion of using linear regression

The regression model is not to be used to serve as a direct base for conclusions. We selected the ABM paradigm for our study in order to be able to capture the complex bottom up, complex system and internal system interactions. With such characteristics we ex-ante expected the model to show complex and adaptive behaviour. The linear regression method does not have the objective to serve as a tool to analyse such behaviour.

However, in our study the usage of linear regression turned out to more valuable than expected. Due to the difference between results (a good linear fit) and our prior expectations (a poor linear fit due to the dynamics of the ABM) our attention was drawn to investigating the lack of dynamic behaviour of our ABM. As a result we identified that the limited hydrogen production capacity in relation with the high hydrogen demand of stationary FCVs results in continuous hydrogen production and the profit margin for the CPPP to dwindle.

The regression model also gave a first feel about the financial position of the different CPPPs which was not very optimistic. The cause of the poor financial position of the CPPP is found in the combination of continuous hydrogen production and conversion losses. In the case of continuous production, energy is purchased, converted and sold in the same time step. Due to the conversion losses, the production of each kilogram of hydrogen requires more energy than the same kilogram again yields when converted in FCVs.

8.1.3 Sensitivity analysis

Based on the preliminary runs we selected three variables to include in our sensitivity analyses. As a result the setups of these analyses are dependent on the preliminary runs and the insights gained from examining the results of the linear regression estimation.

The number of three sensitivity analysis was chosen due to time considerations. As a result we chose the factors that we expected to have the largest effect on the chosen main outcome of interest for our modelling study; the ROI of the CPPP. We have varied the following factors; the FCV conversion efficiency, the electricity price and the gas price. We found that all three factors had linear effects on the ROI of the CPPP.

Furthermore we found by looking at the other KPI's that unrelated to the design of the CPPP the link between financial operation of the CPPP and the behaviour of drivers was very weak if not non-existing. We found that the current formalised policy of driver reimbursement by a full tank of hydrogen has insignificant impact on the perception of the drivers to consider CaPP. Due to the low fuel consumption of the FCVs, the amount of hydrogen that is refilled is limited. This policy rewards drivers with about €1500 a year, where Parsons et al. (2014) have reported numbers in the range between €1000 to €4000 to have significant effects.

8.2 Meta-analysis

For our model we have used numerous assumptions. Loosening or removing any of the used assumptions will result in a different system being simulated and possibly different behaviour. The used assumptions thus limit the applicability of the results of our study. By reflecting on a selection of the used assumptions we again zoom out from our model and discuss how the system that we used to gain an understanding of the operation of a CPPP, is positioned with respect to other system identifications. Below we discuss the different types of assumptions separately.

8.2.1 Meta-analysis on technical assumptions

Steady state operation
For the operation of the hydrogen system within the CPPP we have used studies that assume that the devices reach steady state operation (Fernandes et al., 2015, In press; Spanjer, 2014). Start-up times and partial load efficiencies are neglected in this study. As a result the modelled CPPP represents the theoretical operation of a CPPP rather than the practical operation. In reality conversion efficiencies and the flexibility of the installation can be expected to be lower.

Fuel cell operation
Operating the fuel cell during the times the FCV is not driving will result in a reduced fuel cell life time. The current limited fuel cell life time is currently seen as the biggest obstacle in the whole CaPP project. The inclusion of fuel cell degradation can be expected to have negative influence of the perception of CaPP by consumers and might result in higher desired remunerations.

The efficiency of the fuel cell in our study is on the other hand based on outdated fuel cell modules (Spanjer, 2014). The current and future fuel cell efficiency can be expected to be significantly improved. The usage of the outdated information reflects the lack of knowledge concerning this influential parameter at this moment in time.

Types of methane reformers
In this study the SOFC and steam methane reformer are considered as alternatives for the devices that reform natural gas into hydrogen. The SOFC is at the time of writing not yet commercially available on the scale as required for a CPPP. Furthermore other hydrogen production methods are currently being studied at the Green Village. The used technical design is thus still subject to possible changes, and the results of this study only apply to a limited set of the future possibilities.

Storage method
Compressed storage is currently the most logical method of hydrogen storage. Other storage methods such as liquid storage have similar functional implications. The storage of hydrogen by converting it to ammonia would however allow much different functionalities. Ammonia can be stored under atmospheric temperatures and could be used to bridge seasonal energy demand differences. The characteristics of a system that uses ammonia as a storage medium are fundamentally different from the system in this study. As a consequence the results of this study should not be extended to these types of designs.

Other forms of CaPP
In this study we have solely studied a Car Park Power Plant as described by van Wijk and Verhoef (2014). The essence of CaPP is using parked FCVs for the production of electricity. This objective can, however, also be achieved by smaller scale car parks or decentralised installations (possibly without on-site hydrogen production). Also the size of five hundred parking spots could be problematic for certain locations such as existing car parks at offices. The scaling effect of the size of the car parks and the operation of decentralised CaPP applications have not been studied in this study and our results should not be extended to these cases.

SYNTHESIS
For the technical operation of a CPPP we have used assumptions that result in an optimistic representation of a CPPP. Mainly the assumption that the hydrogen production system operates following the steady-state flows on the one hand and neglecting fuel cell degradation on the other hand result in an over optimistic representation. The optimism is somewhat dampened due to the recent and expected increase of fuel cell efficiencies.

8.2.2 Meta-analysis on institutional assumptions

Alternatives for peak load production and secondary control use cases
The use cases that are considered in this study have been selected mainly due to their relatively short contracting period. The use cases of primary and tertiary control were excluded due to their contracting periods of respectively weeks and years during which the contracted capacity is to be available at all times. These two use cases are however interesting for the CaPP project as they are reimbursed by a capacity fee, possibly limiting the amount of electricity produced by the FCVs and mitigating the fuel cell degradation. The operation of a CPPP depending on capacity fees is expected to follow different strategies. The possibility of changing the contracting times of the primary and tertiary control use cases in consultation with TenneT are at this stage unknown.

The local use case has been excluded from this study due to the difficulties of generalisation of the different locations, demands and objectives. The local use case offers possibilities of picking locations which allow for fine tuning of the CPPP operation demands and desires for both the demanders of the CPPP as for the owners of the CPPP. In early stages the CaPP project can as such 'pick the winners' from all the possible locations. At these locations the business model of the CPPP could be fundamentally different (e.g. the CPPP could be mainly valued for the production of residual heat instead of electricity). Our generalisation of the operation of a CPPP is unable to reflect the possible fine-tuned operation of a CPPP for the local use case, and the results of this study should not be extended to these types of designs.

Secondary control: adhering regulation down signals by using electricity
Regulation down signals are issued by TenneT if the supply of electricity exceeds demand. In the current situation contracted generators can fulfil a regulation down signal by lowering their production. If the regulation down price is negative the contracted parties are paid by TenneT.

For our model we have assumed that the regulation down signals can also be adhered by installations that can increase their electricity demand and as such contribute to the balance of the grid. For a CPPP this would allow being paid to produce hydrogen with an electrolyser. Although the mechanism is currently not in place, the increasing penetration of intermittent energy sources leads us to determining this scenario as plausible. As such we have included it in our representation of the designs that pursue a secondary control use-case.

The working of the electricity market and subsequently whether or not this mechanism will be in place at the time of the CaPP introduction is highly uncertain. The assumption as made for this project results in negative electricity prices a few times a day which is a rather optimistic view from the perspective of CaPP.

Neglecting selling heat and water
The value of water and heat in the current markets are negligible when compared with the value of electricity (Palazzi, 2013). As a result we have neglected the incomes from water and heat. Besides possible added values in the local use cases, we do not foresee large implications on the financial position of the CPPP of this simplification.

Tax and subsidies
Our representation of CaPP does not include receiving any subsidies or paying any taxes. Although these means would have direct effect on the financial position of the CPPP, they would not bring about a structural difference in the behaviour of the model as used. Structural fiscal support might result in the CPPP becoming profitable for its owner.

Low gas prices
From the data of the CBS (2015a) we learned that the gas price decreases with the amount of gas annually purchased. From our estimation as presented in Appendix F a threshold will be surpassed if roughly twelve CPPPs can jointly purchase their natural gas collectively, resulting in a gas price of 39 cents per m^3 instead of 74 cents per m^3.

We have assumed the lower gas price for the CPPP in our representation. If the CPPP cannot be part of some sort of collective purchase, its costs will significantly increase.

Method of driver reimbursement

For our study we have assumed that drivers are reimbursed with a full refill of their FCV. As discussed in section 7.3 we have identified this factor as causing a minimal interaction between the operation of the FCV and the behaviour of the drivers. Due to the low fuel consumption of the FCVs the value of full refills are limited. For future research it is deemed important to select an improved method of driver reimbursement.

Car ownership

The ownership of the ICVs and FCVs are in our model the drivers themselves. However different form of alternative ownership such as fleet management or car sharing could be considered. Fleet management would require the CPPP operator to make fine-tuned arrangements with this manager. Similar to the argumentation above concerning the exclusion of the local use case, a generalisation such as our modelling study is unable to capture this mechanism. Fleet management might be interesting as it again allows the CPPP owner to influence the way the CPPP is operated. The dynamics of our model would not be adequate to represent these car ownership possibilities and therefore the results should not be extended to these possible futures.

SYNTHESIS

Many of the used assumptions on institutional aspects are made due to high uncertainty about the possibilities. As a result our model only represents one of the many possible institutional designs. When interpreting the conclusions of this study, one should be aware that these conclusions might not be valid for systems in which different institutional assumptions were made. Furthermore it is important to acknowledge that our study is based on the set of institutions of today, not taking into account the design and construction or emergence of new institutions that would open up new possibilities for CaPP.

Some of the assumptions on the institutional aspects of CaPP have been made in order to be able to generalise typical CPPP operation. If the CPPP operates following a local use case or targets FCVs that are managed in fleets, the CPPP owner can influence his own environmental operational conditions. This could be especially valuable for the early introduction phases of CaPP. Such approach could follow the guidelines of the strategic niche management theories (cf. 2.2.3) and would allow for concept testing and knowledge generation before the CaPP concept is deployed on a large scale.

8.2.3 Meta-analysis on behavioural assumptions

Used choice models

For both the consumer choices of buying FCVs and the adoption of a CaPP parking behaviour we have used choice models that have been constructed based on surveys of drives from the US. The choice model for car purchase has been based on a model that represents the choice between ICVs and EVs. The choice between parking behaviours has been based on the choice between supplying V2G services with an EV or not by the consumer. More information on how these choice models were adjusted can be found in 5.2.6.

First of all it is safe to assume that Dutch drivers will behave differently from US drivers. We expect differences in the valuation of fuel costs and overall car preferences. Furthermore the assumption that FCVs and CaPP are perceived similarly as respectively EVs and V2G services with EVs has been made. Both assumptions are not likely to hold for the real future system. We do not find ourselves in the position to be able to draw conclusions about the effects of loosening or improving the choice models. At this stage essential knowledge on how Dutch drivers will react to FCVs and CaPP is lacking and more research is required.

Social mechanism

The used social mechanism, the used parameters for this mechanism and the time frame in which the mechanism operates are all uncertain. The actual mechanism of information diffusion that is of effect for the CaPP case would require substantial additional research efforts. For this project we have assumed one mechanism to be applicable and have used it. The implications of using a different mechanism could however be substantial.

If we reflect upon the used mechanism we expect the mechanism to be rather on the strong side. This means that the diffusion of information is in our model rather quick, and our intuition would expect the information to diffuse at a slower pace. This statement is mainly caused by the perceived short time frame of the mechanism (being weekly) and the large connection of all drivers (each driver talks to all his colleagues at work). We emphasize that this statement is based on our gut feelings, and that more research is required to validate the social mechanism as used.

CPPP operation tactics

The operation of the CPPP has been formalised in relatively simple mechanisms (see 6.2). For instance we have assumed that if the CPPP follows a peak load production use-case, it will have the objective to produce for all peak load hours. The operation tactics of the CPPP could be improved by allowing the CPPP to determine if the price of the current moment in time is high enough to cover the marginal production costs of the potential produced electricity (similar to the bidding process of today's electricity power plant; produce only if the price is higher than the marginal costs). Improving the control of the CPPP will greatly improve its financial operation. Whether this would result in sustainable ROI for the CPPP owner is then still to be researched. Our expectation is that due to the high energetic losses making a profit under any operation tactic will be a large challenge.

SYNTHESIS

Both the used choice models and social mechanism should be further investigated. Currently the knowledge on how either of these elements would look like for the CaPP project in the Netherlands is lacking. Both elements have large influences on the behaviour of the drivers in the simulation. The financial operation of the CPPP in our simulation is however independent from the behaviour of the drivers. Improving the social mechanism and choice models and implement these it in the model as it currently is, would not lead to different behaviour of the CPPP concerning financial indicators. It would on the other hand impact the FCV and CaPP adoption rates. Currently a population of 10.000 drivers is required to study the operation of a CPPP as the adoption rate is around the 3 to 5%. If due to improved social mechanisms or choice models this adoption rate would increase, the pool of drivers could decrease. The pool of available drivers might in the future affect the choice of location for the first CPPP.

The CPPP as currently formalised has relatively simple operation rules. Improvement of these rules would allow for significant improvements of the financial position of the CPPP.

8.3 Discussion of modelling effort

8.3.1 Using the AOF

We found the approach of the AOF very useful for structuring the identification of the system. However the model that was constructed following this approach showed some drawbacks. Including operational aspects forced us to switch to relatively small time steps. In order to still observer middle-term behaviour the model is required to simulate a very large number of time steps.

As a consequence the model analysis became a challenge as the required computational time for experiments was about one minute with the available computers. The resulting duration limited the choice of analyses that could be executed. The relatively long simulation time also makes the use of alternative analysis method such as EMA difficult, as this method relies on the execution of a very large number of runs. Additionally due to the large number of simulated time steps we were unable to log the data of every time step.

One of the largest difference we found between the intentions of the AOF and our approach is that we have assumed that due to our smaller time period of interest, certain mechanisms (mainly social) are not present in the CaPP case in the way Yücel (2010) describes them. This brings up the question if different mechanisms should be suggested to be used for studies on the operational time frame.

Lastly in section 5.2.8 and 5.2.10 we have made additions to the system identification step. First of all we observed that the AOF does not guide the definition of the time step. Secondly the AOF does not include the as-is dynamics. The latter is understandable as the AOF focusses on transitions which are types of change. However for our model with a focus on the operation of a system innovation we are also interested in the model behaviour if it does not change.

8.3.2 The model

As discussed in section 8.1 the analysis of the model was limited due to the used time scales. We were however still able to use the model for our purposes. The model or its analyses should not be seen as the main deliverable of this project. Instead this study has the objective of the identification of the possible barriers for the successful exploitation of a CPPP. The model served this purpose in two separate ways;

1. The modelling process forced us to very thoroughly examine each subpart of the CaPP system until such a level that we could tell a computer how we view this world. The main benefits of this approach are that a computer is unable to handle ambiguity, and therefore our explanation had to be perfectly clear.
2. The constructed model allowed for computation of all the knowledge we fed it in parallel. Although we as humans are capable of constructing single coherent mechanisms, we lack the ability to process parallel processes and the phenomena's including chance (Kahneman, 2011). We could view the model as a place in which we stored the different stories and use the computer to show us what it means if all the stories are executed (pseudo-) simultaneously. As such it can show us dominant or unexpected mechanisms or interactions between mechanisms. We have used the model and the executed analyses to direct our search for interesting and relevant runs to be analysed in further detail.

We conclude that the guidelines of the AOF in combination with a minor amount of additions of our own have resulted in a suitable model for this study. However, as we have seen that the operation of the CPPP and the behaviour of the drivers are almost unrelated the complex emergent behaviour that we typically see in ABM is absent in our case. We acknowledge that this study could have been executed with a simpler model in for instance excel. This acknowledgement is based on hindsight knowledge and could be challenged if different assumptions (in our case mainly on the remuneration of the CaPP parking drivers) were made. Additionally we expect the ABM to have additional value in the form that it can be relatively easily adjusted, tweaked, expanded or be and as such possibly serve future studies.

8.4 What do the results mean for the CaPP project?

In this work we have executed a selection of experiments and analyses of the enormous range of possibilities. If time would have allowed we could have explored our model much more. The experiments and analyses that we did execute did result in the identification of several possible barriers. As such the used approach in this thesis is adequate for our research objective. We did not aim to provide an all covering list of all the possible barriers CaPP could face. Instead we have focused on coming up with an approach that is able to identify these kinds of barriers.

The CaPP project is a very complex problem and will require a substantial amount of further research. Our study and subsequently results cover a part of this complex problem. The results of the experimentation phase are subject to several limitations. We will discuss the two important limitations below.

1. Results based on financial performance indication of CPPP

For our experimentation we have taken the operational financial position of a CPPP as leading. However, besides the economic opportunities, the CPPP concept is expected to also provide much value for society in the form of providing additional flexibility of future energy systems. The barriers as identified in this study could be seen as potential barriers for an independent financial operation of a CPPP. The results however did not have the focus of covering the complete potential value proposition of a CPPP. Taking this into account, even if all barriers as identified in this study might become reality, the CPPP concept might very well still be a viable, desirable and profitable concept when considering the complete potential value proposition.

2. Experimentation on one simplified possible future.

As we have studied a future development we have been forced to create a representation of this future that we assess to be useful. This future is the subject of many uncertainties (which we have to a limited extend explored with the sensitivity analysis) and many unknowns. If this future is substantially different from our representation our results might lose their value. Important unknowns that are of importance for our research include but are not limited to:

- The assumption of the existence of a widely implemented hydrogen refilling infrastructure.
- Implementation of novel substantial changes in the energy system: other system innovations.
- The possibility of the introduction or emergence of new institutions.

Organisations such as the Green Village can influence the direction of development of some of these unknowns, but only to a limited extend. Although we do not know the exact development of these unknowns, the results of this study show that certain mechanisms and elements can present itself as risks for the successful operation of a CPPP in one of the simplified realities and thus gives reason to prepare ourselves for these risks.

SYNTHESIS

The results from chapter 7 can on the one hand be seen as a proof of concept. We observe that the approach as we have used it is capable of identifying possible operational barriers for CaPP and possibly for system innovations in general. On the other hand the resulting identification of mechanisms can be interpreted as direct result for the Green Village. Although we do not claim that the mechanisms as identified will definitely happen or are threats for the CaPP concept, our results does provide substantiation for research into these risks. Some of the risks are already known by the Green Village and their causes are the subject of other research projects (e.g. the control tactics of the CPPP). Others might be new insights providing base for new research into ways to mitigate these risks (e.g. low valuation of benefits offered by CPPP).

9. Conclusions and recommendations

The main objective of this research was to aid in the process of delineating the design space for CaPP, by providing an approach that is capable of identifying possible barriers for the successful operation of a CPPP when introduced in different forms. The main research question has set the end goal of this research to the formulation of possible barriers. The objective of this research is fulfilled in the process of pursuing this end goal. This chapter presents the answers to our research question as stated in chapter 1. First the sub questions are repeated and answered and subsequently the answer to the main research question is presented.

9.1 Answering the research sub-questions

9.1.1 Which theory is able to guide the system identification of the operation of a system innovation?

The Actor Option Framework (AOF) is fit to guide the system identification steps for the CaPP case. The AOF is a theory from the body of transition literature and has been constructed with the particular goal of supporting analyses of transition dynamics. CaPP can be characterised as a system innovation as it is expected to bring about a substantial change in the business models, assets, products, services and markets of the energy and transport sector. The complexity of the system in which such a concept is to operate, make it difficult to identify the relevant aspects, relations and dynamics that are important to consider. The body of transition literature offers a wide range of theories that focus on change processes in these complex systems.

From the available theories, the AOF was chosen for following reasons;

- Unlike the other considered theories, the AOF uses a focus on transitions that supports for research at the level of individuals and their interactions.
- The AOF provides a clear stepwise approach for system identification.
- The AOF consists out of a set of concepts that are flexible enough to be applied to a specific case, but are sturdy enough to allow for comparison between AOF based models.

Although the AOF was guiding in the system identification, the focus of the AOF on transitions and our focus on a system innovation lead to some adjustments and additions to the approach of the AOF. These steps are the definition of a time step, the definition of a time scale, the definition of key performance indicators and the addition of as-is dynamics.

9.1.2 What are important technical and institutional design choices that are expected to impact the operation of a CPPP and can be formalised with the current available knowledge?

One technical design choice and three institutional design choices are identified that have functional impacts on the operation of a Car Park Power Plant (CPPP) and do not require additional research of substantial scale. The eight design options that follow from the four identified design choices are presented in Table 9-1.

Table 9-1: studied design choices and accompanying design options

	Design options	Functional impact
Methane reforming technology	Steam methane reformer	High hydrogen production from natural gas
	Solid oxide fuel cell (SOFC)	Lower hydrogen production from natural gas, compensated by side production of electricity
CPPP location	Near households	FCV availability during the nights, drivers having to walk distances between CPPP and home
	Near offices	FCV availability during the days, no availability during the weekends
Use case	Peak load production	Production of electricity between 09:00 and 20:00
	Secondary control	Production of electricity when regulation up signal issued by TenneT & Electricity intake when regulation down signal issued by TenneT
Driver parking incentive	Parking obligation	High certainty of amount of FCVs parked in the installation for each moment of the day. Perceived disutility by drivers
	No parking obligation	Little certainty concerning FCVs parked in the installation at any moment in time.

Besides the design options as listed in Table 9-1 there are numerous other choices still to be made. However these choices were assessed to either have little functional impact on the operation of the CPPP or require additional research of substantial scale.

9.1.3 What is a relevant system delineation to explore the environment and operation of a CPPP?

An agent based model with a structure and a process sequencing as shown in respectively Figure 9-1 and Figure 9-2 has proven to be a useful method to explore the possible operation of a CPPP and its environment. Both the identification of the system and the experimentation with the model leads to a deeper understanding of the dynamics of the operation of a CPPP and its environment. The system delineation was guided by the use of the actor option framework.

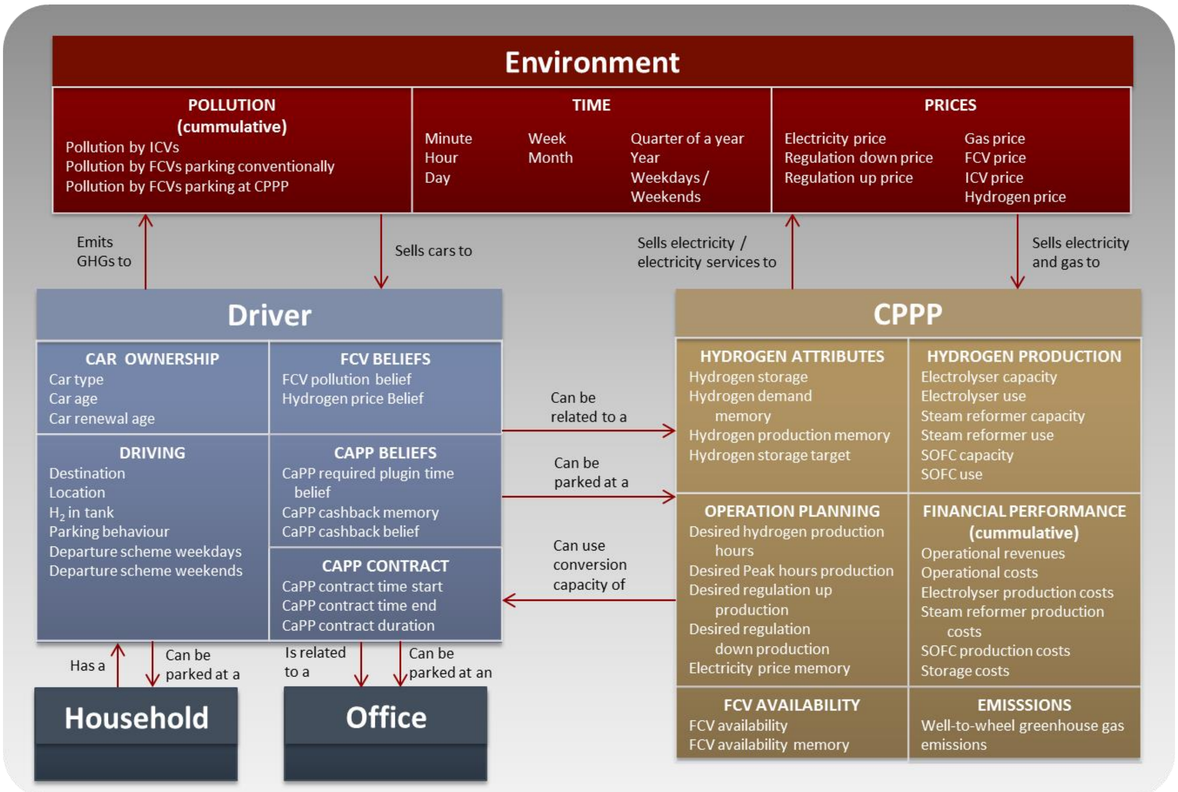

Figure 9-1: ABM Model elements, attributes and relations

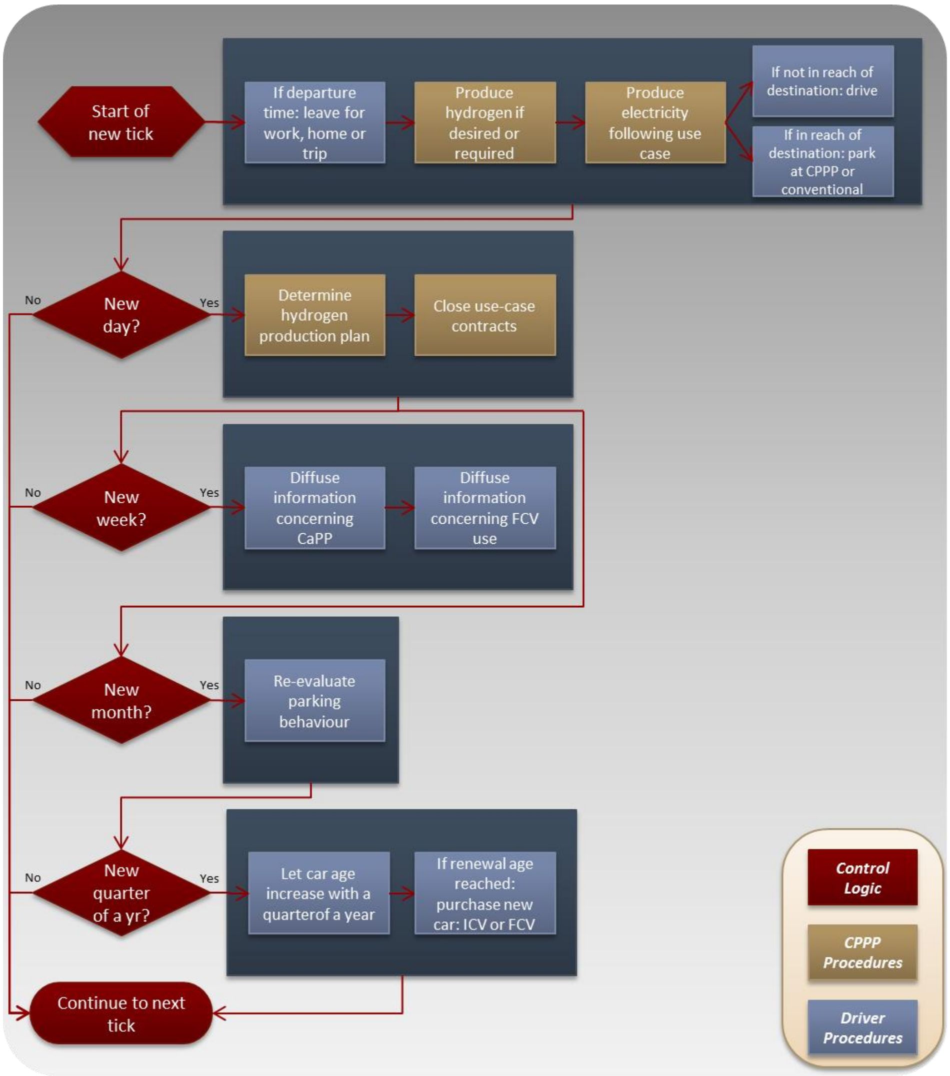

Figure 9-2: Agent based model sequencing

9.2 Answering the main research question

The main research question of this research is:

Which CPPP design elements or environmental factors could form barriers for the successful operation of an introduced Car Park Power Plant installation?

The answer to the main research question is found by exploring an agent based model that was constructed for this project. The computer model is a simplified representation of the complex reality and can be seen as a set of coherent assumptions. Exploring the model behaviour has provided insight into the simultaneous effects of the used assumptions and allowed for the identification of certain factors as being potentially blocking for a successful CPPP operation.

The exposed factors were found to be possible barriers due to being part of a blocking mechanism. In this thesis two blocking mechanisms were found which are discussed in the subsequent sections. The first blocking mechanism consists out of the following factors:

- Simple CPPP electricity production control tactic.
- Insufficient hydrogen production capacity.
- Significant conversion losses.

The second mechanism is the result of the interplay between the following factors:

- The CPPP offering a free hydrogen refill as reward to drivers using the CPPP.
- Low hydrogen consumption for driving by fuel cell vehicles.
- Low valuation for benefits that can possibly be obtained by using a CPPP.

9.2.1 Continuous hydrogen demand leading to financial losses

From the exploration of the simulation model we find that the financial position of a CPPP might be problematic. A large and unsatisfiable hydrogen demand was in our exploration the cause of this behaviour.

The usage of a simple CPPP operation tactics in our model results in CPPPs to produce electricity at all moments that satisfy the selected use-case. This simple electricity production control tactic does not include an assessment of whether the sales revenues of electricity generation will cover the production costs of the hydrogen. As a result the CPPP desires to produce electricity during many hours of the day.

An FCV as formalised in this study has a production capacity of 100 kW. To maintain this capacity for a full hour the car requires 6,25 kg of hydrogen. The installed production capacity of both hydrogen production methods combined is 4000 kilograms per parking spot per day which is comparable with today's production capacities of ten on-site methane reformers. With production capacities of these magnitudes each car can only be fed hydrogen for a bit more than 75 minutes per day. As the CPPP, due to the simple operation tactics, desires to produce electricity during many hours of the day, the hydrogen production methods are used constantly at nearly full capacity.

If continuous production of hydrogen occurs, a CPPP would no longer be able to maintain a profit margin by buying electricity when the price is low (during off peak hours) and selling the electricity when the price is high (peak hours). Due to the large continuous demand of hydrogen for electricity generation, hydrogen is consumed quickly after it was produced and the price difference of the electricity when it is bought and when it is sold becomes small. In these cases the value of storing energy between off-peak and peak hours is not large enough to compensate for the conversion losses within the CPPP.

The occurrence of this mechanism shows that a CPPP will require advanced control tactics. These tactics should maximise the profit margin of each kilogram of hydrogen by taking into the conversion losses within the CPPP and a limited hydrogen production capacity. If either the conversion losses within the CPPP or the limitation of hydrogen production are too severe, the control tactics will independent of their ingenuity be unable to result in viable profit margins.

9.2.2 Low valuation of CPPP benefits preventing a perception shift of drivers

In this research we have, among others, studied the effects of offering a free hydrogen refill as a reward for the drivers parking at the CPPP. We encounter that due to the low hydrogen consumption per day by the fuel cell vehicles this reward could have an insignificant impact on the perception of drivers. This results in a low share of drivers that is willing to structurally park their car at the CPPP.

Also the effect of a CPPP on the perception of driver with respect to fuel cell vehicles could be very limited if the CPPP rewards its uses with a free hydrogen refill. CPPPs can provide benefits for fuel cell vehicles owner by lowering the fuel cell costs and improving the environmental performance of their vehicles. We are however confronted by the fact that these benefits are marginally valued by drivers when deciding to purchase a fuel cell vehicle or a conventional vehicle. This choice is instead dominated by the difference in vehicle prices. As a consequence the share of drivers that owned a fuel cell vehicle compatible with the CPPP was decreasing in our simulations.

The combination of a small fuel cell vehicle share and a small CPPP adoption share would require each CPPP to rely on a very large driver base population. These populations would be in the order of 10.000 drivers. This would make it difficult to find a central location that could serve as a daily parking location for potentially all these drivers.

The main lesson we learn from the observation of this mechanism is that the required size of the driver population for each CPPP might be problematic. If car drivers are not persuaded to buy a FCV and subsequently make the decision to use this FCV in combination with a CPPP, the concept of a centralised application of CaPP does not appear to be feasible. The benefits of a free hydrogen refill and improved environmental performance of the FCVs are found to have insufficient impact on the perception of drivers. This calls for further research towards these perceptions and the exploration of different types of driver rewards.

9.3 Relevance

9.3.1 Practical relevance – value for Green Village

The practical value of this thesis is the system delineation for the operation of a CPPP. This thesis acts as a filter between the complex real world and a human understandable model. The main insights for the Green Village have been generated during the modelling process. Knowledge has been gained and or strengthened concerning among others the relevance of sub-systems, possible configurations of these subsystems and the existing knowledge gaps.

By providing the possible barriers and related mechanisms above, we have shown that the chosen approach has been successful to serve the objective of identifying possible barriers for the successful operation of a CPPP. The specific barriers that have been found are the products of the chosen set of assumptions on which the model was built. This work does not claim to provide the correct set of assumptions. The value of this work is instead in providing, for the first time, an overview of which types of assumptions are required and how these assumptions can be structured to study the operation of a CPPP. This thesis should rather be seen as a tool than a final outcome.

The model can act as a base for future studies that for instance aim to further explore the operation of the CPPP, or are in search for an optimal CPPP design and environment. By improving and or altering the set of assumptions the model can be extended and adjusted to fulfil the needs of these kind of studies.

9.3.2 Scientific relevance – contribution to Transition Literature

A method to guide the formalisation of system innovations was found to be lacking in the body of literature. In this thesis we have adopted the Actor Option Framework for this purpose. The framework is intended to guide in the formalisation of transitions. This thesis shows that with some adaptions the framework can be used for projects that focus on system innovations. By executing this project we have added a case study to the body of literature in which we have successfully studied a system innovation by using the guidance of an explanatory transition theory along with some adaptations.

9.4 Limitations

An important limitation to this work is that the representation of the system is not yet according to the ideas of the Green Village. One should refrain from drawing conclusions upon the viability of the CaPP concept as a whole based on this thesis. The system representation used in this thesis is only one of the many possible futures. Due to the complexity of the studied system we cannot draw conclusions upon the other possible futures without further research. A change in one of the larger assumptions could reveal completely different dynamics, especially if these assumptions target the blocking mechanisms as discussed earlier in this chapter. Some of the assumptions are already being studied, such as the control tactics of the CPPP[13].

Furthermore this thesis concerns the possible future development of the implementation of CPPPs. As a natural limitation, we have not taken unknowns into account. For instance we have used the dynamics of the electricity markets as they are now, however the future working of this market at the actual time of CPPP implementation might be completely different. Such changes, system innovations, are expected to influence the electricity market in the middle-long term future, limiting the relevance of this thesis for the long term.

[13] Since early 2015 F. Alavi has started a PhD research on this topic at the TU Delft.

9.5 Recommendations for future CPPP focused research

9.5.1 Outlook

We have argued that this work should be mainly seen as a tool for the CaPP related research. The main body of the tool is not the model itself but knowledge concerning subsystems, the configurations of these sub-systems and knowledge gaps. This thesis does not give an answer to what the boundaries of the CaPP solution space exactly are; it does however make a new step towards this answer.

To progress down this line of research we would recommend any researcher to first determine if he understands and believes the agent based model as built for this project. If this is not the case the researcher is encouraged to follow the same approach with using the AOF for system identification and build a model in a language of his or her own choice. This model can be based on the assumptions used and insights gained during this project. Subsequently we recommend aligning all assumptions with the beliefs and intentions of the Green Village. This will allow for testing the current intentions of the Green Village and explore for operational barriers that are not yet known to the Green Village. The resulting model can serve as a base for discussions on the design of CPPPs and a tool to test solutions to newly found barriers.

9.5.2 Specific knowledge gaps

During this study we have encountered numerous of specific uncertainties for which we have used simplifications or assumptions. By conducting further research the use of these simplifications can be mitigated. We have structured the different types of uncertainty in different themes.

9.5.2.1 CPPP business model and technology

- From our exploration the capacity of on-site production methods is insufficient for the goals as envisioned for the CPPPs. A study towards other sources of hydrogen is recommended.
- The conversion efficiencies of the FCVs has for our study been based on outdated models. An estimation of the FCV efficiency for the years in which CaPP is to be operational results in a more accurate operational representation.
- We have not taken into account that the life time of the fuel cells will be reduced when the FCVs are used for electricity production in the CPPP. More knowledge on this reduction and the consumer perception towards this fact is required. It is likely the consumers will require some extra compensation for this reduction and it will possibly impact the control tactics of the CPPP (e.g. is operating 100 vehicles at 10% more favourable than operation 10 vehicles at 100%?).
- Autonomous driving is seen as a CaPP favouring development as it prevents the driver from walking from the centralised CPPP towards its destination. The prospects of autonomous driving and the possible combinations with a CPPP are however unknown.
- In this study institutions were for this study taken as granted. The possibilities for adjusting, removing or creating institutions has not been considered. The construction of an ideal business case could contribute to a better understanding of the limitations of the current institutions.
- Lower gas prices are available if gas is bought in large quantities. Collective gas purchasing with other CPPPs or other parties should be studied.
- The unreliable FCV availability leads to serious limitations to the operation of the CPPP. A deeper understanding of the possible operation of CPPPs could be gained if the concept of CPPPs is compared to a scenario in which the conversion with FCVs is substituted by a stationary PEM fuel cell.

9.5.2.2 CaPP deployment strategy

- The year in which CaPP is to deployed has to our knowledge not been defined. As a result estimating factors such as relevant prices, efficiencies and the public opinion becomes difficult. Generating an understanding of a favourable deployment planning would result in the possibility to study the operation of a CPPP with more accuracy. The model used for this study could also serve as testing the possible operation of the CPPP in different years when estimations are available of key parameters for these years.

- Producing for local demand allows for picking favourable CPPP locations. A study towards the possible different locations that would benefit from a CPPP would provide valuable insights.
- Fleet operation managers can better predict their car availability. An exploration of possible collaborations between a CPPP owner and a fleet manager is recommended.
- Niches in which the CPPP can be deployed in early stages should be mapped. Literature on these niches is available by van Rijnsoever, Hagen, and Willems (2013) and Koetse and Hoen (2014).
- The executed actor analysis was done based on a desk research. Strengthening this analysis with for instance interviews will give a better understanding of the perceptions towards CaPP.

9.5.2.3 Consumer behaviour

- For this study consumer information with respect to EVs and V2G with EVs of US drivers has been used. Insight into the consumer choices made of European drivers with respect to future FCVs and CaPP is essential.
- CPPPs are designed to be central locations. The perception of drivers towards a potential difference between parking location and destination should be investigated, especially for the situations in which drivers use CPPPs near their homes.
- The driver behaviour included only commuting movements and day trips in the weekends. Improving this behaviour to match the real behaviour of drivers with less predictable movements and for instance holidays would give more insight into the effects of unpredictable FCV availability for the CPPP.
- We have used the driver obligation as the sole possibility to attract the drivers to the CPPPs. However a more complex mechanism including (dynamic) remunerations might be favoured by drivers. Additional research towards the possibilities of such remunerations and the perception of drivers towards them is recommended.

9.6 Recommendations for applying the AOF on the operation of system innovations

9.6.1 Outlook

From our literature review we learned that no explanatory theory on the working of a system innovation existed. For our research we have selected the AOF and used this theory to guide our system identification step. From our experience the usage of the AOF was valuable as a supportive structure to base our filtration of reality upon. Given our experience and our expectation that this approach can be general applicable we would recommend other researchers interested in studying system innovations to seriously consider the framework as an aid. Before a general approach of studying system innovations with the AOF can be established some additional work will have to be executed.

First of all we have found validation of our approach to be problematic. Seeing that our approach has not been executed before and that our case concerns a future development we deal with a model that is based on two uncertainties. If a validation error would occur, we would be unable to assess if this error is caused by our understanding of reality or the method we used to represent this reality. The execution of more case studies and studies towards historical event could validate the AOF as a useful method to study system innovations and give more certainty for future studies.

A second point of improvement would be reviewing the list of basic mechanisms as used in the AOF. This list contains mechanisms that are expected to be of relevance for transitions. We have observed that many of the mechanisms were deemed not to be of effect for the CaPP case and this brings up the question if this list is adequate for formalising system innovations. Again, applying the AOF on historic case studies could strengthen the approach for this cause.

Lastly we were forced to make four additions to the guidelines of the AOF: the definition of a time step, the definition of a time scale, the definition of key performance indicators and the addition of as-is dynamics. We expect that additionally executing these steps will be relevant for any research using the AOF for studying system innovations, but more case studies should confirm this.

9.6.2 Specific points for improvements

We have encountered some mismatches and gaps between our needs and the guidance as offered by the AOF. An overview of these points is given below. These points could act as a starting point for researchers who have the objective to come up with a general approach of studying system innovations based on the AOF.

9.6.2.1 Time

- The AOF does not specify a time period of interest. For studying the operation of innovations after their deployment, a time period of interest is to be defined.
- Due to the more detailed focus, the time step of a model based on the AOF is to be defined in an early stage.
- The relation between the time period of interest and the time step should be assessed in an early stage of the system identification. It should be assessed if the combination of the selected time step and the time period of interest results in workable model results that can satisfy the objectives of the study.

9.6.2.2 KPI's

- Opposed to transitions, the observed behaviour of interest is not per definition a change in the way a societal need is fulfilled. For studying the operation of installations a useful and feasible performance indicators should be defined.

9.6.2.3 Mechanisms

- We encountered that many of the mechanisms that are suggested by Yücel (2010) are not applicable to our case. We do not know if this is caused by the characteristics of our specific case or the operation of system innovations in general. It should be assessed if an adjusted or alternative list of expected mechanisms should be created for studying the operation of system innovations.

10. Reflection

In this chapter I will reflect upon my master thesis project as a whole. For each major research activity a reflection is written, along with the choice to graduate at the university instead of at a company.

10.1 Research proposal

It has taken me about a month to formulate my MSc thesis subject. I have spoken to many different people within and outside the TPM faculty. Although numerous interesting topics were available I insisted on defining my own topic. Looking back I did not expect this phase to have cost me this much time. I was confronted by the fact that my views upon what is achievable in a few months for such complex problems are somewhat flawed. This might have been caused by receiving nicely delineated and prepared topics for projects during the master and bachelor. Delineating problems and finding the right information were steps I never truly had to execute before. I am happy that I have learned how to do these steps during the final course of my master's. Furthermore I would also say that investing this amount of time in finding a topic is worth it. I was able to work on a graduation topic that had my sincere interest. As a result I enjoyed and take pride in the work I have been doing.

I found writing the research proposal challenging. Before I could actually go to work I had to make choices what to do, and more importantly what not to do. It is safe to say that I found it difficult to say no and was quite ambitious throughout the whole project. I am thankful for the coaching I have received on these matters, as I clearly still would be busy graduating for several months if I would be doing everything I wanted to.

I think that my research proposal could have improved if I would have involved the Green Village more and earlier. The Green Village organises Science & Innovations meetings with all students that are currently involved with the projects. I think these meetings have enormous value for the students, but unfortunately I have only attended these meetings when my project already was in an advanced stage. If I would be allowed to select one thing that I would have done differently, it would definitely be involving the Green Village from the start of the research. Although I do not think the thesis would have been fundamentally different, the involvement of the Green Village from the beginning of the project would have speeded things up.

10.2 Literature study

I knew the literature study was a slow progress in many thesis projects but I experienced again that I had to limit myself in what to read and include and what not to. I could easily read a whole paper, and instead of gaining clear insights I would end up with five new questions and the same amount of new papers that I expected myself to read. The use of the dissertations of both Émile and Gönenç Yücel proved to be an outcome. By studying the literature chapters in these theses I gained a general understanding of the field and what aspects I should be focussing on and which I did not.

A large question mark that still remains is the question if the chosen body of transition literature was absolutely necessary for the CaPP project. In section 1.2.2 I described why the subject of this thesis (operation of a system innovation) is not covered in the body of transition literature. Why select a body of literature then that does not match our focus? Now after completing this thesis I'd say that it is very likely that the practical problem as laid down in this thesis could also have been solved starting from another body of literature. However I was familiar with the body of transition literature and I tasked myself to solve the practical problem. It was and still is my assessment that given the available time for this project and my prior knowledge the transition literature was the best choice to base my research on. Given the tremendous amount of literature available, it is safe to say that the approach as I used is not the optimal one, but it did serve its purposes and yielded the desired insights. Although this explanation does not really satisfy my perfectionistic approach, I find comfort in the advice of Zofia; 'Mens moet wat'.

10.3 CaPP design decomposition

Starting the work on mapping the CaPP design marked the beginning of the case study. I was happy to move from the tangled and often vague transition theories to steam methane reformers, operational revenues and contract obligations. I found joy in figuring out how the technology and institutions worked in detail. My enthusiasm might have resulted in a very high level of detail and thorough description of the current state of the CaPP design. With hindsight I might also have been able to answer the research question of this project without this level of detail. I however found that an overview as I constructed was lacking and I hope that my work on this point can be valuable for new researchers who will be looking into CaPP.

10.4 Modelling and the model

One thing that I did know before starting the thesis project was that I wanted to execute a modelling study. I enjoyed all modelling courses and projects in the bachelor and master. I enjoy structured working and coming up with solutions for programming problems. Overall I experienced few problems in this phase. I knew what I wanted to make and was able to code this. I experienced that my understanding of the CPPP and its surroundings really came together when I was constructing the model. For instance I was finally able to truly understand how a certain parameter would influence the system, or what aspects of the system I did 'kind of' covered before but clearly required more attention. The challenge in this phase was (as it is usually) to stop modelling and label the model as final. Also due to my joy in modelling itself I would probably not have minded to keep modelling for a few more weeks. To mitigate this risk I made an excel file with a list of things my model should incorporate and do along with a planning how long these elements should take me to code. I found this approach very useful and it helped me to determine that my model was finished at a certain moment in time.

The modelling process has from my point of view been the major knowledge generator for this thesis and should be seen as its main deliverable. The resulting model is not more than a tool to test this process. Although I am satisfied with the formalisation of the available knowledge, using the resulting model was proven to be much of a challenge. The combination of a relative complex model, a time step of 15 minutes and the simulation time of three years led to relative long simulation times and Netlogo being unable to store the information of the KPI's for each tick. A point for improvement in my approach would have been to make an ex-ante estimation of the model that would result from my efforts. This might have resulted in the selection of a different modelling programme for this project.

10.5 Experimentation

The suggestion I received to make a clear experimental design proved to be very valuable. By choosing the types of analyses I wanted to execute and the type of insights I wanted to obtain upfront, I was able to quickly go through the experimentation phase. Although I did found errors in my model after some experiments ran, I was able to keep the time I spent on the experiments well within acceptable boundaries.

The results that I obtained from the experiments were however somewhat disappointing. The model behaves predictable, indicating the absence of complex emergent patterns that one would expect to encounter with agent based models. An interaction between the part of the model that manages the CPPP and part governing the dynamics of the drivers was absent. This would mean that the same insights could have been achieved with a simpler and less complex model. With the insights I have now, I would not include the purchasing of cars in the model if I would have to rebuild it. However I could only have obtained this insight after experimenting with a model that does include this mechanism. Although I find it a shame that certain more complex elements that I coded into the model were found to be unnecessary, I understand that this is an inherent risk when executing an explorative study.

I found it relatively easy to find the causes of the blocking mechanisms. I however found it very difficult to translate these causes in a format that would be readable for someone else. Something that really helped me to approach this challenge was to sit down with one of my fellow study friends and explain them schematically on one piece of paper what was going on. Using arrows and illustrations and a single piece of paper made sure my explanation was not too detailed. Using my friends made sure the explanations were complete and at the right level of detail.

10.6 Graduating at the university

At TPM the general tendency is to try to graduate at a company. Although I definitely see the value in getting to know a company during executing a project, I would advise students who start their graduation project to reconsider this decision. Graduating at the university gives you the unique opportunity to have the complete freedom to study something you are interested in detail. Even better, you can do this from the role of an independent researcher and can direct your work towards the elements you find most interesting. I have greatly enjoyed this freedom and have additionally learned how to deal with the accompanying responsibility.

Although I was warned that graduating at the university could be a lonely experience, I did not experience the project as such. A couple of my friends from the SEPAM programme also executed their graduation project at about the same time. We set up a chat group and daily checked who would be studying where each day. The existence of the group was very pleasant from a social point of view, but definitely also increased my productivity as we could discuss our different projects with one another.

My expectations that graduating at the university would lead to a fully scientific thesis were wrong. By contributing to an application of science my work is from my point of view an ideal mix of substantial practical and scientific value. The existence of the Green Village at the TU Delft is definitely a source of great research subjects. I stated that the Green Village was the problem owner of my research. In reality it was me. Graduating at the university allowed me to select my own research topic and really fine-tune it to my interests. Looking back at the work I have done also teaches me what kind of work I apparently find interesting.

I am proud on the resulting thesis that now lies before you. I truly belief this work can contribute to both the scientific field of transition literature and to the research of the Green Village. The combination of transitions and the energy system always had my attention, and with that in mind this work might have been the ideal master thesis project for me.

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Appendix A. Technical decomposition

In this appendix the functional decomposition and the accompanying alternatives per function are discussed. Currently mainly information on the possible configurations of the thermodynamic devices is available. These devices are mainly used in the hydrogen system, which we view as devices as the technical 'core' of concept. The hydrogen system can be categorised in the following subsystems: the production, handling, storage and refilling of hydrogen on site. An overview of these devise is presented first. Subsequently a short discussion is presented on other technical components that are envisioned by van Wijk and Verhoef (2014), but are not yet dealt with in the CaPP specific literature.

Based on the description of van Wijk and Verhoef (2014), a process flow diagram and an initial sketches of the technical design have been made by Spanjer (2014) and Fernandes et al. (2015, In press). Spanjer (2014) and Fernandes et al. (2015, In press) based their work on the same set of models. The work of Spanjer (2014) reports mainly on the exergy efficiency of the hydrogen system where the (currently non-published) manuscript of Fernandes et al. (2015, In press) the system is comprehensively described in a compact formulation. Additionally information was retrieved from the work of Palazzi (2013) who reported on the value of electricity production via CaPP and made a technical decomposition for estimating the costs.

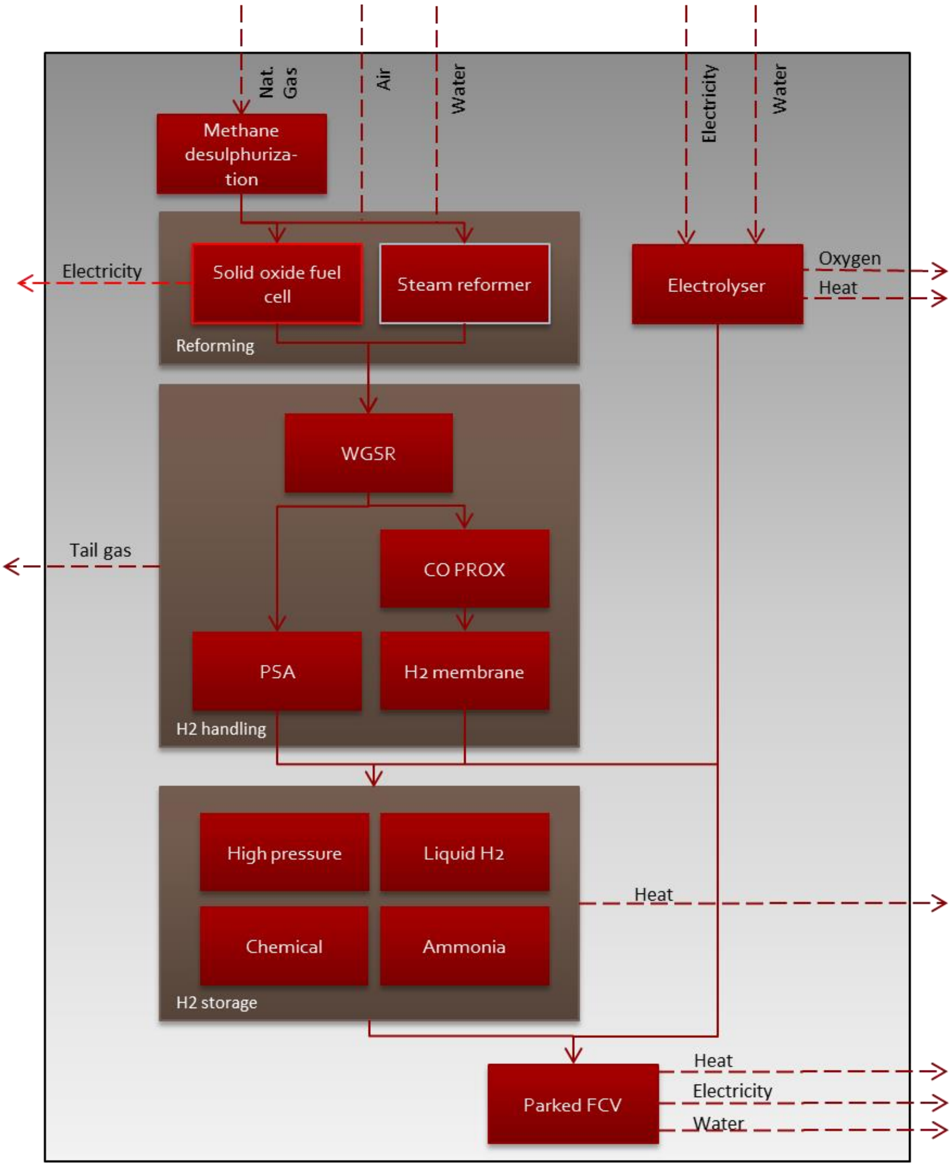

Figure A-1: Detailed technical flow diagram. Based on (Fernandes et al., 2015, In press; Spanjer, 2014).

Figure A-1 illustrates the technical system that is currently being researched at the TU Delft. Below we will discuss each of the components as depicted.

Methane desulphurization

Natural gas contains sulphur which can poison the catalysts in the hydrogen production modules. Via a desulphurization process the sulphur is removed from the natural gas (Fernandes et al., 2015, In press).

Electrolyser

An electrolyser converts electricity and water into hydrogen and oxygen. Van Wijk and Verhoef (2014) suggested to use the electrolyser when there is an abundant amount of electricity available from for example wind turbines. Industrial electrolysers typically range between production capacities of 20 to 2000 kg H_2 per day. The production of one kilogram hydrogen requires about 55 kWh of electricity and costs about €3 per kilogram. Both capital costs and variable costs scale linear with production, with the latter being responsible for 80% of total costs (Genovese, Harg, Paster, & Turner, 2009).

The electrolyser is not much discussed in the consulted literature. Spanjer (2014) mentions that the modelling program used for her research (Cycle Tempo) is not able to model an electrolyser. The work of Fernandes et al. (2015, In press) is highly related and is also based on models built in the same program. Both studies exclude the electrolyser from their scope as a result.

For our study the inclusion of the electrolyser in any to be implemented CaPP design is of large importance. The electrolyser would allow CPPPs to profit from low electricity prices.

Methane reforming

By including a method to produce hydrogen from methane, the CPPP can at all times guarantee availability of hydrogen to refuel FCVs or to produce electricity. By extracting gas from the existing network and converting it to hydrogen on site would eliminate the need of a parallel hydrogen network. The consulted literature discuss two types of devices that could produce hydrogen from natural gas with its main component natural gas.

Steam reformer

Steam reforming is the current dominant method to produce hydrogen and should be seen as the alternative to the SOFC (as discussed below). In a steam reformer a hydro carbon reacts with steam under the presence of a catalyst (often nickel). For the case of natural gas reforming this process follows Equation A-1.

$$CH_4 + H_2O \rightarrow 3H_2 + CO$$

Equation A-1: Steam reformer reaction

The reaction is highly endothermic and requires the addition of heat. Most commonly this is done by burning a portion of the incoming methane feedstock (Spanjer, 2014). Industrial steam reformers have a capacity of 240-2400 kg H_2 per day and require about 3,5 kilograms of methane per kilogram of hydrogen. The costs of production are estimated at about €2,50 per kg H_2 (Palazzi, 2013).

Besides steam reforming, there are two different reforming processes used in industry. By using only oxygen as an oxidiser instead of steam, a partial oxidation (POX) reaction takes place. A POX is exothermic, preventing the need for an external heat source. The downside of POX is the production of only two moles of hydrogen per mole methane, in contrast with the three moles hydrogen produced via steam reforming.

A combination of steam reforming and POX is called auto-thermal reforming (ATR). ATR basically is the addition of oxygen to the steam reforming reaction, allowing the energy of the exothermic POX to drive the steam reforming reaction. ATR however requires pure oxygen, resulting in a more complex installation (Fernandes et al., 2015, In press). The steam reforming reaction dominates today's industry and is subsequently the type of methane reforming on which the consulted work at the TU Delft focuses. We follow this approach and will not consider POX or ATR for the reforming of methane.

Solid Oxide Fuel Cell

The Solid Oxide Fuel Cell (SOFC) is a relatively new and promising electrochemical technology for electricity production from hydrocarbons. A SOFC module should for our purposes be seen as an alternative for a steam reforming module as discussed above.

The anode of a SOFC is typically covered by a layer of nickel. This makes the combination of a fuel cell and the process of steam reforming possible and attractive. This combination is called SOFC with direct internal reforming (SOFC-DIR) (Fernandes et al., 2015, In press). For readability we will use the abbreviation SOFC in the main body of this report instead of SOFC-DIR. The reactions of the fuel cell are (Iora, Aguiar, Adjiman, & Brandon, 2005):

$$H_2 + O^{2-} \rightarrow H_2O + 2e^-$$

Equation A-2: SOFC anode reaction

$$2e^- + \frac{1}{2}O_2 \rightarrow O^{2-}$$

Equation A-3: SOFC cathode reaction

The steam reforming reaction (Equation A-1) takes place due to the presence of nickel, steam at the cathode and high temperatures (Spanjer, 2014). If we add Equation A-1 with the reactions of the fuel cell we obtain:

$$CH_4 + \frac{1}{2}O_2 \rightarrow 2H_2 + CO + Electricity$$

Equation A-4: SOFC reaction

When comparing Equation A-1 and Equation A-4 we can see that steam reforming results in three moles of hydrogen where a SOFC results in two moles hydrogen per fed mole methane. The exergy efficiency of the SOFC is however much higher as most chemical energy is converted to electricity and only a minor amount into heat. A steam reformer converts all chemical energy into heat (Fernandes et al., 2015, In press). An accompanying advantage of the SOFC is that the fuel cell produces heat due to internal resistances. This heat is sufficient to drive the reforming reaction (Fernandes et al., 2015, In press; Spanjer, 2014).

Industrial SOFC applications are until now unknown to us. In Japan a combination of different companies is however operating several dozen SOFC installations for domestic use. These systems called ENE-FARM's, provide both electricity and heat from natural gas. The overall efficiency (when hydrogen, electricity and heat are considered as usable product) is reported to be 90%. The electrical efficiency lies at 42%. An installation of 700 Watt-electrical roughly costs €20.000 and occupies an area of about 2 m^2 (Kyocera, 2012).

Figure A-2: ENE-FARM. Image from (Kasuh, 2013)

The main advantage including a SOFC in a CaPP design would be the production of electricity parallel to producing hydrogen. The overall exergy efficiency of a system with a SOFC is higher than with a steam reformer, when assuming that the produced electricity can be used effectively. A SOFC would however require more natural gas than a steam reformer to produce the same amount of hydrogen. A SOFC is also an expensive. Due to its high operating temperature (750-800 °C) the lifetime of the fuel cell is very limited unless durable expensive materials are used (ECN, 2009).

An overview of the characteristics of both reforming technologies is presented in Table A-1.

Table A-1: Theoretical limits of reforming technologies based on (Spanjer, 2014)

	Steam reforming	SOFC[14]
Hydrogen yield per mole methane	3 moles hydrogen	2 moles hydrogen
Other energetic products	Heat	Electricity + heat
Energy in one mole methane (LHV)	803 kJ	803 kJ
Other required energy input per mole methane	225 kJ heat	0 kJ
Energy in produced hydrogen (LHV)	942 kJ	628 kJ
Energy in other energetic products per mole methane	86 kJ	197 kJ el.

WGSR

Both a steam reformer and a SOFC produce a gas stream of syngas (CO and H2) mixed with the remaining unreacted CH_4, CO_2 and H_2O. A water gas shift reaction (WGSR) can be used to increase the amount of H_2 gas mixture. To have the mixture undergo a WGSR, typically two reactors are used which are filled with different catalysts and operate at different temperatures (Fernandes et al., 2015, In press). The exothermic reaction goes as follows;

$$CO + H_2O \rightarrow CO_2 + H_2$$

Equation A-5

The gas stream exiting the water gas shift reactors typically contains less than 0,5% CO. Within a SOFC the WGSR also takes place due to the presence of high temperature steam. In this case the reaction does however not convert the same amount of CO as when using two shift reactors (Spanjer, 2014).

When we add the WGSR to the steam reforming and the SOFC reactions we can compare the produced hydrogen per mole methane for the two production options;

[14] Table A-1 presents maximum possible production capacities of all types of products. For the SOFC these maximums are achieved at different temperatures, making it impossible for these values to be achieved at the same time. This explains the possible implied violation of the energy balance (Spanjer, 2014).

$$CH_4 + 2H_2O \rightarrow 4H_2 + CO_2$$

Equation A-6: Hydrogen production after the WGSR using a steam reformer

$$CH_4 + \frac{1}{2}O_2 + H_2O \rightarrow 3H_2 + CO_2 + Electricity$$

Equation A-7: Hydrogen production after the WGSR when using a SOFC

Hydrogen handling

PSA

In order to separate the hydrogen from the other components often a Pressure Swing Adsorption (PSA) reactor is used. This technology is mature but energy intensive (Spanjer, 2014). In PSA reactors the gas is fed through a bed of solid adsorbents under high pressure. Depending on the desired end product different reactors can be used. So called Poly-bed PSA units are relatively simple and recover about 86% of the hydrogen. Gemini PSA units recover 99,999% of the hydrogen and 99,4% of the CO_2 in the stream, which makes the unit suitable for CO_2 capturing (Fernandes et al., 2015, In press).

Hydrogen membranes

Hydrogen membranes are a fairly new technology and an alternative to the PSA process. The advantage of the membranes is that the process is much less energy intensive. Due to a difference in the partial pressure over the membrane the hydrogen splits from other gasses (Spanjer, 2014). The membrane technology is still under development. Currently experienced drawbacks from the technology is that the membrane can be easily poisoned by sulphur, CO and water compounds (Fernandes et al., 2015, In press).

CO-PROX

In order to protect the H_2 membrane from being poisoned all the CO has to be removed which can be done by a CO Preferential Oxidation (CO-PROX) reaction. After the WGSR about 0,05% CO is still present in the gas stream. The remaining CO is oxidised with the aid of a catalyst and a small stream of oxygen (Spanjer, 2014).

Hydrogen storage

Compressed storage

Compressed hydrogen storage is the most mature hydrogen storage method. The technology uses compressors and composite high pressure tanks. The technology is simple and has an easy charge and discharge operation (Fernandes et al., 2015, In press). The efficiency of compressed storage at 750 bar is around 95% (Spanjer, 2014).

Liquid storage

By cooling hydrogen to -251 $^{\circ}$C the hydrogen becomes liquid and is fairly easy to store. The energy requirement to cool to this temperature is however very high and subsequently costs are made to isolate the storage tanks in order to prevent the hydrogen from boiling off (Palazzi, 2013).

Chemical storage

Hydrogen can also be stored within other chemicals. Because of its small size the hydrogen could be put inside the bonds of for example metal hydrides. This technology is however not yet commercially available (Palazzi, 2013).

Ammonia

A different view on the storage of hydrogen is processing the hydrogen to ammonia. Ammonia (NH_3) has a relatively high density, is widely used in industry and can be easily stored with moderate pressure (10 bars at room temperature) (David et al., 2014). An additional advantage of using ammonia as hydrogen storage is the fact that the SOFC can operate on ammonia (ECN, 2009). Storing hydrogen in ammonia would allow for storage over long time periods such as several months or even years. This way seasonal energy requirement differences could be balanced.

Fuel Cell Vehicle

The fuel cell vehicle (FCV) is being developed by several well-known car manufacturers. The frontrunner being the Toyota Mirai should be available on the market in 2015 for roughly €70.000 (Schenk, 2014). The FCV contains a fuel cell that generates electricity for an electric motor. Most commonly the Proton Exchange Membrane (PEM) fuel cell is used. The PEM fuel cell could reach efficiencies of 40-60% (Spanjer, 2014) but is relatively sensitive to contaminations, leading to high purity requirements for the hydrogen (Fernandes et al., 2015, In press). AN FCV typically has a storage tank for 5 kg hydrogen under a pressure of 350 bar. This results in the availability of roughly 100 kWh electricity and a range of about 300 km (Fernandes et al., 2015, In press; Palazzi, 2013).

The fuel cell in the vehicle is the current technical bottleneck for the realisation of CaPP. The current fuel cells last for about 4000 operating hours. If the fuel cells are also used when parked, these 4000 hours will not be enough for conventional usage. It is estimated that the lifetime of the fuel cells has to be improved by at least a factor 5 for CaPP to be successful (van Wijk & Verhoef, 2014).

Although there might not be much variation in possibilities concerning the usage of FCV's given the core characteristics of CaPP, the amount of FCV's that can be parked in a CPPP is a variable that is still to be determined. An amount of 500 cars is the starting point of the concept as suggested in (van Wijk & Verhoef, 2014). Palazzi (2013, pp. 42-43) based his model on this starting point and assumed all 500 parking spots to be filled daily following a variation of driving schemes. For the objectives of estimating energy and exergy efficiencies both Fernandes et al. (2015, In press) and (Spanjer, 2014) assumed a constant availability of 100 FCVs at all times. A non-constant availability does not affect the efficiencies of the installation as energy and exergy efficiencies are independent of the amount of cars connected (double the amount of connected cars results in a doubling in produced energy and exergy) (Spanjer, 2014, p. 34).

Decreasing the size of the CPPPs (the amount of parking spots) would allow for a higher density of CPPPs over an area, at the cost of a higher price per kWh as scale efficiencies are lost (e.g. two smaller electrolysers costing more than a large one with the same output`.

Other functionalities

From the vision presented in (van Wijk & Verhoef, 2014) a number of technical functionalities can be derived that have not yet been discussed in the earlier presented literature. Below we list these functionalities and briefly discuss them.

Automated parking

The CPPPs are not only innovative on the usage of the car when parked, but also how they are parked. In the vision of the GreenVillage a car will automatically be parked once entering the CPPP. The system would require some advanced robotics, but these kind of systems are already commercially available (Automotion, 2015; Autostadt, sd).

Automated connection CPPP to car

Once a car is parked in a CPPP it will need to be connected to the CPPP control system, and to the hydrogen, water and electricity grid. The connection between the CPPP and the car will have to be established by a robotic system if the parking is also done automatically. The challenge for this application is results from the diversity of possible cars that could be handled. Some sort of standard will need to be established between the designers of the CPPP and the automotive sector concerning the location, and type of the connectors within the cars.

Refuelling design

Palazzi (2013) mentions the possibility of two different refuelling designs. The first refuelling design is the one currently being implemented by the car manufacturers. In this configuration compressed hydrogen is injected in the FCV fuel tank under 350 bar.

The CaPP concept explicitly includes the possibility to directly generate electricity from hydrogen using the fuel cells of the FCV (van Wijk & Verhoef, 2014, p. 64). If the FCV would only have one refuelling inflow point, the supplied hydrogen for direct electricity generation needs to be compressed to 350 bars only to be expanded a few seconds later to 3-10 bars (resulting in energy losses), or the hydrogen tank of the user needs to be emptied first.

The second refuelling design would bypass the hydrogen tank of the FCV by including a second refuelling inflow point. The hydrogen could then be fed towards to the storage tanks as well directly to the PEM fuel cell (Palazzi, 2013). This configuration could lead to higher system efficiency as the possible useless compression is no longer needed. Palazzi (2013) however concluded that it is unlikely that the car-manufacturers will add a second fuelling connection to their designs. Similar to the automated connection functionality discussed above, a standard will need to be discussed with the automotive sector.

Control system

Important for a proper functioning of the whole system is the control system behind the CPPP. The CPPP will have to balance demand of energy with supply. This means taking different demanding entities into account (the cars, nearby houses, the electricity market) and different energy carriers (hydrogen, electricity, heat and water) (van Wijk & Verhoef, 2014). The control system is most likely to be even more complex when CaPP becomes a major player on the electricity market as envisioned. At this stage the system will no longer be an electricity price taker, but will have a significant impact on the market. A control system would then be required that optimises the profit of the interregional network of CPPP's with taking regional and inter-regional demands into account.

App for users to give restrictions & preferences

The usage of the cars could be subject to some user defined boundary conditions if the cars are privately owned. One way to facilitate an interface between user and CPPP would be an app through which for instance a maximum parked-production time, a preferred payment (a full hydrogen tank or monetary) and the desired time of departure can be communicated.

An additional functionality of such an app would be defining the pick-up location of the car once autonomous driving becomes the norm. Such a technology would also allow the location of the CPPP's to be outside busy city centres (as cars could autonomously drive to the CPPPs outside the cities).

Demi water to drinking water

A 'waste' product of the CPPPs is hot water. Due to being a product of a chemical reaction, this water is demineralised (demi-)water which is different from drinking water. There are health risks when drinking (only) demi-water (Kozisek, 2005). Fernandes et al. (2015, In press) also concluded that water produced by CPPP configurations with a SOFC might be contaminated with chromium, making it unsafe to drink.

It is most likely that water treatment is required in any configuration of CaPP before the waste water can be used for drinking or other purposed (van Wijk & Verhoef, 2014).

Heat exchange waste water

The 'waste' heat produced by the CPPP is carried by the demi-water. A system of heat exchangers will be required to extract this heat to for instance a district heating system.

Car park: geometry and design

The whole CaPP system will have to be housed. The main challenge for designing such a building will be how the available space is most efficiently used, while incorporating all the envisioned functionalities (such as automated parking) and all legal requirements (such as safe hydrogen handling).

Synthesis

The work of Fernandes et al. (2015, In press) represents the current state of the art research of the TU Delft considering the CaPP hydrogen sub-system. The other functionalities as discussed and envisioned by van Wijk and Verhoef (2014) could for now be seen as subordinate in terms of research priority. These functionalities are complementary to the hydrogen system and their design and application will depend on the configuration of the hydrogen system.

Major elements in the CPPP's will be the device or devices that can produce hydrogen. Van Wijk and Verhoef (2014) envision the existence of two complementary production devices; An electrolyser to produce hydrogen from excess electricity and a Steam reformer or SOFC to produce hydrogen from natural gas. The choice between using a steam reformer or a SOFC can be seen as the most important technical design choice at this stage (Fernandes et al., 2015, In press; Spanjer, 2014).

An overview of all technical functionalities and the options to fulfil these functionalities is given in Table A-2. The detailed flow diagram in Figure A-1 has been further expanded to include all functionalities. This flow diagram can be found as Figure A-3. In this figure different options that could fulfil complementary functionalities, internal water reuse flows and heat reuse flows are not included for the sake of readability.

It should be noted that this appendix aims to give a full overview of the technical design space of CaPP. However there is still much work to be done before the exact technical configuration of CaPP is established or essential bottlenecks (such as the lifetime of the PEM fuel cells) are removed. In this process many technical options or even functionalities might emerge, change or be removed from the concept as currently known. Vincent Oldenbroek recently started a PhD research at the Process Energy department of the TU Delft with the objective to further research the different technical options and strengthen the Well to Wheel and Wheel to Person efficiency analyses.

Table A-2: Full CaPP technical morph chart

Technical Core				
Handling methane	Compression + desulphurization			
Reforming methane	Steam reformer	Solid oxide fuel cell		
Producing hydrogen with electricity	Electrolyser			
Handling H_2	Pressure swing adsorption	Hydrogen membranes + CO-PROX		
Storage of hydrogen	High pressure tanks	Liquid stage storage	Chemical storage	Ammonia
Convert H_2 to electricity	50 FCV capacity	200 FCV capacity	500 FCV capacity	
Complementary functionalities				
Exchanging heat	Heat exchangers			
Parking FCV	Automated parking	Manual parking		
Connecting FCV	Automated	Manual		
Purifying water	Purification unit			
Controlling system	Automated IT system	Manual		
Interaction with owner	App	Terminal in CPPP		

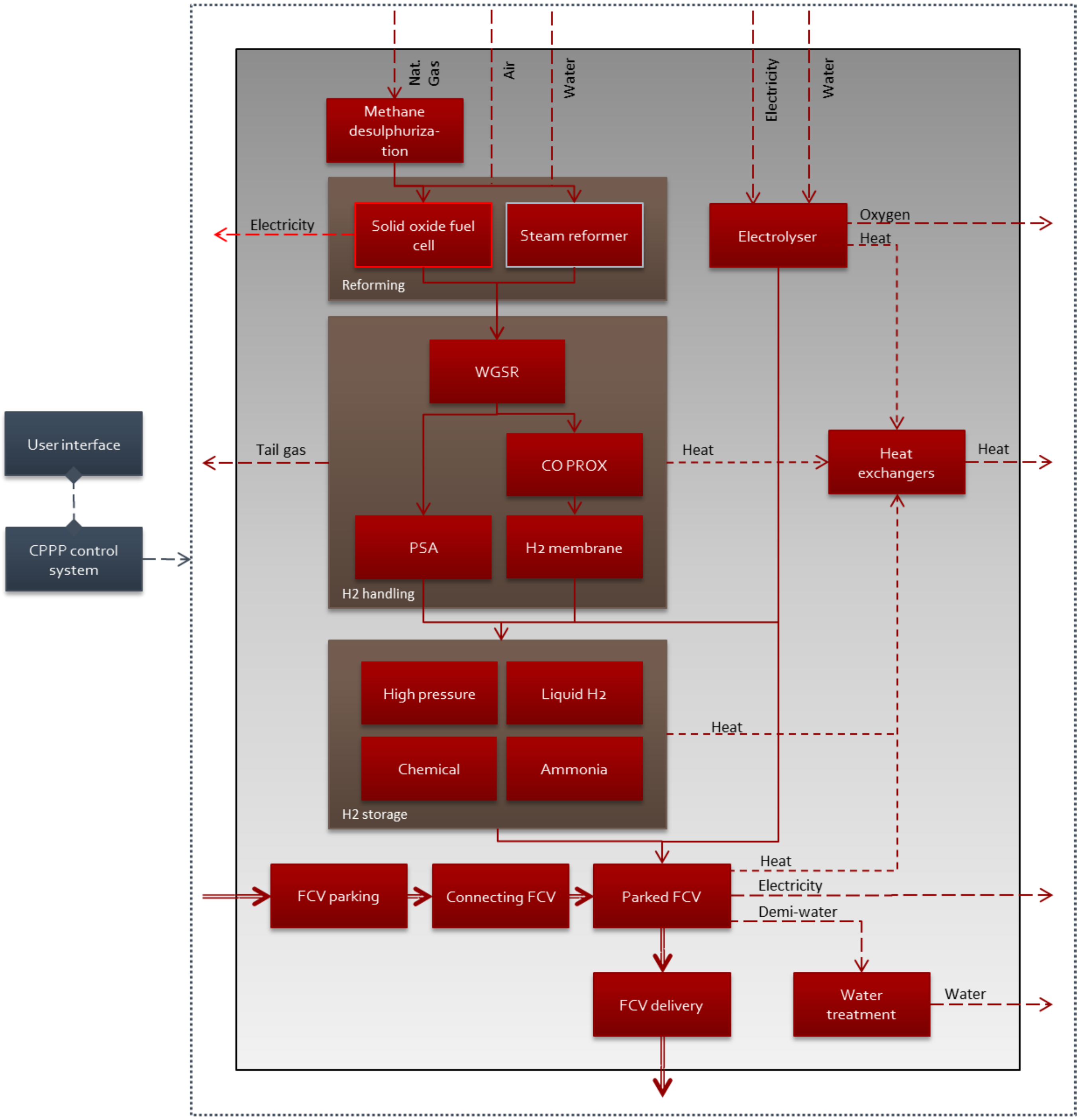

Figure A-3: Full flow diagram based on (Fernandes et al., 2015, In press; Spanjer, 2014; van Wijk & Verhoef, 2014)

Appendix B. Actor analysis

In this appendix we aim to obtain an overview of the possible involved actors around CaPP and what roles they could play during the implementation of the concept. The approach of this appendix is based on (Enserink et al., 2010, ch. 4). Different institutional designs will prove to be a better match with different involved parties and vice versa. As an example the operating strategy for a CPPP will be different when the installation is owned by a network operator (which aims to stabilize the electricity grid) than when it is owned by an entrepreneur (pursuing maximum profits).

Analytical perspective

For the actor analysis we need to define a reference point to relate the other actors to. Such a reference point could be the actor that is the problem owner, or a statement of some sort to which we can relate the interests and influence of the different actors. In this study we analyse the possible implementation paths of CaPP and are interested in the possible barriers or drivers that could present themselves during any implementation trajectory. This leads us to analyse the different actors from a stance that is very positive towards the success of the implementation of CaPP. This perspective aligns for instance with the interest of the GreenVillage, being the founder of the CaPP concept and looking for methods to implement it. In the rest of the analysis we will map actors that have an interest in a successful implementation of CaPP, or could possibly influence this process.

Actors

In this section we present a list of possible actors that have a stake in the successful or unsuccessful implementation of CaPP concept. We have used a high abstraction level in order to limit the amount of discussed actors. The list of actors is in-exhaustive and author dependant.

Table B-1: Considered actors categories

Automotive sector	Electricity sector	Gas, water & heat infrastructures	Governmental	Other
Car manufacturers	Electricity network operators	Network operators	Ministry of Finance	Car users
Fleet operators	Electricity producers	Housing cooperatives	Ministry of Infrastructure & Environment	New CaPP entrepreneurs
Traditional private carpark owners	Electricity retailers		Municipalities	Residents

Car manufacturers

For CaPP to function as intended different connections between different types of FCVs and the CPPPs are to be established. The cooperation from the car manufacturers for these connections are thus of large importance. As described in Appendix A, connections are made for electricity, (hot) water, hydrogen and control. Additionally the system of the CPPP and the different FCV's will need to have a functional interface with each other to communicate.

Being private companies, most if not all manufacturers will aim for profit maximisation. Making CaPP compatible cars would require new investments in a new product line. Such investments are accompanied by risks, but might be justified if an advantageous market and knowledge position is acquired. An example of a manufacturer who took such a risk was Renault-Nissan who designed a car suitable from battery swapping stations (Dijk, Orsato, & Kemp, 2013).

Fleet operators

Currently most car drivers also own the car. Well known exceptions are situations where the drivers lease their car from the company they work for. For the case of CaPP a wider variety of ownership could be possible. Where the objective of the current car owners would be providing mobility for the car user, this could be different in the future. In a world with a wide CaPP penetration, fleet owners might offer lease constructions in order to improve the amount of CaPP compatible FCV's and offer financial incentives (a lower monthly rent) for influence on the driving behaviour of the user. Such fleet operators could have multiple objectives besides offering mobility to the lessee, such as optimising the duration of the FCV being connected in a CPPP. Fleet operators can also manage a fleet of non-road vehicles, such as forklifts in warehouses (Kempton & Tomić, 2005b).

Dijk et al. (2013) describe the expected upcoming market for mobility providers. These companies provide mobility in different forms like car sharing (where one car is sequentially used by different consumers). In the Netherlands the company Green Wheels offers such a service at many railway stations. The Green Wheels' cars can be used by consumers for a reserved time slot. When the car is not being driven it is parked at a predetermined location (Green Wheels, 2015). Even though this company manages a large fleet of vehicles, a major element in its business case makes it unsuitable for CaPP. GreenWheels relies on a spread of its cars all over of the Netherlands, where the CaPP concept is based on the conglomeration of a number of FCVs at one place in order to facilitate a number of cars with one installation.

Traditional private carpark owners

In the last few years a number of companies with a full focus on exploiting car parks have emerged. A good example is the European wide company Q-park, owning one or multiple parking facilities (both garages and lots) in almost a hundred Dutch municipalities (Q-Park, sd.). Being private parties the private carpark owners are be pursuing the goal of profit maximisation. The possible implementation of CaPP could be interpreted as a threat or an opportunity for these companies. A successful implementation of the CPPPs would result as a change in business models for the parking industry. If these companies do not adapt their strategy to align with this new innovation, their current business might lose ground. On the other hand if the current owners manage to be included in the development process of CaPP in time they might be able to incorporate the concept in their existing facilities, prolonging the economic life time of their current investments.

Electricity network operators

The Dutch transmission and distribution network operators are responsible for a well-functioning electricity grid. In the Netherlands the network operators are regulated and have to comply with the regulator ACM. The ministry of economic affairs is responsible for the guidelines that are being enforced by ACM (Raad van State, 1997).

The network operators have a strong facilitative role, resulting in a market following approach. The organisations are obliged to connect electricity demanding and supplying installations to their grid (Raad van State, 1998). From the traditional perspective, the implementation of CPPPs in will make the grid more complex and might not be supported by the network operators.

One of the main advantages of the CaPP concept is however the possibility to store excess energy in hydrogen. *If* this functionality is used for the good of the electricity networks, CaPP might be (part of) the solution to facilitate the implementation of intermittent renewable resources. The priorities of the network operator are with the stability of the network, currently leading to the possibility of the rejection of renewable electricity if this endangers the network stability (i.e. wind turbines could be forced to a hold if the current network demand is high). We however assume that the network operators are well willingly to pursue a goal of maximum renewable electricity use. This assumption is partially based on the websites of the operators on which they all showcase different renewable energy projects[15].

Electricity producers

We view any company that owns a centralised power plant as an electricity producer. The electricity producers often own a variety of generators that can provide electricity for different market segments (see p. 112). Produced electricity is sold via long term contracts or on a short time basis on the Dutch electricity spot market. The introduction of CaPP in the market will result in more competition for the electricity producers, depending on the use case of the CPPPs. Little

[15] E.g. http://www.stedin.net/over-stedin/projecten, http://www.tennet.eu/nl/grid-projects/projects-in-the-netherlands.html

support from the electricity producers can be expected for the implementation of CaPP as long as they are expected to be part of the business case.

Electricity retailers

Companies selling electricity to the consumers are electricity retailers. Companies like Oxxio or the "Nederlandse Energie Maatschappij" do not own electricity generators but buy electricity from the electricity producers and sell this electricity to the consumers. The electricity producers themselves often have a retailing branch next to their business as producers, here we view these two branches of the same companies as different actors. The CaPP concept does not pose a direct threat to the retailers. The existing business relationship between retailers and consumers however places the retailers in a favourable position approach the consumers and start buying vehicle to grid capacity from them (Kempton & Tomić, 2005b).

Gas, water & heat network operators

The CPPPs will have to be connected to the gas, water and heat networks (van Wijk & Verhoef, 2014). During times when the demand for hydrogen (for either cars or electricity production) is high, extra gas and water will need to flow to the CPPP. The output of electricity producing FCVs is water and heat, which can be fed to the heat and water grid if there is no internal demand within the CPPP.

The characteristics of CaPP are from the perspective of the gas network operator not much different than for any other large industrial user. Although the gas demand might be fluctuating we do not foresee any complications in arranging the gas connection.

Allowing to feed water into the water grid might however be more complicated. As this water network is also providing drinking water to households, feeding water into this grid is governed following strict regulations. The quality of the water of the grid falls under the responsibility of the local drinking water company (such as Vitens or Evides) (Raad van State, 2009). It is questionable if these companies would provide their support to the feed of residual water to the grid, as they would be accountable for any problems. The alternative would be to store the excess water near the CPPP for later use.

The production of water for distribution via channels other than the grid is allowed as well, but also under the strict regulations and only in small quantities (maximum 10 m^3 and 50 customers per day) (Raad van State, 2009). An advantage of this approach is that the drinking water companies do not have to be involved. The producer of this 'private extraction' is obliged to have quality checks in place which will be inspected by the authorities. Due to the small quantities of producing water without the grid, the impact on the business case would be marginal. We therefor do not consider this possibility of selling water to be interesting at this stage of the CaPP design process.

Heat networks are quite common in the Netherlands, going by the name "Stadsverwarming". Via heat exchangers the residual heat of a CPPP can be transferred to these networks, preventing the mixing of the different fluids. The heat networks are owned and operated by a variety of organisations among which several electricity producers (Stichting Warmtenetwerk, 2013). The ease of coming to an agreement with the owner of the nearby heat network will depend on the objectives of the owner. An agreement seems logical if the owner can reduce its production cost by buying the heat from the CPPP. If the owner has recently invested in large gas boilers to produce the heat for the network he might not be willing to buy the heat from the CPPP. If the owner is opposing the introduction of CaPP for other reasons (e.g. the electricity producer which perceives a CPPP as a new entrant in its market), it might sacrifice the possible heat gains in favour of these other goals (e.g. protecting its electricity market share).

Housing cooperatives

Housing cooperatives are interesting parties for the CaPP business case as they serve a large set of households. On the one hand these tenants demand heating and the housing cooperation could buy the heat from the CPPP (see above). On the other hand the tenants also park their cars during prolonged time periods at locations that are under the management of the housing cooperatives. The housing cooperative could be a party that could profitably exploit a CPPP if the times the FCV's are parked near these locations and the operating strategy of the CPPP match.

Ministry of Finance

Several tax issues will have to be resolved before CaPP can be implemented. First of all it is questionable if fuelling of FCVs with hydrogen by the CPPPs will be free of tax. At the moment the Dutch government taxes 48,2 and 76,6 cents per litre on respectively diesel and gasoline (Belastingdienst, 2015). The goal of this excise on fuel is to provide the government an income but also to discourage the use of the specific goods. A lower excise seems to be possible seeing the environmental gains from using hydrogen as a fuel.

Secondly the government taxes electricity use with 7 cents per used kWh (Palazzi, 2013). CaPP would profit if the electricity produced by the CPPPs would not be taxed and thus be prioritised by consumers. Such an exemption is however unlikely as it would require complicated regulations that would have to be introduced in the electricity bills of the end users. The same holds for residual heat and water.

The last question surrounding excises concerns the road tax on bought vehicles. Currently there is an exemption in place for vehicles with a CO_2 emission less than 50 grams per kilometres. This exemption is planned to last until 2016. Cars running on gasoline are currently taxed between the 400 and 1000 euro's per year, depending on the weight of the car (Belastingdienst, sd.).

The ministry of finance is also the empowered government entity to grant subsidies for renewable initiatives. The current programme for these kind of initiatives is the "SDE+". This programme grants a subsidy that equals the difference of production costs and market price per produced kWh. Each year a set fund is defined (3,5 billion in 2015) which is allocated to different initiatives. Applications for subsidies are first allocated to technologies that have been determined to be most promising by the ministry. If the fund is not exhausted, a new set of technologies is allowed to apply. In 2015 a total of nine of these allocation rounds are planned. If the CaPP concept is to receive funds from this programme (assuming it will still exist at that moment in time) it will have to be acknowledged by the ministry as renewable energy production technology and opt for a profitable status in the application order. Currently energy production from hydrogen is not included in the programme (RVO, 2014).

Ministry of Infrastructure & Environment

The ministry of infrastructure and environment (I&E) focuses on a 'liveable, accessible and safe' Netherlands. The Dutch organisation 'Rijkswaterstaat' which is tasked with the supervision and maintenance of the road network falls under the umbrella of the ministry of I&E. The ministry drafts and maintains different regulations concerning the environment. For any hydrogen fuelling station an "omgevingsvergunning milieu" (roughly translated an environmental vicinity permit) will be required and different norms as described in the 'Activiteitenbesluit' will apply (Rijkswaterstaat, sd.), depending on the exact technical parameters of the CPPP. A report of the applicable norms can be downloaded from the website of the ministry[16] after filling in an extensive questionnaire.

Municipalities

Although it is the ministry of I&E who drafts the legislation concerning the permits, the local municipality (or in the case of an inter-municipal area the province[17]) is the authority who is in charge of issuing the permits. The ministry facilitates an online portal through which all applications for environmental vicinity permits can be filed[18] . In principle the municipality cannot refuse an application for the "omgevingsvergunning milieu" permit as long as the installation complies within the legislation as formulated by the ministry (VNG, sd).

Next to the environmental vicinity permit, a building permit will be required. For this building permit the municipality has more control via zoning plans. These plans are drafted by the municipality and define what kind of activities are

[16] aim.vrom.nl
[17] we will not further discuss this authority as we do not expect these areas to be attractive for CPPPs
[18] www.omgevingsloket.nl

allowed at certain areas within the boundaries of the municipality. For each CPPP the corresponding municipality will have to be contacted in order to determine if the zoning plans allow all the activities as envisioned.

Car users

The prime use of the car these days is to transport the drivers from A to B. A demand for mobility can be fulfilled in the cases when the car is owned by the user, but also when the user is the lessee. The CPPP will benefit most if the user will predictably and frequently park the car in the CPPP. Such a schedule can be voluntary or be contractual when for instance the car driver leases the car from a fleet owner. We assume that the wish for relatively cheap and flexible mobility is the primary objective for the car user. The term flexible relates to a certain range buffer (ca. 30 kilometres) that should always be available for the user for unanticipated trips (cf. (Kempton & Tomić, 2005a)).

New CaPP entrepreneurs

We classify any new party that can make a living due to the emergence of the CPPPs as a 'new CaPP entrepreneur'. We find it important to mention this 'residual' category here to explicitly acknowledge the possibility of the emergence of new players in the field. Being a commercial party, a profit maximisation objective can be expected. We do not include these new players in the rest of the analysis as we cannot define a problem formulation for this group.

Residents

The general public view on the safety of hydrogen is fairly negative. Although the technology is inherently and passively safe (Pollet et al., 2012) local resistance to hydrogen production and storage can be expected. Residents around CPPPs could influence the perception of their municipality towards the CPPP and thus indirectly hinder the implementation. For the rest of the analysis we will assume that the interest of the residents near any potential CPPP will be represented by the municipalities.

Actors' problem formulation

In Table B-2 an overview is given of the perceptions of the actors as discussed above. The uncertainty concerning the exact technical and institutional design of the CPPPs subsequently result in uncertainty concerning the perceptions of the different actors towards a possible implementation of CaPP. We slightly deviate from the exact approach as suggested by Enserink et al. (2010). Due to the different possible configurations and the resulting wide range of possible futures we found it unfeasible to list causes of possible deviations from the desired situations of the different actors (in the words of Enserink et al. (2010) causes of gaps between expected situation and ideal situation).

We note that this overview has been based on a desk research and further research is recommended. Such research could include interviews with the different types of actors.

Table B-2: Overview of actors' problem perception

Actors	Interest	Objective	Existing or expected situation and gap	Ideal situation	Own means
Car manufacturers	Profit maximisation, market share	CPPP user preference for own brand	Uncertainty concerning successful breakthrough CaPP	Once CaPP is determined to become successful, the brand is the only supplier of CaPP compatible cars	Timely investments, Knowledge sharing.
Fleet operators	Making profit by provide cheap appropriate mobility to user	Full use of financial potential of fuel cell	Car users' comfort & behaviour. Aggregation issues if ownership is not bundled	Gaining control over car usage and parking behaviour. Users adjust plans to car availability	Investments. Cost reductions through smart car control and availability algorithms. Strength in numbers.
Traditional private carpark owners	Profit maximisation, market share	Securing profitability of made investments & market share	Upcoming demand for CaPP parking spots requires new investments	Increase attractiveness of garages by making them compatible with CaPP.	Investments, knowledge sharing.
Electricity network operators	Stable electricity gird	Possibility of cheap/profitable electricity storage.	Lack of economic viable energy storage	High controllability over operation scheme of CPPP installations.	Investments. Prevent infrastructure related process barriers
Electricity producers	Profit maximisation, market share	Securing profitability of made investments & market share	Increased competition in market segments by CaPP, depending on operating strategy.	Prevention of implementation of CaPP or owning CPPP installations.	Investments. if owning retail branch; influence perception of consumers w.r.t. CaPP
Electricity retailers	Profit maximisation, market share	Cheap supply of electricity & exploit market potential V2G	Car users' comfort & behaviour. Uncertainty concerning CaPP operating strategy	Retailers become the connection between consumers and the CPPPs, allowing to trade V2G capacity	Investments, influence perception of consumers.
Gas, water & heat network operators	High quality of commodity provision	Uphold quality norms of commodities.	Possible threat from CPPP installations.	Assure proper norms and regulations by government.	Knowledge sharing. Prevent infrastructure related process barriers
Housing cooperatives	Renters comfort, profit maximisation	Cheap supply of heat and exploit market potential V2G	Car users' comfort & behaviour. Additional investments	Construction of CaPP installations near managed properties, using excess heat for nearby houses.	Investments, communication to tenants.
Ministry of Finance	Financially strong Netherlands	Secure excises income from mobility sector, minimalize required subsidy funds for sustainability, reduce costs of electricity transport	Uncertain environmental potential of CaPP. Uncertainty w.r.t. taxing hydrogen	Increase of usable renewable production by CaPP storage, excises loss compensated by reduction of expenses on SDE+ and network expansions	Subsidies, tax exemptions
Ministry of I&E	Liveable, accessible and safe Netherlands	Uphold environmental and security norms	Possible threat from CPPP installations. Feeling of insecurity from civilians concerning hydrogen	CPPP installations fitting in the existing norms	Regulation, knowledge sharing
Municipalities	High quality of living & working of inhabitants	Improve image and allow for new business. No safety and environmental concerns.	Possible threat from CPPP installations. Feeling of insecurity from civilians concerning hydrogen	Safety guarantees from CPPPs, frontrunners image with first implementation	Regulation, adjustment zoning plan, communication to inhabitants
Car users	Cheap flexible mobility	Maintain acceptable level of comfort and reduce cost of car usage	Possible freedom limitations for users, resulting in the choice to either not use the CaPP and not receive the financial benefits, or sacrifice the mobility freedom.	Maintain balance between comfort from control over car while reducing parking and possibly fuelling costs.	Consumer preference and market steering

We observe four major themes in which we can categorise the uncertainties of the different actors; 1) production of the CPPPs, 2) FCV 'supply', 3) legislation and 4 the likelihood of a successful implementation. The latter theme largely overlaps with the topic of this research as a whole and will depend on the uncertainties in the other three themes. It could be seen as the all-embracing topic in which all uncertainties and design questions fit. For this reason not discuss it as a whole in the rest of this appendix.

CPPP production

Concerning the production of the CPPP it is vital to determine at what time of the day the CPPPs are likely to produce. The use case that is being followed by a CPPP results in production for a certain market segment of the electricity market and could give more or less ground for opposition from the current players in the electricity sector. Different use cases furthermore lead to different times during which FCV's are required.

FCV 'supply'

As discussed above, the required FCV availability depends on how the operator of the CPPP wants to operate the installation. A match between institutions that facilitate an appropriate availability of the FCV and the operating strategy seems essential for the proper functioning of a CPPP. How and if the drives of the vehicles (which are not necessarily the owners of the car) will accept a reduction in freedom of usage also depends on when the FCV's are needed in the CPPP.

Governmental

Lastly there are questions concerning legislation and tax. For the latter a dialogue with the ministry of finance seems logical. The perception of the ministry concerning the environmental gains from using CaPP could possibly be influenced by parties such as the GreenVillage. The issues concerning legislation like the building permit and environmental vicinity permits are crucial for the success of CaPP, but are however not related to the position of the other involved actors.

Appendix C. Institutions

While the technical design of CaPP is documented in several theses and manuscripts, there is currently no documentation on the institutional design of the concept. At the TPM faculty, Esther Park Lee has started a PhD research on the possible institutional design of CaPP.

In this appendix we give an overview of the different institutional elements that should be considered. The list is mainly based on Vehicle to Grid literature and a discussion with Esther Park Lee. The overview is split into the three themes as drafted in Appendix B.

Table C-1: Considered institutional design choices for CaPP

Production	FCV availability	Governmental
CPPP owner	Car ownership	Legislation
CPPP operator	CPPP location	Excises
Use cases	Interaction with driver	Subsidies

CPPP owner

The owner of a CPPP is the actor that is willing to take the risk of investing. The CPPP would be expected to generate revenue in order to make up for this investment plus a reasonable surplus. Synergies might be exploited if the owner can fit CaPP into its existing business model. It is likely that the main revenue stream from a CPPP will come from the production of electricity. The value of the residual heat and clean water produced by the CPPP are estimated to be respectively a factor five and two lower than the value of the produced electricity (Palazzi, 2013).

The ownership of a CPPP could be split into two; the building itself and the technical devices. Accordingly the ownership of a CPPP could be in the hands of one party owning the whole, or two parties owning either the building or the technical devices.

Arguments in favour of split ownership would be the possibility to have different owners with different areas of expertise. For instance an engineering company might maintain the technology more effective, while a traditional carpark owner has more experience in parking systems. If the sum of savings coming from efficiencies due to split ownership is more than the additional transaction costs due to the split ownership, this structure should be considered. Below we have listed a number of actors that could fulfil the role of (partial) owner.

Traditional carpark owners

Carparks in the Netherlands are owned by a variety of organisations such as municipalities, associations of residents and real estate companies. Furthermore some companies with a full focus on car-parks have entered the market in the last few years, such as Q-Park. Depending on the actor, an underlying motivation to own a CPPP will differ.

Current owners of parking garages might see opportunities to include CaPP into their business model. This inclusion will be more likely if the chosen CaPP design keeps the way of parking and car handling similar to the current practice. Features like automated parking or complicated CPPP control systems will make the inclusion of the CaPP concept more of a challenge for the traditional carpark owners. In any case the additional technical complexity of CaPP will most likely lead to a service contract of some sort with an engineering company.

It should be noted that for CaPP to be effective it is likely that the FCV needs to be present in the carpark for long time periods. A carpark near the supermarket will only have cars available for a maximum of a few hours, making it unlikely to be a suitable location for CaPP. Locations where people leave their cars for several hours, such as near train stations or airports are likely to be more suitable for the CaPP concept.

Offices

Employees of companies have a very predictable traveling schedule and park their car for long time periods at the same location. The office hours are the hours during which the electricity demand is relatively large. Additionally the office is in use during these hours and could potentially use the produced electricity itself. With respect to the inclusion of the concept into the existing business model and the technical complexity the same argumentation holds as discussed above for the traditional carpark owners.

Electricity network operator

When considering locations where production of electricity is favourable, the transmission or distribution system operators could be interesting actors to initiate the build and own a CPPP. The on-demand storage and production of electricity might have high value in areas where both electricity supply and demand are volatile. An operational CPPP could then mitigate the need for investments in large electricity cables. An example of such a location could be a coastal city where an offshore wind park is connected to the national grid.

Electricity retailers

Similar to the argumentation above, the value of storage and production of electricity might differ at different times. As in the current situation on the electricity market, it could be the electricity retailers who are profitably trading electricity. CaPP provides the additional possibilities to buy electricity when it is cheap and store it, and cost-effectively produce electricity once again with the CPPP when demand is high.

Housing cooperatives

With a large number of car users moving from and towards the houses, the housing cooperation could be an interesting actor to own CPPPs. Additionally the cooperative could use the residual heat coming from the CPPP in its buildings. The management of the technical components of CaPP are however not likely to align with the expertise of the cooperatives, making a contract with an engineering company likely.

New entrepreneurs

Next to existing companies, new companies could emerge that have developed their business model around the CaPP concept. This would require that operating a CPPP should be (expected to be) profitable. The operation of CaPP is discussed in more detail below.

CPPP operator

Just as in the case of office rental by a company, the owner and the operator of the CaPP installations could be different. In those cases the owner of the installation would be fairly experienced in building the CPPPs and it could rent it to a variety of other organisations. A split between ownership and operation is more likely if the existence of a CPPP is of most value for the owner and he is less interested in the exact operation of the system, such as the network operators (interest in functional electricity network) or municipalities (public image considerations). The actors that we would consider to fulfil the role of a CPPP operator are the same ones that could possibly own the installation.

Use case

The CPPP will produce electricity following a certain strategy. Although modern prosumers of electricity, who both use and produce electricity locally, are allowed to feed in electricity with priority in the network, we do not foresee the CPPPs to gain this advantage due to their envisioned production capacity. A typical CPPP that can house 500 FCVs will have a peak capacity of 50 MW (van Wijk & Verhoef, 2014). A situation in which several of these installations can uncontrolled feed in any amount of electricity will lead to unacceptable imbalances on the grid. As such we foresee CPPPs be obliged to supply electricity services as any other centralised power plant. There are different types of electricity services that can be sold which are discussed below.

Local
Production for local demand is production for nearby offices, industries or houses. An operator pursuing this strategy will give priority to produce for the nearby customers and could feed any excess electricity to the grid.

If the owner of the nearby demanding buildings and the CPPP are the same, this strategy would be favourable as it prevents paying transaction costs for the electricity supply of the demanding building. If the owner of the CPPP is not the demanding party, some sort of contract will have to be arranged. Possible advantages of local production could be a higher remuneration (as the demanding party has more certainty of adequate electricity delivery) and electricity related safety issues. Such a construction could be advantageous for example hospitals.

A more traditional business model would be production for the national market. This would be feeding all the electricity produced by the CPPP to the distribution or transmission grid with the purpose of selling it to the electricity market. The different market segments are explained in more detail below.

Baseload hours
A power plant producing for baseload is designed to run for as many hours as possible per year. Generators with the lowest costs per kWh such as nuclear plants are typically used to produce for this segment of the electricity market, producing for the demand that exists round-the-clock. Due to predictable operation times and demand, baseload is usually traded via long term contracts. A focus of CaPP on the baseload segment of the electricity seems unlikely. The characteristics of the baseload generators (low price per kWh, long lifetimes, continuous operations) are directly opposed to the principles behind CaPP (intermittent production, relative high price per kWh, low capital costs) (Kempton & Tomić, 2005a). Prices for the off peak hours are in the order of 35 €/MWh (APX group, 2015).

Peak load
During the peak hours a large electricity demand is expected. The APX group (2015) defines this period as the hours between 9 in the morning and 8 in the evening. Generators specifically built for these periods typically run on gas, are quickly ramped up, have low capital costs and run for periods of three to five hours (Kempton & Tomić, 2005a). When producing during peak hours, the price per kWh is high due to the large demand. Peak power is usually sold via day-to-day contracts (Palazzi, 2013). The characteristics of the peak load segment of the power market fairly match with the characteristics of a CPPP *if* there are sufficient FCVs available during the peak hours. This might be problematic as car use during these times is expected to be high. Prices for peak hours are in the order of 45 €/MWh.

Primary control: Real time regulation
Real time regulation or so called primary control is used for the final fine-tuning of the electricity network. Contracted companies increase or decrease their power output when a deviation of the standard network frequency is detected. This detection is done by the companies themselves mitigating the need of a signal of some sort coming from the TSO. If a frequency disturbance is detected, the contracted generators must be adjusted within less than a minute. A bidding process is organised in which companies bid to obtain contracts with durations of full weeks. The TSO must contract a predetermined amount of primary regulation at each moment in time, according to its production share in the ENTSO-E network (European electricity network) (TenneT, 2014). The companies are paid a capacity-fee for providing the option to be used for primary regulation. There is no energy-fee for the actual produced or not-produced electricity (TenneT, 2014). The bids are submitted via the portal of the former German TSO (now managed by TenneT) and are in the order of 4500 €/MW*week (Regelleistung.net, sd). Kempton and Tomić (2005a) estimated that in California around 8% of the contracted capacity of an average contracted generator is dispatched and a contracted generator will adjust its output in the order of 400 times a day. A balancing effort for the 15 minutes horizon (secondary control, discussed next) is however not present in California.

Real time regulation might not be suitable to become the core business case behind CaPP. In the case of a full focus on primary control, a call for ramping up would mean ramping the connected FCVs within less than a minute. The time before a PEMFC reaches maximum output is a bit more than 3 minutes (Rabbani, Rokni, Hosseinzadeh, &

Mortensen, 2013) and rapid ramping of fuel cells has negative effects on its durability (Palazzi, 2013; Wu et al., 2008). An advantage of providing this service would be the reimbursement via a capacity-fee. The FCVs would be generating a turnover when being plugged in. The CPPP operator will however need to bid this capacity a week ahead, requiring high certainty concerning the availability of a number of FCVs.

Secondary control: 15 minute interval regulation

During the day the Dutch TSO TenneT has several contracts available to increase or decrease the power output of several generators. The owners of these generators submit an option to TenneT one day ahead. If TenneT calls the option of a contracted generator, this generator is obliged to adjust his power output within 5 minutes (Palazzi, 2013). A call for regulation down results in a decrease in output of a power plant. When demand exceeds supply a regulation up call can be expected. Regulation up services can also be provided by large demanding parties (such as large factories) that could temporarily decrease their electricity demand (Kempton & Tomić, 2005a). The suppliers of the secondary regulative capacity are reimbursed via an energy-fee which is based on the additionally produced or production mitigated electricity (TenneT, 2012). Fees paid for additional production are in the order of 50-200 €/MWh. For regulation down, fees range between +30 €/MWh (contracted party pays TenneT, as a saving of not producing is made while electricity is already sold via for example long term contracts) to -150€/MWh (TenneT pays contracted party) (TenneT, sd-c).

The business case for secondary regulation is fairly similar to the business case of production for the wholesale market. The incorporation of regulation down signals might be specifically interesting as CaPP can increase the demand side of the network by using the electrolyser. In this case the CPPP would be paid to produce hydrogen. The regulation up calls might be harder to adhere due to the possible uncertainty surrounding the availability of FCVs.

Tertiary control: Spinning reserves

Tertiary control is used when both the secondary and primary control are not able to maintain the system balance. Causes to use tertiary control are usually unexpected events such the failure of a power plant or international connection. Contracted generators are required to increase their production within 15 minutes. This requirement leads to the need to have the generators synchronised with the grid during the contracted period. For this synchronisation the generators are fired up but run on a very low capacity, hence the term spinning reserves. The frequency of usage of the spinning reserves is around 20 times a year for usually no longer than periods of one hour (Kempton & Tomić, 2005a).

TenneT organises bids once or twice a year for contracts with a minimum 20MW for full calendar years. A contracted party must have the contracted capacity available at all times. This limits the freedom of the contracted party to profit from high or low electricity prices on the spot market. The contracted party is mainly reimbursed via a capacity-fee for the full period of the contract (TenneT, sd-b). The capacity-fee for emergency power is estimated to be 3000 €/MWh*week for the German market (VEMW, 2012). If the emergency power is called, the producer receives a compensation of the market price +10% with a minimum of 200 €/MWh (TenneT, 2013, sd-b).

Tertiary control could be very attractive for CaPP seeing the low actual power production and the existence of the capacity-fee. A large downside is however the requirement to have the contracted capacity (with a minimum of 20MW per contract) available for full years. The uncertainty of the FCV availability would make this very challenging. A solution for this problem might be pooling with existing generators. TenneT allows this kind of pooling (TenneT, sd-b). If the CPPP or a pool of CPPPs would be unable to produce the required power at the time of the call from TenneT, the other generators in the pool would start producing. The extra reliability of this pooling option comes at the price of investing and maintaining backup generator(s).

Table C-2 offers an overview of the different national market segments of the electricity. We did not include local production as contract specifics as agreed upon by CPPPs and local actors will be different for different locations.

Table C-2: Possible national market segments for CaPP production

Type of production market	Production times/ call times	Contract period[19]	Reimbursement type	Typical fees[20]
Baseload	Around-the-clock	Long term	Production-fee	35 €/MWh
Peak hours	09:00 – 20:00	Day-ahead	Production-fee	45 €/MWh
Primary control	400 times a day per generator	Week	Capacity-fee	4500 €/MW-w
Secondary control	Every 15 minutes	Day-ahead	Production-fee	50-200 €/MWh (r. up) -150 to 30 €/MWh (r. down)
Tertiary control	20 times a year nation-wide	Year	Capacity-fee	3000 €/MW-w

CPPP location

In the actor analysis in Appendix B we found that there are many parties that *could* play a role depending on the location of the CPPPs. For instance office owners might combine the CPPP with their usual parking garages, but also housing cooperatives could be parties to include when the CPPPs are located near homes.

The location of the CPPPs has furthermore large implications on the production of the CPPPs. Heating and water demands will differ per location type, but more importantly the availability of FCVs is influenced by the location of the CPPP as most cars are used for commuting purposes. The peak of FCV availability will be during daytimes if the CPPPs are near offices, and during the night when CPPPs are located near homes.

The possibility of CPPPs at other locations than offices of households seems unlikely. Parking facilities near points of interest such as city centres or theme parks would face a large FCV availability uncertainty. The defined commuting locations of home and office provide a much more stable behaviour.

Interaction with driver

One of the major uncertainties is the availability of the FCV vehicles. When and how will the drivers of the vehicles make their FCV available for CaPP? Each driver will have its own preferences and daily schedule. It is however possible to delineate the freedom of the FCV drivers.

Car Ownership

The fuel cell in the FCV is an expensive piece of technology. Although it might be economically comparable with gasoline cars in combination with for instance CaPP it would require a large upfront investment. If there is a profit to be made with the fuel cells, the owner of the car or only the fuel cell might be different from the car user. Through aggregation an owner of a fleet of FCVs might be able to exploit the advantages that CaPP offers in a more efficient way than when the cars are in private ownership. The aggregator could for instance bid on larger contracts and can develop knowledge about expected FCV availability. An FCV aggregator could be an existing company as discussed in Appendix B such as an electricity retailer or a new entrepreneur.

One step further from the current business case would be implementing a system of car sharing. In these cases individual cars are no longer 'linked' to individual customers, but one car can provide mobility for multiple customers subsequently. An advantage is the higher load factor of the car itself. In our case this option might not be so suitable as subsequent use of the car reduced parking time lowers the time the car is available for CaPP.

Parking incentives

Depending on the use case of the CPPP the availability of a certain amount of FCVs might be essential to predict or to guarantee. If this is the case the CPPP operator could implement certain institutions to steer the behaviour of the drivers.

[19] Day-ahead: contracts are closed latest one day ahead of actual production. Duration of contract can vary from quarters of an hour to several hours
[20] MWh: Megawatt hour, being one megawatt produced for the period of one hour.
MW-w: Megawatt-week, being one megawatt of production capacity available for the duration of one week.

First of all the CPPP operator could oblige the FCV driver to park his car at the designated CPPP. This obligation could be ratified if the FCV driver has closed a contract with the CPPP (for instance a certain fee is paid if the driver places the FCV in the CPPP on the designated times) or when the FCV driver is leasing the FCV from another party. In the case of car sharing the FCV driver is allowed to use the FCV, but only between certain times and he must bring the FCV back to the CPPP after use.

Secondly a monetary incentive could be in place to 'lure' FCVs to the CPPP when electricity demand is high. This option will however require a (nearly) real time connection between an FCV and all CPPPs in the area. Furthermore it is unknown how car owners will react to monetary incentive to park their cars during specific times at specific places. Questions arise such as how high such a remuneration should be, if car drivers would include this option when planning their trips (would they park and switch to public transport?) and how the high remuneration times should be communicated.

The last option concerning parking incentives is simply not to implement any incentive. This could be preferred if the CPPP is placed at such a location where the FCVs can be expected to be parked with a high reliability. An example of such a location would be currently popular car parks or offices.

Operational preferences

Once the FCV is parked in a CPPP, the driver might give certain preferences to the usage of the FCV. He could set a maximum to the usage of his FCV for electricity production, the times between the FCV may be used, or the minimum amount of hydrogen that should be available at any moment in time in the FCV. A more complex strategy would allow the FCV drivers to bid for production in a similar way as how central power plants bid on the APX.

The other end of the spectrum would be a full control of the CPPP operator over the FCV. This allows the operator to maximise profits at the costs of less control for the driver. Mainly the reduction in fuel cell lifetime when extensively used in a CPPP might be reasons for owners not to participate in CaPP.

Payment to car owner

During the times the FCV is parked in the CPPP, it has value for the CPPP owner. It is to be expected that some sort of compensation will be given to the owner of the FCV for the usage of the car. The most logical compensation seems to be a remuneration. With 500 FCVs parked in a typical CPPP, making payments to each FCV owner might be time consuming. Instead or additionally the CPPP could fill the hydrogen tank of each connected FCV as compensation.

If the car driver is willingly to park his FCV according to the demands of the CPPP owner a periodic payment could be considered. This could result in a kind of subscription or contract.

Legislation

CaPP can only be successful if the legal requirements are met. First of all the requirements for building a CPPP and operating it should be of concern. A discussion of these requirements can be found on page 107. Summarised they concern the environmental characteristics of the CPPP ('milieu omgevingsvergunning' and norms as established in the 'Activiteitenbesluit') and the permit to be allowed to construct a facility for hydrogen refuelling ('bouwvergunning').

The other regulations that need to be adhered are the requirements set by the network operators of the electricity, gas, heat and water networks. Mainly the latter will involve strict regulations as discussed on page 106.

Governmental income

Although there are environmental gains from using hydrogen as a fuel for road transport, it can be expected to be the subject of excises. The current income of the excises on fuel are roughly four billion euros per year (Ministerie van Financiën, 2014). A nationwide implementation of FCVs would result in a large substitution of gasoline, potentially lowering the governmental incomes significantly. The excises on hydrogen are of large concern for the CaPP business case as the owner of the fuel station is the actor that is being taxed. Although the ministry of finance has the full authority to determine the exact height of the excise, a discussion between the ministry and the proponents of CaPP seems worthwhile. The proponents such as the GreenVillage could give the following arguments in favour of a lower excise tariff:

- The environmental gains with respect to CO_2 might lower the needs of investments in other renewable initiatives.
- The environmental gains with respect to local pollution will contribute to the environmental goals of the local governments.
- Depending on the use case, a large grid balancing potential could be available. By balancing the grid, investments in additional grid capacity are no longer needed, lowering the electricity bill of consumers and industries.
- Hydrogen is produced from electricity or natural gas, allowing for a reduced dependency on the import of foreign energy in the form of oil.

A different source of governmental income which is related to the CaPP concept is the income from parking which is governed by the municipalities. For a large city such as Rotterdam the incomes from parking are around €65 million (roughly 1,5% of the total exploitation) of which one third are fines (Algemeen Dagblad, 2014; Gemeente Rotterdam, 2014). An implementation of CaPP will have consequences for the municipal budgets. We however do not foresee a large bottleneck here due to the allowance of the already existing private car parks (such as Q park) and the relatively low impact on the municipal budget (1,5% in the case of Rotterdam).

Subsidies

The current instrument for the support of renewable energy production is the SDE+. As discussed in more detail on page 107, the benefits for CaPP would be depending on the potential as determined by the ministry of finance. Furthermore the renewable production of hydrogen, or the renewable generation of electricity from hydrogen are currently not covered in the programme (RVO, 2014). If CaPP is accepted in the programme, a subsidiary in the order of €35/MWh electricity and 14 €/GJ heat are possible, depending on the assigned potential.

Synthesis

When related to the technical design options we conclude that there exists much uncertainty concerning the institutional design of CaPP and much less work has been reported. The existence of independencies among the different institutional options results in a complex design space. An overview of the discussed institutional design options can be found in Table C-3. It is unlikely that this overview is exhaustive. It will be subject to many changes and additions during the future CaPP design process. We again refer to the current work-in-progress by Esther Park Lee at the TPM faculty of the TU Delft for future new insights and refinements concerning the institutional design of CaPP.

In the overview as presented below we have not included the aspects in the governmental theme; legislation, tax and subsidies. Although they are of major concern for the implementation of CaPP they cannot be seen as a design option at this stage. With respect to legislation the only plausible options is to comply with the regulation as imposed by the central and local authorities. With respect to the financial aspects the ministry of finance is critical as it has full control over the taxes and subsidies. The final CaPP design could influence the likelihood of receiving a tax benefit or a subsidy. But we conclude that all aspects which we discussed in the governmental theme should at this stage be seen as uncertain external forces instead of CaPP (institutional) design options.

Table C-3: Institutional CaPP morphchart

CPPP owner	Traditional carpark owners	Offices	Electricity network operator	Electricity retailers	Housing cooperative	New entrepreneur
CPPP operator	Traditional carpark owners	Offices	Electricity network operator	Electricity retailers	Housing cooperative	New entrepreneur
Use Case	Local demand	Baseload hours	Peak hours	Primary regulation	Secondary regulation	Tertiary regulation
Car ownership	Private	Aggregator: leasing	Aggregator: car sharing			
Payment to car owner	Monetary	Full H_2 tank				
Driver input - parking	Obligation from owner	Monetary incentive	No incentive			
Driver input - operational	Driver preferences	Full control by CPPP operator				

Appendix D. Model data structure

Documenting a software data structure forces the modeller to carefully think about how he formalises the real world but also allows others to gain insight into the choices made in the modelling process and prevents ambiguity. The tables below present the software data structure for the CaPP model.

Table D-1: Software data structure – environmental variables

Environmental variables			
Pollution			
Variable	Unit	Data structure and range	Range
Pollution by ICVs	Kg CO_2-eq	Floating point	
Pollution by FCVs parking conventionally	Kg CO_2-eq	Floating point	
Pollution by FCVs parking at CaPP	Kg CO_2-eq	Floating point	
Time			
Variable	Unit	Data structure and range	Range
Minutes	Minute	Integer	0; 15; 30 or 45
Hour	Hour	Integer	>= 0 and <= 23
Day	Day	Integer	>= 1 and <= 365
Week	Week	Integer	>= 1 and <= 52
Month	Month	Integer	>= 1 and <= 12
Quarter of a year	Quarter of a year	Integer	>= 1 and <= 4
Year	Year	Integer	>= 0
Weekdays/Weekends		Boolean	Weekdays/Weekend
Prices			
Electricity price	€/kWh	Floating point	
Regulation down price	€/kWh	Floating point	
Regulation up price	€/kWh	Floating point	
Gas price	€/m^3	Floating point	0,39 or 0,73
FCV price	€	Floating point	
ICV price	€	Floating point	
Hydrogen price	€/kg	Floating point	

Table D-2: Software data structure – driver variables

Driver variables			
Car ownership			
Variable	Unit	Data structure and range	Range
Car type		String	"ICV" or "FCV"
Car age	Quarter of years	Floating point	>= 0
Car renewal age	Quarter of years	Floating point	>= 0
Driving			
Variable	**Unit**	**Data structure**	**Range**
Destination	[selected agent]	Agent	
Location		String	"AtHome"; "AtWork"; "AtCPPP"; "OnTrip"; or "Driving
H_2 in tank	Kg	Floating point	
Parking behaviour		String	"Conventional" or "CaPP"
Departure time from home to work hour	Hour	Integer	>= 0 and <= 12
Departure time from home to work minutes	Minute	Integer	0; 15; 30 or 45

Departure time from work to home hour	Hour	Integer	>= 12 and <= 23
Departure time from work to home minutes	Minute	Integer	0; 15; 30 or 45
Departure time for weekend trip hour	Hour	Integer	>= 9 and <= 15
Departure time for weekend trip minutes	Minute	Integer	0; 15; 30 or 45
Return time from weekend trip hour	Hour	Integer	
Return time from weekend trip minutes	Minute	Integer	0; 15; 30 or 45
FCV Beliefs			
Variable	**Unit**	**Data structure**	**Range**
FCV Pollution belief	kg CO_2-eq /km	Floating point	
Hydrogen price belief	€	Floating point	
CaPP beliefs			
Variable	**Unit**	**Data structure**	**Range**
CaPP required plugin time belief	Hour	Floating point	
CaPP cashback memory	€/departure from CPPP	List of floating points	
CaPP cashback belief	€	Floating point	
CaPP contract			
Variable	**Unit**	**Data structure**	**Range**
CaPP contract time start	Hour	Floating point	
CaPP contract time end	Hour	Floating point	
CaPP contract duration	Hour	Floating point	

Table D-3: Software data structure – CPPP variables

CPPP variables			
Hydrogen attributes			
Variable	Unit	Data structure and range	Range
Hydrogen storage	Kg	Floating point	"ICV" or "FCV"
Hydrogen demand memory	Quarter of years	Floating point	>= 0
Hydrogen storage target	Kg	Floating point	
Operation planning			
Variable	**Unit**	**Data structure**	**Range**
Desired hydrogen production hours	Hour	List of integers	Non-repetitive set of values >= 1 and <= 23
Desired Peak hours production	kWh	List of 96 floating points	Set of values >= 0
Desired regulation up production	kWh	List of 96 floating points	Set of values >= 0
Desired regulation down production	kWh	List of 96 floating points	Set of values >= 0
Electricity price memory	€/kWh	List of 720 floating points	
FCV Availability			
Variable	**Unit**	**Data structure**	**Range**
FCV availability	FCV	Integer	
FCV availability memory	FCV/15 minutes	List of 2880 floating points	
Hydrogen production			
Variable	**Unit**	**Data structure**	**Range**
Electrolyser capacity	Kg/15 minutes	Floating point	
Electrolyser use	Kg/15 minutes	Floating point	
Steam reformer capacity	Kg/15 minutes	Floating point	
Steam reformer use	Kg/15 minutes	Floating point	
SOFC capacity	Kg/15 minutes	Floating point	
SOFC use	Kg/15 minutes	Floating point	

Financial performance			
Variable	**Unit**	**Data structure**	**Range**
Operational revenues	€	Floating point	
Operational costs	€	Floating point	
Electrolyser production costs	€	Floating point	
Steam reformer production costs	€	Floating point	
SOFC production costs	€	Floating point	
Storage costs	€	Floating point	
Emissions			
Variable	**Unit**	**Data structure**	**Range**
Well-to-wheel greenhouse gas emissions	Kg CO_2-eq/kg	Floating point	

Table D-4: Software data structure – simulation variables

Pre-simulation settings			
CPPP design			
Variable	Unit	Data structure and range	Range
CaPP Use case	String	Boolean	"Peak load production" or "Secondary control"
CPPP Reformer Technology	String	Boolean	"SOFC" or "SteamReformer"
CPPP Contract Obligation	String	Boolean	"Obligation" or "No Obligation"
CPPP location	String	Boolean	"Near Households" or "Near Offices"
CPPP company size	String	Boolean	"Large user" or "Small user"
Number of households		Integer	>= 0 and <= 1000
Office size	Employees/office	Integer	>= 0
Initial FCV percentage	%	Floating point	>= 0 and <= 100
CPPP size	Parking spots	Integer	500
Hydrogen price	€/kg	Floating point	>= 0
FCV price	€	Integer	
Learning Diffusion Coefficient	%	Integer	>= 0
Share of wind electricity for CPPP	%	Integer	>= 0

Appendix E. Hydrogen system formalisation

Within the model we have formalised the CaPP as a sort of black box. For the sake of possible future expansion we have split the CaPP agents into 5 modules following the decomposition of Spanjer (2014). This appendix reports on the used assumed technical characteristics of these modules and how they have been calculated. First some used physical properties are listed that have been used in the calculations.

Used physical properties

- The molecular weight of hydrogen is 2,0158 g/mol
- The number of Avogadro is 24,5 l/mol at T=298 and p = 1 atm
- The caloric value of natural gas is 31,65 MJ/m^3

Steam reformer

We base the operation of the steam reformer module on the work of Spanjer (2014). The module comprises besides the steam reformer the device also additional devices required for the correct operation of the steam reformer. This are devices such as heat exchangers, methane handling (as discussed on page 96) pumps etc.

Table E-1: Operation streams for one mole H2 produced with a steam reformer and accompanying devices. Based on (Spanjer, 2014, p. 53)

	IN			OUT		
	Molar flow [mol]	Energy [kJ]	Exergy kJ	Molar flow [mol]	Energy [kJ]	Exergy [kJ]
Methane	0,52	397,01	372,06	-	-	-
Electricity	-	3,67	3,67	-	-	-
Hydrogen	-	-	-	1	285,04	236,09
Heat	-	-	-	-	86,19	13,80
Water	1	-	-	0,8	0,61	0,02
Air	3,08	1,39	0,01	3,32	5,58	6,17
CO_2	-	-	-	-	-	-
Total	4,6	402,07	375,74	5,12	377,42	256,07

The steam reformer module requires 0,52 moles methane to produce one mole of hydrogen (Spanjer, 2014, p. 53). Thus for one kg of hydrogen we require:

$$\frac{\left(0{,}52\ moles\ methane * 1000\,\frac{g}{kg}\right)}{2{,}0158\,\frac{g}{mol}} = 257{,}9621\ moles\ of\ methane$$

In the Gronings natural gas the molar percentage of methane is 81,29% (Nederlandse Gasunie, 1980). 257,9621 moles of methane thus equals:

$$\frac{257{,}9621 moles\ of\ methane}{81{,}29\%} * 0{,}0245\,\frac{m3}{mol} = \ 7{,}774722\ m3\ natural\ gas$$

Note, we here see a large difference between our calculations based on the work of Spanjer (2014) and the work of Palazzi (2013). Where Palazzi (2013, p. 18) reports the requirement of 3,2 to 3,7 kg of natural gas per kg of hydrogen, we arrive at a requirement of roughly 6,5 kg of natural gas per kg of hydrogen. We suspect that the differences can be explained by a more detailed decomposition of Spanjer of the required devices and processes. As an example we did not find the inclusion of the combustion of some of the natural gas for the heating of the steam reformer in the work of Palazzi.

The size of the steam reformer module is by our knowledge not yet determined by the researchers of the Green Village. Spanjer (2014, p. 35) reports an used production capacity of 0,05 kg per second for a CPPP with a capacity of 100 FCVs. When we examined her sources we came to the conclusion that the reported number is most likely subject to a type error and the correct number is 0,05 kg per minute[21].

For a CPPP of the size of 500 cars, a steam reformer module of the size as suggested by Spanjer (2014) would result in a daily production of 360 kg hydrogen. If we compare this to the hydrogen use by FCVs (1 kg / 100 km) and they daily commuting distance (60 km) we conclude that such a system would not allow for any hydrogen production for electricity production. We have tested different sizes of the steam reformers and have selected 4 kg hydrogen production per day per car capacity. This would thus roughly leave 3 kg hydrogen per car to be used for electricity production.

SOFC

Also for the SOFC module we base ourselves on the work of Spanjer (2014). Also the SOFC module requires additional devices to operate. Table E-2 presents the numbers by Spanjer converted to the streams per produced mole of hydrogen.

Table E-2: Operation streams for one mole H_2 produced with a SOFC and accompanying devices. Based on (Spanjer, 2014, p. 57)

	IN			OUT		
	Molar flow [mol]	Energy [kJ]	Exergy kJ	Molar flow [mol]	Energy [kJ]	Exergy [kJ]
Methane	0,88	698,55	654,85	-	-	-
Electricity	-	84,50	84,50	-	309,32	309,32
Hydrogen	-	-	-	1	365,04	236,09
Heat	-	-	-	-	149,51	23,93
Water	1,64	-	-	2,24	1,67	0,06
Air	6,68	4,33	0,03	5,8	16,58	11,88
CO2	-	-	-	0,76	8,07	6,54
Total	9,2	783,05	739,35	9,8	745,53	569,39

Following Table E-2 the production of one mole of hydrogen with the SOFC module requires 0,88 moles of methane. If we follow the exact same calculations as used above for the steam reformer module, we come to a natural gas requirement of 13,15722 m^3 for the production of one kilogramme hydrogen.

An important side product of the SOFC module is the production of electricity. When producing one mole of hydrogen an additional 224,8164 kW of electricity is produced (Spanjer, 2014). This is equivalent to;

$$\frac{224{,}8164\,\frac{kWe}{molH2}}{2{,}0158\,\frac{g}{mol}} = \frac{111{,}52714\;kWe}{gH2} = \frac{111527{,}14\;kWe}{kgH2}$$

$$\frac{111527{,}14kWe}{60min * 60s} = 30{,}97976\;kWh$$

The production of one kilogram of hydrogen via an SOFC module will require 13,15722 m^3 natural gas and yields 30,97976 kWh of electricity as a side product.

[21] Spanjer compares the used capacity for her study with a system of Hyfleet in Stuttgart and states that these are of comparable size. The output of the German system is 50 Nm^3/hour which corresponds to 4,5 kg per hour or 0,075 kg per minute (HyFleet, sd.).

For the objective of comparison we will assume that if a SOFC module is in place, it will have the same production capacity as the steam reformer as described above; 4 kg hydrogen per day per parking spot.

Electrolyser

Unfortunately the electrolyser has not been discussed by Fernandes et al. (2015, In press) and Spanjer (2014). For our purposes we have used the information as provided by Palazzi (2013): for the production of on kg of hydrogen 50 kWh of electricity is used. We assume a size that is equal to the installed capacity of the steam reformer; 4 kg of hydrogen per day per parking spot.

Storage

The storage module includes all devices require for the storage of the hydrogen in the CPPP. For the storage of one mole of hydrogen, 31,23 kW electricity is required. This thus equals for each kg of hydrogen;

$$\frac{\left(31{,}23kw * 1000\frac{g}{kg}\right)}{2{,}0158\frac{g}{mol}} = 15495{,}78\ kWe$$

$$\frac{15495{,}78kWe}{60min * 60s} = 4{,}304384\ kWh$$

The size of the storage is still a design parameter to be determined. For now only Fernandes et al. (2015, In press) has reported a number of 25 kg H_2 storage per parking spot. For our study we shall assume that the storage of the CPPPs is sufficient in all cases, and will thus not pose a limit to the operation of the installation.

FCV

Also the FCV module as we use it is *more* than just the hydrogen vehicle. Based on the demarcation as used by Spanjer (2014) this module also includes all other devices required to operate the fuel cell, such as pumps, heaters and membranes. We expect this to be the main cause of the differences in numbers used by Spanjer (2014, p. 62) and Palazzi (2013, p. 30).

In the FCV module, one mole of hydrogen is converted to 117 kW of electricity (Spanjer, 2014, p. 62). One kilogram of hydrogen is thus converted into:

$$\frac{\left(117\frac{kw}{mol} * 1000\frac{g}{kg}\right)}{\begin{array}{c}2{,}015\\ 8\frac{g}{mol}\end{array}} = 58041{,}47\ kW$$

$$\frac{58041{,}47kW}{60min * 60s} = 16{,}12263\ kWh$$

The total conversion of an FCV module of a CPPP is the amount of fuel cells parked times 100 kW (van Wijk & Verhoef, 2014). The time step of the model is 15 minutes. One FCV can thus produce 25 kWh in one time step.

Appendix F. Financial & environmental estimations

Capital costs

Steam reformer

Steam reformers are relatively well developed technologies and prices are relatively well known. We have used data from Lipman (2011); Yang and Ogden (2005). The steam reformer as we have modelled has a production capacity of 2000 kg per day (cf. Appendix E). By using Guthrie index of a capital cost estimations we have calculated the costs of a steam reformer with a capacity of 2000 kg hydrogen per day[22]. The estimated investment costs for the installation of this size is €1,35M.

SOFC

Weimar, Gotthold, Chick, and Whyatt (2013, p. 38) and Thijssen (2009, p. 25) report cost estimations of around $680/kWe when the technology can be deployed on large scale. The SOFC in a CPPP with a capacity of 500 FCVs would have a hydrogen production capacity of 2000 kg / day or 0,023 kg/s (cf. Appendix E). In Appendix E we have calculated that with each produced kilogram of hydrogen additional 111527,14 kW of electricity is produced. The electrical capacity for the installation for a CPPP with 500 parking spots would therefore be

$$111527{,}14\, kWe/kg/s \;*\, 0{,}023\; kg/s \;= 2581{,}65\; kWe$$

The capital costs of SOFC device itself the can then be estimated to be $1,75M or €1,6M.

Electrolyser

For the costs of the electrolyser we base our estimations on the base scenario of Genovese et al. (2009, p. 20). An electrolyser with a capacity of 1500 kg/day is estimated to cost $1,2M. Genovese et al. (2009, p. 7) also reports a Guthrie index of electrolysers of 0,7. This brings our estimation for the costs of a electrolyser with a capacity of 2000 kg/day to $1,55M or €1,4M.

Other

Next to the investments into the hydrogen production devices, a CPPP will require investments in piping, structure, parking spots etc. We use the Lang factor for fluid processing of 4,7 times the major equipment costs.

Total capital costs

We formalised two different designs for this study. Based on the cost estimations for the devices as above, we come to the following rounded estimations of the total required investments:

CPPP with 500 parking spots, a steam methane reformer and electrolyser: € 13M.

CPPP with 500 parking spots, a SOFC and electrolyser: €14M.

[22] the index of the cost estimation was found to be 0.9 based on the data of Lipman (2011). Using this index gave us consistent values when using the data from Yang and Ogden (2005).

Electricity incomes and expenses

Peak load production

Both the incomes of peak load electricity are dependent on the electricity price. Due to the intermittent production capacity of CaPP we have assumed that it will sell its electricity on the Dutch spot day-ahead market.

Although asked, we were not able to obtain the hourly price of the Dutch electricity market from the APX group. As a solution we have taken the price information of four different days (which are available for download on that specific day at (APX group, 2015)): 30 January 2015, 13 March 2015, 19 March 2015 and 12 April 2015[23]. The model is programmed to take a different source day for each day in the simulation and vary all the prices with ± 10%.

Secondary control

Regulation up

Historical data for the regulation up services are available for download at (TenneT, sd-a). As there is a different price for each quarter of a hour, the data for one year would consist out of 35000 data points. The site of TenneT was not able to process data requests for full years, and we expected this many data points to make the model instable. As a proxy we have used the first month of each quarter of a year. For the first quarter the prices of January 2014 were used, for the second quarter the prices of April 2014, for the third quarter the prices of July 2014 and for the fourth quarter the prices of October 2014.

Regulation Down

The data sheets as used for regulation up also provided the prices for regulation down. For a CPPP only the regulation down signals that are negative, i.e. result in TenneT paying the contracted party to increase production are interesting. Here we assume that regulation down signals can also be fulfilled by increasing electricity demand. These kind of payments are currently not present in the Netherlands, but are to be expected when the share of intermittent renewables on the system increases.

Electricity purchase

The CPPP in our model buys electricity when it desires to produce hydrogen with the electrolyser. For the prices at which the CPPP can buy its electricity we have used the same day-ahead spot prices. This requires the assumption that CaPP is exempted of excises on electricity prices (i.e. it does not have to pay tax for the bought electricity).

Gas expenses

For the costs of production we take the gas price as given by the CBS (2015a). Companies pay a price that depends on the amount of gas they use yearly. A company using less than 285333 m^3 of gas a year pays roughly €20 per GJ, or 73 cents per m^3. A user using between 285333 m^3 and 28533300 m^3 of gas a year pays €11 per GJ, or 39 cents per m^3. As discussed later, 285333 m^3 is enough to produce;

$$\frac{285333m3}{7,774722\ m3natgas/kgh2} = 36700{,}09\ kg\ h2$$

With which an FCV's can produce (as discussed in Appendix E):

$$36700{,}09\ \ kg\ h2 * 16{,}1263\frac{kWh}{kgh2} = 591836{,}272\ kWh\ electricity$$

[23] Although the APX group states that 'bespoke data services' are available upon request we have not received an answer to our requests for more detailed data.

The typical size of a CPPP as envisioned by van Wijk and Verhoef (2014) is 50 MW. In order to produce 590 MWh at least twelve of such large envisioned CPPPs will have to operate at full capacity during the year, only producing hydrogen from natural gas. For our model we assume that the CPPPs are owned by one company and the lower price of 39 cents per m^3 applies. Recommendations for future research on this topic are given in section 9.5.2.1.

Hydrogen prices

Recently the first Dutch public hydrogen refilling station was opened for the public. At this station one kilogram of hydrogen is sold for €10 (Tankpro, 2014). This hydrogen was reformed in a nearby installation and is tapped from the transport line between Rotterdam and Antwerp. Many European governments have set the targets of hydrogen production costs below €5/kg (Pollet et al., 2012). In a scenario in which CaPP can be deployed we have assumed that FCVs are widely adopted, and the target hydrogen prices have been achieved.

Gasoline prices

The gasoline price at the pump is at the time of writing around €1,70/L for gasoline and €1,35/L for diesel. The prices have lately been very volatile. Different scenarios exist and depending on the year of interest the price might be in a wide range of possibilities. For our settings we have chosen a relatively high gasoline price of €1,70/L.

Car purchase and fuel costs

FCV and ICV prices

Estimated FCV prices are expected to be in the range of 1,2 to 1,3 times the price of an ICV (Veziroglu & Macário, 2013). With average price of ICVs at €40.000 in 2014 (Bovag-Rai, 2014), we have assume the FCV price to be €50.000.

Fuel costs

We assume that ICVs use 1 litre of gasoline per 15 kilometres. As the average commuting distance is 60 kilometres per day (CBS, 2014b), a driver on average spends €3,20 per trip.

AN FCV can drive 100 km on one kg of hydrogen (Schenk, 2014). Thus one litre of hydrogen a driver can travel the same distance as with 6,66 litres of gasoline. This leads to a gasoline-like price of €1,20/L for hydrogen.

Well to wheel pollution

Hidrue et al. (2011) included the valuation of a relative pollution reduction of different cars by drivers. However the measure of pollution is not specified. We here assume that the pollution of a certain vehicle is valued by the well to wheel (WTW) emissions of the vehicle and its fuel. We base our formalisation on the WTW data of a research group of the EU (Edwards et al., 2014).

Conventional diesel vehicles are expected to have a GHG emission of 105 g $CO_{2\text{-eq}}$/km. FCVs are expected to have a WTW emission depending on the production method of the hydrogen. When natural gas is reformed on site the emissions are 68 g $CO_{2\text{-eq}}$/km. On-site electrolysis based on the EU mix of 2009 would result in an emission of 120 g $CO_{2\text{-eq}}$/km, and electrolysis from electricity coming from wind or nuclear plants would result in an emission of roughly 10 g $CO_{2\text{-eq}}$/km. For our purposes the two hydrogen production paths are of interest

1) FCVs who do not refuel at CPPPs
   For these types of vehicles we assume a hydrogen production by central reforming and pipeline transport to the refuelling stations. The $CO_{2\text{-eq}}$ emissions are then estimated to be 60 g/km

2) FCVs who do refuel at CPPPs
   The hydrogen production of the CPPP can occur following three types of pathways

a) Electrolysis.

The WTW emissions of the production of hydrogen by electrolysis depend on the used electricity source. If the EU electricity mix of 2009 is used the emissions are estimated to be 120 g $CO_{2\text{-}eq}$/km. If the electricity is produced with wind turbines the estimation of the emissions come down to 10 g $CO_{2\text{-}eq}$/km.

b) Steam Reforming

On site reforming with natural gas is expected to result in emissions of 68 g $CO_{2\text{-}eq}$/km.

c) SOFC

The estimation of greenhouse gas emissions by SOFC are not covered in (Edwards et al., 2014). For our purposes we assume that the CO_2 emission per used amount of natural gas of a SOFC device is equal to that of a steam reformer (cf. the chemical reactions as presented in Appendix A). The hydrogen yield of a SOFC is however lower than that of a steam reformer, compensated by the produced electricity as side product. The steam reformer produces one kg of hydrogen from 7,77 m^3 natural gas. The SOFC produces one kg of hydrogen from 13,16 m^3 natural gas. The side production of 30,98 kWh per produced kg of hydrogen could for instance be fed to the electrolyser of the CPPP and converted to an additional 0,62 kg of hydrogen. The amount of natural gas per kg of hydrogen is then 13,16/1,62 = 8,12. This is 4,5% more than the natural gas requirements of the steam reformer. Based on this calculation we assume the GHG emissions of a SOFC to be 4,5% higher than those of a steam reformer; 71 g g $CO_{2\text{-}eq}$/km. This estimation and assumption could be improved by a lifecycle analysis of hydrogen when produced on site by a SOFC and used in FCVs.

For the CPPP we assume that we can calculate the average WTW emissions for their users based on the load factors of each production method (kilograms per production method divided by total kilograms produced). We will treat the electricity source as a variable within the model.

Appendix G. Model Verification

We use the approach of Van Dam et al. (2013) for the verification of the CaPP operation model. We execute several checks that forced us to observe the model closely and test if the displayed behaviour matches our ex-ante modelling intentions. The following types of tests are executed for this project and are discussed in this appendix.

- Recording and tracing agent behaviour
- Minimal model testing: sanity checks
- Breaking the agent in a multi-agent setup
- Full model observing

Please refer to (Van Dam et al., 2013) for detailed argumentation on the why and how these tests are used.

Recording and Tracing Agent Behaviour

For each procedure in the model we test whether the agents that are executing these procedures are computing the outcomes as we intended, given pre-defined input. The different procedures of the model have been tested separately of which the findings are presented below.

SETUP PROCEDURES

Setup procedure – Observer procedure
Input: households = 6. Officesize = 30, initial% of FCVs = 50.
Expectation: The model is initialised with 6 households, 6 accompanying drivers, 1 office (as there are not enough drivers to fill 2 offices) and approximately 3 of the drivers will own an FCV.
Output: 6 households, 1 office, 3 FCVs, 3 ICVs.
Verified: yes.

Load Electricity Price List procedure - Observer procedure
Input: External file with data containing a list of variable size (depending of the input) of prices, for each hour one price. E.g. price of 05:00 equals entry number 5 of the file and has the value 0.03108.
Expectation: A list of equal length as the input file, where each entry corresponds to the entry in the file.
Output: A list of equal length as the input file, where among others entry 5 =0.03108 (please note that entry 5 is the 6th number in the list, as lists are numbered starting at 0 in Netlogo).
Verified: yes.

Load Secondary control prices procedure - Observer procedure
Input: 8 files external files, each containing 2880 data points. Each file represents a different month. Each data point in the file represents a quarter of a hour in the specific month.
Expectation: 8 lists containing an equal amount of data points as the corresponding data file, in which the data points of the lists match those of the corresponding data file.
Output: 8 lists of equal length as the corresponding data file, in which the data points of the lists match those of the corresponding data file.
Verified: yes.

Introduce CaPP procedure – Observer procedure
Input: CaPPsize = 100, Use Case = "Secondary Control", CaPP Obligation = "Obligation", CPPP Reforming Technology = "SOFC".
Expectation: The creation of one CPPP at a location that has the lowest distance to all households. The size of the CPPP is 100, the hydrogen production methods have a capacity of 45 kg/15min, the hydrogen is storage is 5 kg * 100 parking spots and the use case is secondary control with obligation.

Output: One CPPP is created at a location that seems to be at a location close to all households. By monitoring the CPPP we confirm that the capacities of the electrolyser and the SOFC have a capacity of 45. Hydrogen in storage is 500 kg.
Verified: yes.

GO PROCEDURE

Update time procedure – Observer procedure
Input: ticks = 35039. Ticks increased to 35040
Expectation: tick 35039 represents 23:45 of 31 December. If we let the model progress one tick we expect all counters to switch to the stance of a new year. Furthermore we expect that the signals for new 15 minutes, new hour, new day, new week, new month and new quarter of a year are all issued, in this order. We implemented a report function for all the different signals for this test.
Output: Clocks in interface switching to year 2, month 1, day 1, hour 0, minutes 0, quarter 1 and week 1. Signals: Signal quarter of a year – Signal new month – Signal new week – Signal new day – Signal new hour – Signal new 15 minutes
*Verified: n*o. The signals of the start of the new time dimensions are in reversed order. Fixed, Tested, Verified.

NEW 15 MINUTES PROCEDURES

Leave for work procedure – Driver Procedure
Input: Location = At CaPP. Location of CPPP = "Near Households". Departure time to work = 04:45. Time = 04:30. Moving to 04:45.
Expectation: The driver will show its route towards the office, set the office as its destination, sets its location to "driving" and set the amount of hydrogen in tank to 5 kg.
Output: The link between driver and office is now visible and the office is its destination. Hydrogen in tank is 5 kg. Location is driving.
Verified: yes.

Leave for home procedure – Driver Procedure
Input: Location = At Office. Location of CPPP = "Near Households". Parking behaviour = CaPP. Departure time to home = 18:45. Time = 18:30. Moving to 18:45.
Expectation: The driver will show its route towards the CPPP and set the CPPP as its destination. The location becomes driving.
Output: Destination is the CPPP and the link between driver and CPPP has become visible. Location is now driving.
Verified: yes.

Leave for trip procedure – Driver Procedure
Input: Location = At Home. Departure time for trip = 12:30. Time = 12:15. Moving to 12:30
Expectation: The driver sets its destination to a random patch and its location as driving.
Output: A random patch has become the destination. Location of driver is now driving.
Verified: yes.

Execute short-term operation procedure – CPPP Procedure
Input: Total electrolyser use this simulation run =4743,109 kg. Steam reformer use this simulation run = 0, SOFC use this simulation run = 0. Total hydrogen production this simulation run = 4743,109 kg. Time = 04:45. Moving to 05:00. Desired hydrogen production hours = [4 3 2 5 0].
Expectation: The CPPP acknowledges an FCV availability of 29 FCVs. Because the current hour is an hour during which the CPPP desires to produce hydrogen this hour, and the total amount of hydrogen will be increased along with the total hydrogen produced by one or more production methods.
Output. FCV availability =29. Total hydrogen production set to 4788,109 kg. Total electrolyser use set to 4788,109. Steam reformer use = 0. SOFC use = 0.
Verified: yes.

Manage hydrogen storage procedure – CPPP procedure
Input: Current time= 04:45 moving to 05:00. Desired hydrogen production hours = [4 3 2 5 0]. Electricityprice = 0,0316 €/kwh. Gasprice = 0,73 €/m3. Electrolyser capacity = 45 kg/15min. Steam reformer capacity = 0 kg/15min. SOFC capacity 45 kg/15min. Use Case = Secondary Control
Expectation: The CPPP will want to produce 45 kg this quarter of an hour. The price to produce a kg with the electrolyser is 50 kWh* 0,0316 €/kWh = 1,58 €. As the use case is secondary control, the CPPP does not know the electricity demand of upcoming 15 minutes, so he will use the electricity produced by the SOFC in the electrolyser if possible. The price with use of the SOFC is (13,157 [$m^{3]}$ * 0,73 [€/m^3]) / 1,62 [kg H_2/m^3] = 5,93 €/kg. As the electrolyser is cheaper, the electrolyser will be used. The operational costs of the CPPP will increase by 1,58 * 45 = 71,1 €
Output: SOFC cots of 5,93 €/kg. Electrolyser cost of 1,58 €/kg. Hydrogen production of 45 kg. Electrolyser usage increased by 45. Operational costs increase of 71,10.
Verified: yes.

Run use case procedure - CPPP procedure
In the model two use cases have been included; peak load production and secondary control. The secondary control use case can again be divided in two procedures; the regulation up and regulation down service provisions. For peak load production a separate procedure was used. Tests have been executed for all three procedures.

<u>Peak load production</u>
Input: Current hour = 18. Peak Hours = [9 10 11 12 13 14 15 16 17 18 19 20]. FCVs at CPPP = 3. Hydrogen in storage = 491.99 kg. Contracted Electricity demand for these 15 minutes = 50 kWh. Electricityprice = 0.0548 €/kWh
Expectation: The current hour is a peak hour, resulting in the CPPP wanting to produce electricity. The amount of FCVs available is 3, resulting in a possible electricity production capacity of 75 kWh. The hydrogen in storage is more than enough for this purpose. The contracted electricity demand is however only 50 kWh, which will thus be determining the amount of electricity the CPPP will produce. The revenues are expected to be 0.0548*50 = 2.74. The hydrogen required is expected to be 50/16,122= 3,1 kg.
Output: Electricity production of 50 kWh. Hydrogen used = 3,10. Operational revenues = 2,1955.
Verified: No. Electricity price of previous hour was used. Fixed, Tested, Verified.

<u>Secondary control regulation up operation</u>
Input: FCV availability = 11. Regulation up price = 0,11. Hydrogen in storage = 465,88. Desired production for regulation up = 275 kWh.
Expectation: The FCVs can all together produce 275 kWh. The hydrogen is abundant. We expect 275 kWh to be produced. The revenues are expected to be 0.11*275 = 27.7805. The hydrogen used is expected to be 275 / 16,122 = 17,05.
Output: Produced electricity = 275. Revenues = 27,7805. Hydrogen use = 17,05.
Verified: yes.

<u>Secondary control regulation down operation</u>
Input: Desired electricity use for regulation down = 2250 kWh. Regulation down price = -0,023. Electrolyser used these 15 min = 0 kg.
Expectation: Seeing that the CPPP will get paid if he uses electricity these minutes, he will start his electrolyser and produce hydrogen. The maximum capacity of producing 45 kg is equal to an electricity demand of 45 * 50 = 2250 kWh. The expected revenues of using the electricity is -(-0,023) * 2250 = 51,77.
Output: Desired production = 2250. Hydrogen produced = 112500 kg. Operational revenues = 51,77.
Verified: No. Hydrogen production calculated wrongly. Multiplication by 50 instead of division. Fixed, Tested, Verified.

Drive procedure – Driver procedure

Input: Cartype = FCV. Destination = CPPP. Distance to destination = less than driving speed per 15 min. H2 in tank = 4,25. Time = 17:15 moving to 17:30. Hydrogen price = 8 €/kg.

Expectation: As the distance to the CPPP is smaller than the driving speed, the driver will arrive at the CPPP at the next tick. We expect him to use up 0,15 kg of hydrogen, set his location to At CPPP, give his hydrogen in tank to the CPPP and add a memory notion of making a earning of using CaPP of 5 – (4,25 – 0,15) * 8 = 7,20€.

Output: Driver sets his location to At CPPP. Hydrogen in tank set to 0. Added memory point of making €7,20 by parking at the CPPP.

Verified: yes.

NEW HOUR PROCEDURES

The new hour procedure is used for logging some information in the memory of the CPPP. The storage of the entries in the memory lists of the CPPPs has been checked and verified. Other tests are expected to be unnecessary due to the absence of complicated calculations.

NEW DAY PROCEDURES

Determine cheapest electricity hours procedure – Observer procedure

Input: An electricity memory resulting in the following averages of prices per hour (first entry is hour 0 to 1, second entry is hour 1 – 2) [0.03111 0.0316 0.02989 0.0283 0.02816 0.03108 0.04196 0.05093 0.05048 0.05833 0.05244 0.055 0.042 0.03994 0.039 0.03807 0.039 0.04391 0.0548 0.06567 0.04851 0.04291 0.042 0.03611].

Expectation: We expect this procedure to report a list that starts with the number that corresponds to the position of the lowest price, has the position of the second lowest price in second position and so on. That would thus be; [4 3 2 5 0 1 23 15 14 16 13 6 12 22 21 17 20 8 7 10 18 11 9 19] (note that first position has the index number 0 in Netlogo).

Output: [4 3 2 5 0 1 23 15 14 16 13 6 12 22 21 17 20 8 7 10 18 11 9 19].

Verified: yes.

Clean CPPP memory procedure – CPPP procedure

This procedure checks if a certain memory list of the CPPPs is longer than one month, and if so, reduces the list to the equivalent of one month. The procedure is verified as doing so. Due to the absence of complex calculations no other tests are executed for this procedure.

Determine desired hydrogen production plan procedure – CPPP procedure

Input: Average hydrogen usage per hour = 31,78 kg. Cheapest hours = [4 3 2 5 0 1 23 15 14 16 13 6 12 22 21 17 20 8 7 10 18 11 9 19]. Electrolysercapacity = 45 kg / 15 min. Hydrogen in storage = 560,85 kg. Hydrogen required at all times = 500 kg.

Expectation: The optimal case for the CPPP will be to produce the expected required hydrogen overnight with the electrolyser. The expected demand for upcoming day would be 31,78 * 24 = 762,72 kg. An 'excess of hydrogen in storage' is at this moment 560,85 – 500 = 60,86. The amount the CPPP would want to produce is 702,08. The electrolyser would require 702,08 / 45 = 15,6 quarters of an hour to produce this amount of hydrogen. We know the CPPP plays it safe and thus expect the amount of production hours to be 16/4=4. The hours the CPPP would want to produce should then be [4 3 2 5].

Output: [4 3 2 5].

Verified: yes.

Contracting procedure dependent of use case– CPPP procedure

The contracting (or predicting) of production capacity of the upcoming day is dependent of the use case of the CPPP. Also whether a parking obligation is in place or not largely affects this procedure. In the model four different contracting procedures have been written of which one is selected and run dependent on the CPPP design. All four procedures are have been tested. The results are described below.

Peak load production contracting without parking obligation
Input: Memory list with maximum 2880 entries representing the belief of the FCV availability at the CPPP for each quarter of an hour for over one month. For this verification effort we limited the list to 192 entries (= 2 days). The entries 90 and 196 (representing 22:30 at the two days) are both 6 FCVs.
Expectation: The CPPP should reduce the list from belief of one whole month to beliefs for quarters of hours of one day. Once succeeded it is expected to multiply the expected amount of available CPPPs with their production capacity (= 25 kWh per FCV). In our example for 22:30 we thus expect the desired production of 22:30 to be 6 * 25 = 150 kWh.
Output: 150 kWh for item 90 in the desired production per 15 min list.
Verified: yes.

Peak load production contracting with parking obligation
Due to the parking obligation and the logging of the obliged parked times by the CPPP, the availability of FCVs is no longer uncertain. The CPPP can simply multiply the amount of contracted FCVs per 15 minutes times the production capacity per FCV. This process is observed and subsequently verified. No other tests have been executed for this procedure.

Secondary Control regulation up contracting without parking obligation
The secondary control contracting for regulation up is identical to that of the peak load contracting and has thus been verified earlier.

Secondary Control regulation down contracting without parking obligation
Input: Electrolyser capacity: 45 kg/15min. Desired hydrogen production hours [4 3 2 5].
Expectation: The electrolyser can be freely used for secondary control except for the hours the electrolyser is in use for hydrogen production itself. Each quarter of an hour the electrolyser can generate a demand of 45 * 50 = 2250 kWh. We thus expect a list of 96 entries of 2250, minus 4 * 4 entries of 0 (representing the usage of the electrolyser for own hydrogen production).
Output: List of 80 entries of 2250, and 16 entries of 0 at locations that correspond to the desired hydrogen production hours.
Verified: yes.

NEW WEEK PROCEDURES

Diffuse information procedure –Observer Procedure

This procedure let's all drivers with an FCV and all CaPP parking drivers (the source group) diffuse their beliefs concerning the attributes of the FCVs and CaPP to the potential adopters (target group). As the source group executes this procedure simultaneously, it is difficult to monitor. As such we have slightly adjusted the code for this test in order to be able to individually ask a driver with an FCV and CaPP parking behaviour to diffuse his knowledge.

Input: % FCV drivers = 68,57%. % CaPP parking drivers = 9%. Learning diffusion coefficient = 20%. Required plugin time belief of source driver = 8,75 hours. CaPP Cash Back belief of source driver = 347,44€. Hydrogen price belief of source driver = 0€. FCV pollution belief of source driver = 68.
Required plugin time belief of target driver = 18,90 hours. CaPP Cash Back belief of target driver = 2870,62€. Hydrogen price belief of target driver = 6,09€. FCV pollution belief of target driver 70,43.
Expectation: The belief adjustment of the target driver is adjusted following the formula (information gap * learning coefficient) * percentage sourcegroup. The expected hydrogen price adjustment is (0 - 6,09) * 0,2 * 0,6857 = -0.835. The expected FCV pollution adjustment is (68 – 70,43) * 0,2 * 0,6857 = -0,3333. The expected CaPP Required Plugin Time adjustment is: (8,75 – 18,90) * 0,2 * 0,09 = - 0,1827. The expected CaPP Cash Back adjustment is (347,44 – 2870,62) * 0,2 * 0,09 = -45,42. The beliefs of the target driver are expected to become Hydrogen price: 5,255; FCV Pollution: 70,10; CaPP Required Plugin Time: 18,72; CaPP Cash Back 2825,20.
Output: Beliefs of the target driver; hydrogen price = 5,31; FCV Pollution = 70,12; CaPP Required Plugin Time= 18,72; CaPP Cash Back = 2827,37.

The output is slightly different from the expectations. We have looked into this and concluded that the cause was the amount of decimals used in the calculations. For our expectations we limited the amount of decimals for example the FCV population share to two decimals, where Netlogo uses 17 decimals. We have are satisfied with this explanation.
Verified: Yes

NEW MONTH PROCEDURES

Determine parking behaviour procedure – Driver procedure

The determine parking behaviour procedure is fairly large and could be dissected into two; 1) determining the value function by drivers in order to determine if they want to change their parking behaviour to CaPP, and 2) if the parking behaviour is changed to CaPP, closing the contract with the CPPP. We have tested both elements separately.

<u>Determining the Parking Behaviour value function – Driver procedure</u>

Input: CaPP obligation on contract = "obligation in place". CPPP location = "Near households". Currently maximum of contracted FCVs at CPPP at one moment in time = 2. CPPP size = 100 cars. Parking behaviour of monitored driver = "Conventional". CaPP required plugin time belief = 4,775. CaPP cash back belief = 2370,73€.
Expectation: The value function of choosing CaPP as parking behaviour is calculated by:

*Value function = Beta0 + BetaRequiredPluginTime (RequiredPluginTimeBelief) + BetaCashBack * (CaPPCashbackBelief – CompensationRequiredForWalking) / 1000 + errorterm.*

The Beta's are obtained from literature and are: Beta0 = -1,1; BetaRequiredPluginTime = 0 for beliefs between 0 and 10h, -0,11 for beliefs between 10 and 15h, -0,32 for beliefs between 15 and 20h, -0,63 for beliefs higher than 20h. BetaCashBack = 0,16.

Seeing that the CPPPs are near home we know our assumption concerning walking back home is in effect. We have assumed that in these cases drivers will have to walk home for five minutes, and will value this according to a value of time of 18 €/hour. The required extra compensation is then 5/60 * 18 * 365 = 547,50€

If we fill in these beta's and the beliefs of our monitored driver we obtain;
*Value function = -1,1 + 0 + 0,16 * (2370,73 – 547,50) / 1000 + errorterm = -0,81 + errorterm*

Thus if the selected errorterm is smaller than +0,81 the value function will be negative and the CPPP will chose for conventional parking.

Output: Errorterm -0,411. Valuefunction = -1,22.
Verified: No. We note that we have copied the Beta Cash Back from literature, without taking into account that the original value was computed for $/year. Seeing that 1 $ is about 0,90€ we have adjusted the Beta Cash Back to 0,144. Fixed. Tested. Not verified.
We found that the value function contained a term "BetaRequiredPluginTime * RequiredPluginTimeBelief" whilst the RequiredPluginTimeBelief should only be used to determine the Beta, not be used in the value function itself. Fixed. Tested. Verified.

<u>Closing the CaPP contract procedure – Driver procedure</u>

This procedure is only executed by drivers whose calculation of a value function results in a positive outcome. Due to this fact we have deliberately forced a driver with conventional parking behaviour to switch it to CaPP.

Input: CaPP obligation on contract = "Obligation in place". CPPP location = "Near households". Departure time from work to home = 16:00. Departure time from home to work = 5:15.

Expectation: Seeing that there is a parking obligation in place, the driver will have to determine his parking availability. We have assumed that a driver on average takes 30 minutes to travel from work to home, and that they will require half an hour slack at the beginning and end of the contract. We thus expect the driver to close a contract with an obligation to have his car parked at the CPPP between 17:00 and 4:45. The duration of the contract would then be 11 hours and 45 minutes.
Output: Contract time start = 17:00, Contract time end = 4,75 (corresponds to 4:45), contracted time length = 11:75.
Verified: yes.

NEW QUARTER OF A YEAR PROCEDURES

Renew car procedure

This procedure is executed by drivers whose car has reached its renewal age. For this test we have forced a driver to run this procedure.

Input: FCV Pollution belief = 68,30. Hydrogen price belief = 7,51. Gasoline price = 1,80 €/L. FCV Price = 45000. ICV price = 40000
Expectation: The value function of choosing an ICV as next car type is calculated by:

*Value function = Betao + BetaPriceDifference * (PriceDifference / 1000) + BetaPriceDifferenceTimesCarWorth * ((PriceDifference * ICVPrice) / 1000000) + BetaFuelCost * FuelCostDifference + BetaPollution (PollutionReduction) + ErrorTerm*

.

The Beta's are obtained from literature and are: Betao = -0,575; BetaPriceDifference = -0,09; BetaPriceDifferenceTimesPriceWorth = 0,0007; BetaFuelCost = -0,0511; BetaPollutionReduction = 0 for beliefs between 0 and 25%, 0,07 for beliefs between 25% and 50%, 0,10 for beliefs between 50 and 75%, 0,35 for beliefs higher than 75% reduction

The pollution of ICVs is assumed to be 105 g CO_{2eq}/km. Our driver believes that the FCV has a pollution of 68,30 g CO_{2eq}/km which corresponds to a 65% reduction. The driver furthermore beliefs one kg of hydrogen costs €7,51. With one kg of hydrogen he can travel 100 km, and is thus equivalent to 100/15 = 6,6666 L of gasoline. Hydrogen expressed in a relative to litre of gasoline price thus results in 7,51 / 100 * 15 = €1,13 €/L_{eq}

If we fill in these beta's and the beliefs of our monitored driver we obtain;
*Value function = -0,575 + -0,09 * ((45000-40000) / 1000) + 0,0007 * (((45000-40000) * 40000) / 1000000) + -0,0511 * (1,13 – 1,8) + 0,10 + errorterm = -0,75 + errorterm*

Thus, if the selected errorterm is smaller than +0,75 the value function will be negative and a ICV will be chosen as new car.

Output: Errorterm = 1,19. Valuefunction = 0,443.
Verified: yes

CONCLUSION:

The verification test per procedure resulted in the discovery of different computational errors. These have been fixed and the concerning procedures have been retested until they passed the verification test. We can now say that the model computes the variables as we intended it to.

Minimal model testing: Sanity checks

With a very small setting we check if the agents behave as we would expect them to. Do the agents leave their home at the right times, do they renew their car if it is aged and do they park at the CPPP if they are obliged to. For this test we have constructed a run with one household, one office, one CPPP and one driver. For different settings we have tested all procedures by monitoring the CPPP and the driver. The following reports on our experiences with the different procedures. Here we did not check if the right numbers were used, and produced (as we did this in the last test), but rather for instance if certain movement was executed, an attribute value was added or when electricity was produced, some revenue was added to the balance of the CPPP.

15 minutes procedures

Driver: Day dependent behaviour - CPPP near households

Driver: Weekday movements

Driver: Leave for work – Executed as expected

Driver: Leave for home – Executed as expected

Driver: Weekend movements

Driver: Leave for trip – Executed as expected

Driver: Leave for home – Executed as expected

Driver: Day dependent behaviour - CPPP near offices

Driver: Weekday movements

Driver: Leave for work – Executed as expected

Driver: Leave for home – Executed as expected

Driver: Weekend movements

Driver: Leave for trip – Executed as expected

Driver: Leave for home – Executed as expected

CPPP: Short term operation

CPPP: Manage Hydrogen Storage – Executed as expected

CPPP: Run Use Case

Peak load production – Executed as expected

Secondary regulation up – Executed as expected

Secondary regulation down – CPPP behaviour seems strange as hydrogen storage takes off to large numbers. Explanation is the lack of FCVs at the CaPP to use the hydrogen, resulting in an enormous overcapacity of the electrolyser in these cases. Verified.

Driver: Drive – Executed as expected

New hour procedures

CPPP: data logging – Executed as expected

New day procedures

Driver: At Saturdays: set switch day dependent behaviour to weekend & determine trip departure hours – Executed as expected

Driver: At Mondays: set switch back to weekday behaviour – Executed as expected

Observer: Determine cheapest hours – Executed as expected

CPPP: Clean memory – Executed as expected

CPPP: Determine desired production for upcoming day without parking obligation – Executed as expected

CPPP: Determine desired production for upcoming day with parking obligation – Executed as expected

New week procedures

Driver: Diffuse information – Agent does nothing, as expected due to lack of agents to interact with.

New month procedures
CPPP: Calculate WTW emissions following shares of production method – Executed as expected *s*
Driver: Determine parking behaviour of upcoming month – Executed as expected
Driver: Close contract with CaPP without parking obligation – Executed as expected
Driver: Close contract with CaPP with parking obligation – Executed as expected

New quarter of a year procedures
Drivers: Let car age increase – Executed as expected
Drivers: Renew car if renewal age is reached – Error found. CarAge was not reset to 0. Fixed. Tested. Verified.

Conclusion

This test did not reveal many new errors. The reason for this could be that this test is executed after finishing the model During the modelling process similar tests have been executed directly after blocks of codes were finished. The results of these ongoing tests have not been recorded. By executing the test as reported ex-ante we have now double checked that the procedures are showing behaviour that they were intended to show.

Multi-agent testing: Breaking the agent

For this test we see if the agents behave as expected if we feed it extreme input, such that we can easily predict the outcomes of the agent. We have constructed a model with 100 drivers in order to be able to incorporate the tests concerning the information diffusion procedure among the agents.

Procedure tested: Peak load production.
Variable changed: CPPP size to 1.
Expected behaviour: CPPP will operate only minimally.
Result: Only one car at the CPPP at time. CPPP operational revenues and hydrogen use is minimal.
Verified: Yes.

Procedure tested: Renewing car.
Variable changed: Car price of hydrogen cars is set to 1.000.000.
Expected behaviour: No driver will buy an FCV, and all drivers will stick to ICVs.
Result: 100% ICV ownership over several months.
Verified: yes.

Procedure tested: Renewing car.
Variable changed: Hydrogen costs set to 0, gasoline prices to maximum (2€/L).
Expected behaviour: Do to large fuel cost savings, a large proportion of the drivers will chose an FCV.
Result: when forced to renew car only 24% chose an FCV.
Verified: Yes. Although unlike our expectations we have verified that the model does compute the value function properly. The influence of the fuel price is however much less than we expected. We think that the mismatch between results and our expectations is due to the use of data from North American citizens. We know that the car use and stance towards fuel use is different from Dutch views. Summarised, the model did pass this verification test, but exposed a mismatch between our expectations and model behaviour.

Procedure tested: Determine parking behaviour & renew car.
Variable changed: Learning coefficient set to 100; (also hydrogen price set to highest, gasoline price set to lowest).
Expected behaviour: Due to a very good information diffusion, all drivers will soon display similar behaviour and will adopt ICV cars.
Result: from 50 to 25% FCV share in 2 years.

Verified: Yes, although not very convincing. Due to the errorterm in the model and the fact that only cars are renewed once every 3 years this process is much slower than expected.

Procedure tested: Setup.
Variable changed: employees of offices to 0.
Expected behaviour: A stall of the model, as the drivers will not know where to go when ordered to go to offices
Result: runtime error at setup command; division by zero.
Verified: No, minimum employees per office set to 1.

Procedure tested: Hydrogen management.
Variable changed: Gasprice set to 1 cent.
Expected behaviour: Production with natural gas becomes the cheapest and only used method to produce hydrogen with (otherwise this is very often the electrolyser). Furthermore good operational profits can be made.
Result: Only the methane reforming methods are used to produce hydrogen. Profits made of about €25.000 in 5 months with a very small amount of available FCVs.
Verified: yes.

CONCLUSION

This test did not reveal new verification errors. However due to the approach of making expectations of the behaviour of the agents ex-ante we have encountered some mismatches between our expectations of the model behaviour and the actual behaviour.

Full model sanity check

We have executed a final test with all internal logging functions on, tracking multiple drivers, the CPPP and the overall outcomes of the model. Mainly at the beginning of new time scales (new 15 minutes, new hours, new days, new weeks, new months and new quarter of years) we have made expectations on types of behaviour and variables that were to change. We found one large error which presented itself by extremely unrealistic negative hydrogen storages of the CPPPS. The error was traced back to the use of a wrong desired production list by the CPPP when determining the possible revenues of using the SOFC for hydrogen production. The error was fixed and the verification test was done again. We have observed no further unexpected behaviour and therefore are confident that the full model is operating as intended to. We consider this test to be passed and the model to be verified.

Appendix H. Regression model

The regression model is the product of using linear regression on the outcomes of our preliminary runs. The preliminary runs are run for sixteen variations of the CPPP design. Ten replications have been run for each design to prevent simulation artefacts to influence our result. A more elaborate description of the use of linear regression on the preliminary runs can be found in section 7.1.

For our project we have used the free software Minitab. First we have converted our variations into experiments in Minitab and added the mean of the ROI after three years per experiment. The experimental design is shown in Table H-1.

Table H-1: Design of experiments used for linear regression

Std Order	Run Order	Center Pt	Blocks	Obligation	Use Case	ReformerTech	Location	ROI
1	1	1	1	No Obligation	Secondary Control	Steam Reformer	Households	-0,335272
2	2	1	1	Obligation	Secondary Control	Steam Reformer	Households	-0,280398
3	3	1	1	No Obligation	Peak Load Production	Steam Reformer	Households	-0,371802
4	4	1	1	Obligation	Peak Load Production	Steam Reformer	Households	-0,297477
5	5	1	1	No Obligation	Secondary Control	SOFC	Households	-0,348978
6	6	1	1	Obligation	Secondary Control	SOFC	Households	-0,217541
7	7	1	1	No Obligation	Peak Load Production	SOFC	Households	-0,369367
8	8	1	1	Obligation	Peak Load Production	SOFC	Households	-0,250550
9	9	1	1	No Obligation	Secondary Control	Steam Reformer	Offices	-0,379802
10	10	1	1	Obligation	Secondary Control	Steam Reformer	Offices	-0,338632
11	11	1	1	No Obligation	Peak Load Production	Steam Reformer	Offices	-0,446729
12	12	1	1	Obligation	Peak Load Production	Steam Reformer	Offices	-0,408618
13	13	1	1	No Obligation	Secondary Control	SOFC	Offices	-0,275877
14	14	1	1	Obligation	Secondary Control	SOFC	Offices	-0,253083
15	15	1	1	No Obligation	Peak Load Production	SOFC	Offices	-0,330080
16	16	1	1	Obligation	Peak Load Production	SOFC	Offices	-0,308219

Minitab offers among others the possibility to analyse the factorial design by using linear regression. We have selected first order (obligation ; use case etc.) and the second order (obligation * use case; obligation * reformertech etc.) to be used in the estimation. This estimation resulted in the following output;

Factorial Regression: ROI versus Obligation; Use Case; ReformerTech; Location

```
Analysis of Variance

Source                        DF    Adj SS    Adj MS  F-Value  P-Value
Model                         10  0,055860  0,005586    16,45    0,003
  Linear                       4  0,044123  0,011031    32,48    0,001
    Obligation                 1  0,015837  0,015837    46,63    0,001
    Use Case                   1  0,007799  0,007799    22,97    0,005
    ReformerTech               1  0,015941  0,015941    46,94    0,001
    Location                   1  0,004545  0,004545    13,38    0,015
  2-Way Interactions           6  0,011737  0,001956     5,76    0,037
    Obligation*Use Case        1  0,000001  0,000001     0,00    0,971
    Obligation*ReformerTech    1  0,000467  0,000467     1,37    0,294
    Obligation*Location        1  0,004080  0,004080    12,02    0,018
    Use Case*ReformerTech      1  0,000048  0,000048     0,14    0,722
    Use Case*Location          1  0,001212  0,001212     3,57    0,118
    ReformerTech*Location      1  0,005929  0,005929    17,46    0,009
Error                          5  0,001698  0,000340
Total                         15  0,057558

Model Summary

        S    R-sq  R-sq(adj)  R-sq(pred)
0,0184284  97,05%     91,15%      69,79%

Coded Coefficients
```

Term	Effect	Coef	SE Coef	T-Value	P-Value	VIF
Constant		-0,32578	0,00461	-70,71	0,000	
Obligation	0,06292	0,03146	0,00461	6,83	0,001	1,00
Use Case	-0,04416	-0,02208	0,00461	-4,79	0,005	1,00
ReformerTech	0,06313	0,03156	0,00461	6,85	0,001	1,00
Location	-0,03371	-0,01685	0,00461	-3,66	0,015	1,00
Obligation*Use Case	0,00035	0,00018	0,00461	0,04	0,971	1,00
Obligation*ReformerTech	0,01080	0,00540	0,00461	1,17	0,294	1,00
Obligation*Location	-0,03194	-0,01597	0,00461	-3,47	0,018	1,00
Use Case*ReformerTech	0,00347	0,00174	0,00461	0,38	0,722	1,00
Use Case*Location	-0,01741	-0,00870	0,00461	-1,89	0,118	1,00
ReformerTech*Location	0,03850	0,01925	0,00461	4,18	0,009	1,00

Regression Equation in Uncoded Units

```
ROI = -0,32578 + 0,03146 Obligation - 0,02208 Use Case + 0,03156 ReformerTech
      - 0,01685 Location + 0,00018 Obligation*Use Case + 0,00540 Obligation*ReformerTech
      - 0,01597 Obligation*Location + 0,00174 Use Case*ReformerTech
      - 0,00870 Use Case*Location + 0,01925 ReformerTech*Location
```

This first estimation includes all factors but also shows that some factors are insigificant for the estimation. The non-significant terms are excluded from the estimation one by one. From this first estimation the factor with the highest p-value is [obligation * use case] and has been hilighted in gray. We do an interation and again estimate a regression model but without the factor [obligation * use case]. The results are as follows:

Factorial Regression: ROI versus Obligation; Use Case; ReformerTech; Location

Analysis of Variance

Source	DF	Adj SS	Adj MS	F-Value	P-Value
Model	9	0,055860	0,006207	21,92	0,001
Linear	4	0,044123	0,011031	38,97	0,000
Obligation	1	0,015837	0,015837	55,95	0,000
Use Case	1	0,007799	0,007799	27,55	0,002
ReformerTech	1	0,015941	0,015941	56,31	0,000
Location	1	0,004545	0,004545	16,05	0,007
2-Way Interactions	5	0,011737	0,002347	8,29	0,011
Obligation*ReformerTech	1	0,000467	0,000467	1,65	0,246
Obligation*Location	1	0,004080	0,004080	14,41	0,009
Use Case*ReformerTech	1	0,000048	0,000048	0,17	0,694
Use Case*Location	1	0,001212	0,001212	4,28	0,084
ReformerTech*Location	1	0,005929	0,005929	20,95	0,004
Error	6	0,001699	0,000283		
Total	15	0,057558			

Model Summary

S	R-sq	R-sq(adj)	R-sq(pred)
0,0168253	97,05%	92,62%	79,02%

Coded Coefficients

Term	Effect	Coef	SE Coef	T-Value	P-Value	VIF
Constant		-0,32578	0,00421	-77,45	0,000	
Obligation	0,06292	0,03146	0,00421	7,48	0,000	1,00
Use Case	-0,04416	-0,02208	0,00421	-5,25	0,002	1,00
ReformerTech	0,06313	0,03156	0,00421	7,50	0,000	1,00
Location	-0,03371	-0,01685	0,00421	-4,01	0,007	1,00
Obligation*ReformerTech	0,01080	0,00540	0,00421	1,28	0,246	1,00
Obligation*Location	-0,03194	-0,01597	0,00421	-3,80	0,009	1,00
Use Case*ReformerTech	0,00347	0,00174	0,00421	0,41	0,694	1,00
Use Case*Location	-0,01741	-0,00870	0,00421	-2,07	0,084	1,00
ReformerTech*Location	0,03850	0,01925	0,00421	4,58	0,004	1,00

Regression Equation in Uncoded Units

```
ROI = -0,32578 + 0,03146 Obligation - 0,02208 Use Case + 0,03156 ReformerTech
      - 0,01685 Location + 0,00540 Obligation*ReformerTech - 0,01597 Obligation*Location
      + 0,00174 Use Case*ReformerTech - 0,00870 Use Case*Location
      + 0,01925 ReformerTech*Location
```

The iteration step resulted in a model with an R-square-adjusted that is about as high as the first estimation, indicating that the explanatory power of the model could be equally as good as the first estimation, even though the model has been estimated with a lower number of factors (predictors). The factor with the highest P-value is now [use case * reformertech]. We iterate and estimate the regression model without this factor:

Factorial Regression: ROI versus Obligation; Use Case; ReformerTech; Location

Analysis of Variance

Source	DF	Adj SS	Adj MS	F-Value	P-Value
Model	8	0,055811	0,006976	27,96	0,000
Linear	4	0,044123	0,011031	44,20	0,000
Obligation	1	0,015837	0,015837	63,47	0,000
Use Case	1	0,007799	0,007799	31,26	0,001
ReformerTech	1	0,015941	0,015941	63,88	0,000
Location	1	0,004545	0,004545	18,21	0,004
2-Way Interactions	4	0,011689	0,002922	11,71	0,003
Obligation*ReformerTech	1	0,000467	0,000467	1,87	0,214
Obligation*Location	1	0,004080	0,004080	16,35	0,005
Use Case*Location	1	0,001212	0,001212	4,86	0,063
ReformerTech*Location	1	0,005929	0,005929	23,76	0,002
Error	7	0,001747	0,000250		
Total	15	0,057558			

Model Summary

S	R-sq	R-sq(adj)	R-sq(pred)
0,0157969	96,97%	93,50%	84,14%

Coded Coefficients

Term	Effect	Coef	SE Coef	T-Value	P-Value	VIF
Constant		-0,32578	0,00395	-82,49	0,000	
Obligation	0,06292	0,03146	0,00395	7,97	0,000	1,00
Use Case	-0,04416	-0,02208	0,00395	-5,59	0,001	1,00
ReformerTech	0,06313	0,03156	0,00395	7,99	0,000	1,00
Location	-0,03371	-0,01685	0,00395	-4,27	0,004	1,00
Obligation*ReformerTech	0,01080	0,00540	0,00395	1,37	0,214	1,00
Obligation*Location	-0,03194	-0,01597	0,00395	-4,04	0,005	1,00
Use Case*Location	-0,01741	-0,00870	0,00395	-2,20	0,063	1,00
ReformerTech*Location	0,03850	0,01925	0,00395	4,87	0,002	1,00

Regression Equation in Uncoded Units

```
ROI = -0,32578 + 0,03146 Obligation - 0,02208 Use Case + 0,03156 ReformerTech
      - 0,01685 Location + 0,00540 Obligation*ReformerTech - 0,01597 Obligation*Location
      - 0,00870 Use Case*Location + 0,01925 ReformerTech*Location
```

The r-square-adjusted did not change much after this iteration step, indicating that the new model has the same explanatory power as before with less factors, making it a better model than the previous ones. Still there are insignificant terms. For the next iteration step we excluded the factor [Obligation * Reformertech] as it has the highest p-value. We obtain the following model:

Factorial Regression: ROI versus Obligation; Use Case; ReformerTech; Location

Analysis of Variance

Source	DF	Adj SS	Adj MS	F-Value	P-Value
Model	7	0,055344	0,007906	28,57	0,000
Linear	4	0,044123	0,011031	39,86	0,000
Obligation	1	0,015837	0,015837	57,24	0,000
Use Case	1	0,007799	0,007799	28,19	0,001
ReformerTech	1	0,015941	0,015941	57,61	0,000
Location	1	0,004545	0,004545	16,42	0,004
2-Way Interactions	3	0,011222	0,003741	13,52	0,002
Obligation*Location	1	0,004080	0,004080	14,75	0,005
Use Case*Location	1	0,001212	0,001212	4,38	0,070
ReformerTech*Location	1	0,005929	0,005929	21,43	0,002
Error	8	0,002214	0,000277		
Total	15	0,057558			

Model Summary

S	R-sq	R-sq(adj)	R-sq(pred)
0,0166345	96,15%	92,79%	84,62%

Coded Coefficients

Term	Effect	Coef	SE Coef	T-Value	P-Value	VIF
Constant		-0,32578	0,00416	-78,34	0,000	

Obligation	0,06292	0,03146	0,00416	7,57	0,000	1,00
Use Case	-0,04416	-0,02208	0,00416	-5,31	0,001	1,00
ReformerTech	0,06313	0,03156	0,00416	7,59	0,000	1,00
Location	-0,03371	-0,01685	0,00416	-4,05	0,004	1,00
Obligation*Location	-0,03194	-0,01597	0,00416	-3,84	0,005	1,00
Use Case*Location	-0,01741	-0,00870	0,00416	-2,09	0,070	1,00
ReformerTech*Location	0,03850	0,01925	0,00416	4,63	0,002	1,00

Regression Equation in Uncoded Units

```
ROI = -0,32578 + 0,03146 Obligation - 0,02208 Use Case + 0,03156 ReformerTech
      - 0,01685 Location - 0,01597 Obligation*Location - 0,00870 Use Case*Location
      + 0,01925 ReformerTech*Location
```

The R-Square-adjusted decreased only decreased slightly. We deem this decrease insignificant, and the model being better than the previous models. We still have one factor with an p-value above 0,05 (which we use as significance level). We iterate and estimate a regression model without the factor [use case * location]:

Factorial Regression: ROI versus Obligation; Use Case; ReformerTech; Location

Analysis of Variance

Source	DF	Adj SS	Adj MS	F-Value	P-Value
Model	6	0,054133	0,009022	23,70	0,000
Linear	4	0,044123	0,011031	28,98	0,000
Obligation	1	0,015837	0,015837	41,61	0,000
Use Case	1	0,007799	0,007799	20,49	0,001
ReformerTech	1	0,015941	0,015941	41,88	0,000
Location	1	0,004545	0,004545	11,94	0,007
2-Way Interactions	2	0,010010	0,005005	13,15	0,002
Obligation*Location	1	0,004080	0,004080	10,72	0,010
ReformerTech*Location	1	0,005929	0,005929	15,58	0,003
Error	9	0,003425	0,000381		
Total	15	0,057558			

Model Summary

S	R-sq	R-sq(adj)	R-sq(pred)
0,0195092	94,05%	90,08%	81,19%

Coded Coefficients

Term	Effect	Coef	SE Coef	T-Value	P-Value	VIF
Constant		-0,32578	0,00488	-66,79	0,000	
Obligation	0,06292	0,03146	0,00488	6,45	0,000	1,00
Use Case	-0,04416	-0,02208	0,00488	-4,53	0,001	1,00
ReformerTech	0,06313	0,03156	0,00488	6,47	0,000	1,00
Location	-0,03371	-0,01685	0,00488	-3,46	0,007	1,00
Obligation*Location	-0,03194	-0,01597	0,00488	-3,27	0,010	1,00
ReformerTech*Location	0,03850	0,01925	0,00488	3,95	0,003	1,00

Regression Equation in Uncoded Units

```
ROI = -0,32578 + 0,03146 Obligation - 0,02208 Use Case + 0,03156 ReformerTech
      - 0,01685 Location - 0,01597 Obligation*Location + 0,01925 ReformerTech*Location
```

The R-square-adjusted decreased during this iteration step. However the decrease is only small and we deem this decrease insignificant. The resulting model no longer has any factors with a p-value above 0,05. We do no longer see the need for new iteration steps and designate this last model as the final outcome of the linear regression method. For it to stand out among the rest we have used a slightly larger font from the other estimations. Figure H-1 and Figure H-2 show the fitted means for the terms in the regression model. A fitted mean is the resulting average value of the dependent variable (ROI in our case) of all the runs that use designs that include the particular design choice.

Figure H-3 presents the residual plots for the final regression model. Studying the residual plots allow to test if the usage of linear regression was valid. From the plots we do not see reasons to question the validity; both the "versus fits" plots seems to be randomly distributed and the normal probability plot supports the assumption that the errors are normally distributed.

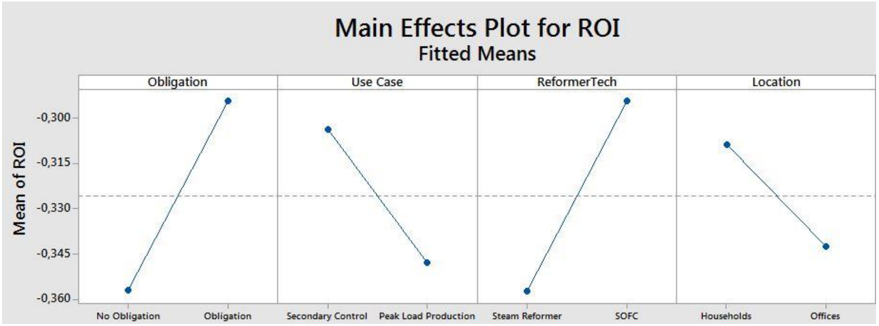

Figure H-1: Fitted means for first order terms

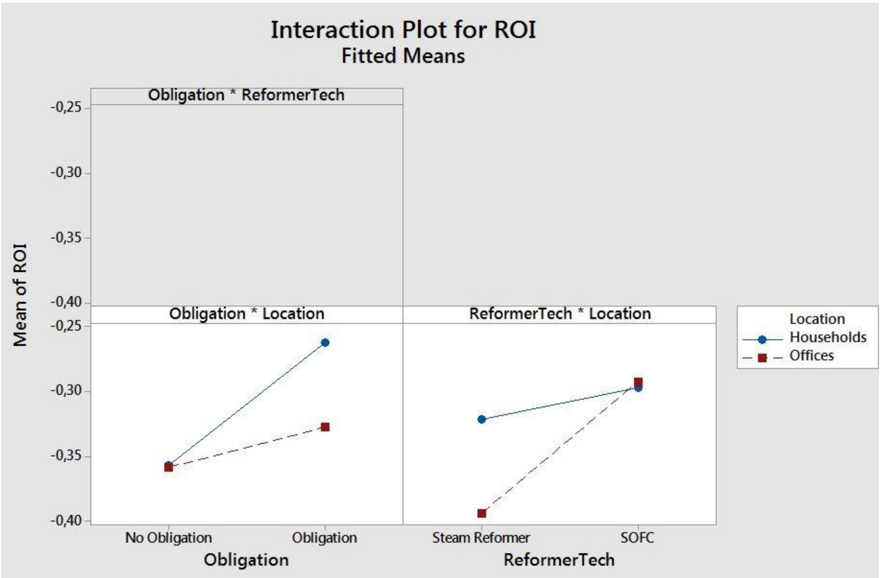

Figure H-2: Fitted means for second order terms

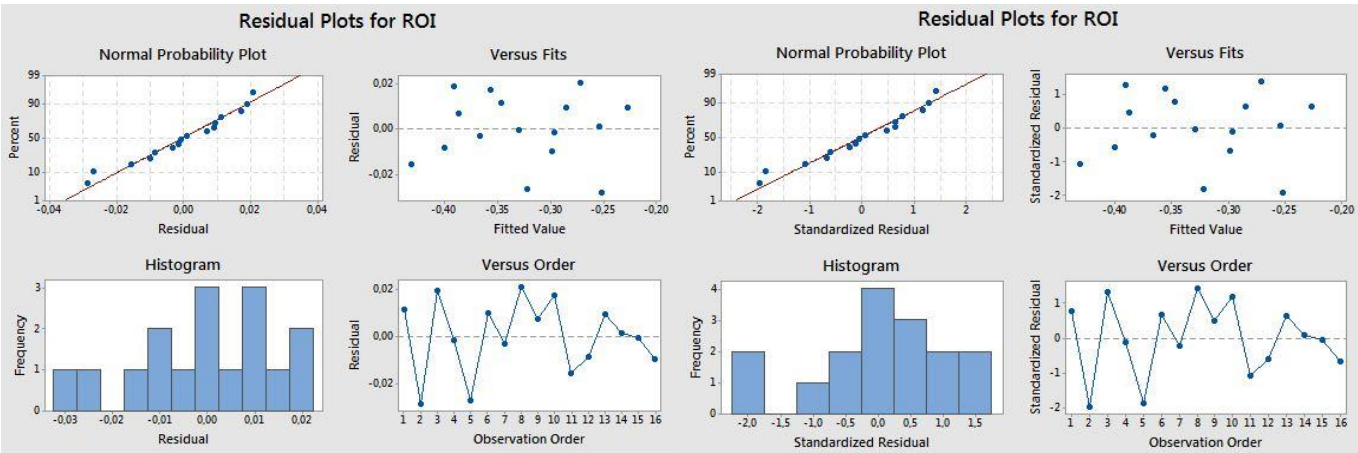

Figure H-3: Residual plots

Appendix I. Sensitivity analysis

The results of the sensitivity runs are presented separately for each factor that has been varied. The results are presented per design for four KPI's: the return on investment of the CPPP after three years, the cumulative greenhouse gas emissions in three years, the share of FCVs in the simulation after three years and the share of drivers who adopted a CaPP parking behaviour. The KPI's of ROI and system pollution are cumulative values over the whole simulation time of three years. The other two indicators concerning adoption rates are recordings of values at specific moments in times (e.g. what was the share of FCVs at the moment exactly three years have been simulated).

For the simulation runs we have varied the setup of the CPPP among eight different designs. For the sake of readability we use abbreviations for each design. The key to these abbreviations is as follows;

Obligation:	[O] for obligation, [NO] for no obligation.
Methane reforming technology:	[SMR] for steam methane reformer, [SOFC] for SOFC.
Location:	[H] for near households, [O] for near offices.

Below the different sensitivity runs are discussed, structured following the variable that has been varied. The reported numbers are the averaged value of the KPI's of the seven replications per base run (varying design and value for sensitivity analysis). Each run had a simulation time of three years. The KPI's of ROI and system pollution are cumulative values over the simulation time. The FCV and CaPP adoption rates are however metrics at specific moments in times, unaffected by prior behaviour.

Variation of FCV electricity production per kilogram of hydrogen

The first sensitivity experiment varied the FCV yield of the model when used for electricity production. In the base case an FCV produces roughly 16 kWh from one kilogram of hydrogen. This value is based on the work of Spanjer (2014) who already indicated that this conversion efficiency is based of FCV simulation modules that are no longer state-of-the-art. In the base run an average FCV produces roughly 16 kWh per kilogram of hydrogen. This value is based on outdated modules of fuel cells as used in (Spanjer, 2014, p. 74). It is thus safe to assume that the yield per kilogram of hydrogen will increase in the future. The results of varying the FCV electricity production per kilogram of hydrogen are presented in Figure I-1.

Variation of the gas price

The gas price influences the costs of the production of hydrogen by the CPPP when using a reforming technology. In the base scenario we use a gas price of 39 cents per m^3 of natural gas. This price is subject to the assumption that multiple CPPPs can cooperate and buy their natural gas collectively (see Appendix F for a more elaborate discussion). If each CPPP buys its natural gas separately the gas price could be expected to be around 70 cents per m^3. The results of varying the gas price are presented in Figure I-2.

Variation of the electricity price

The electricity price plays an important role for CaPP as it influences both costs and income. The electricity prices in the model are based on a limited amount of data of several days from the Dutch spot market. Forecasting the electricity price is challenging as the whole system is the subject of large scale change (possibly including the introduction of CaPP). The results of varying the electricity price in the simulations are presented in Figure I-3.

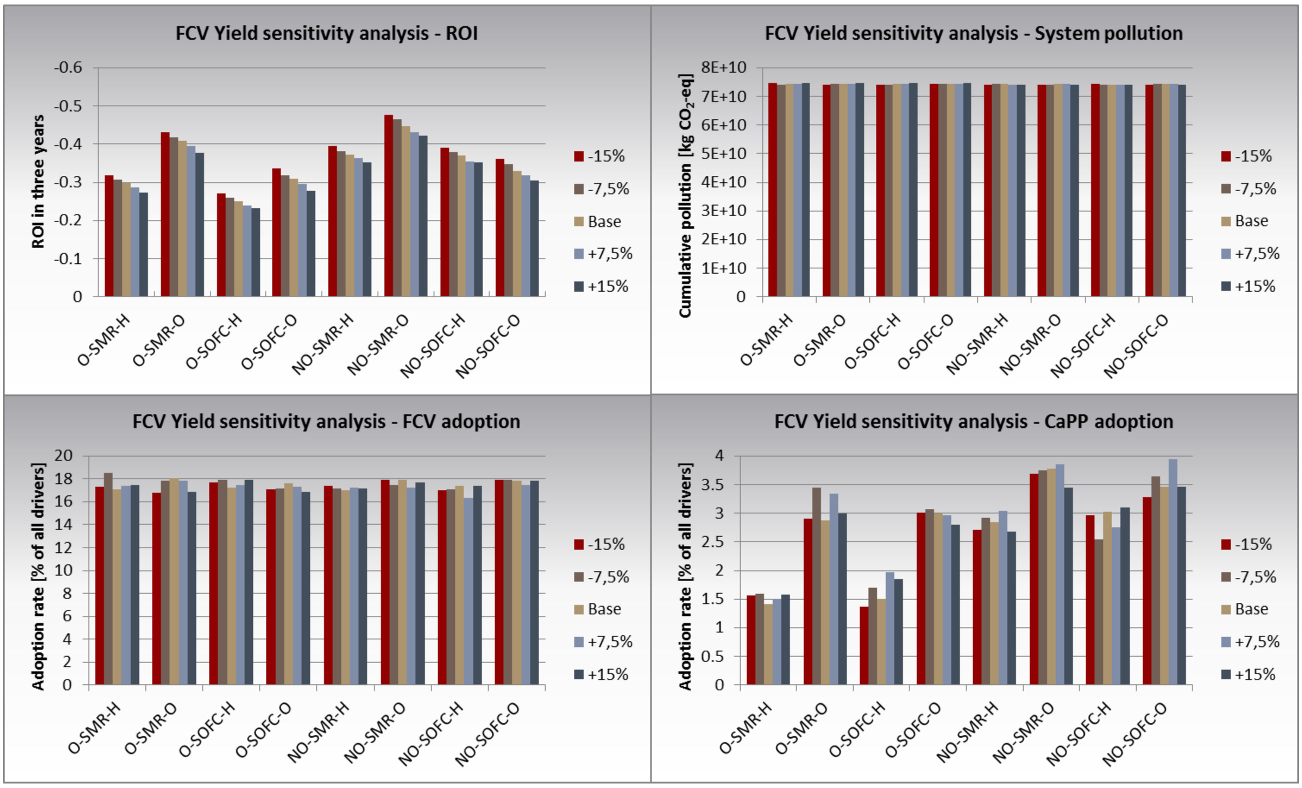

Figure I-1: Sensitivity plots for variation of FCV yield.

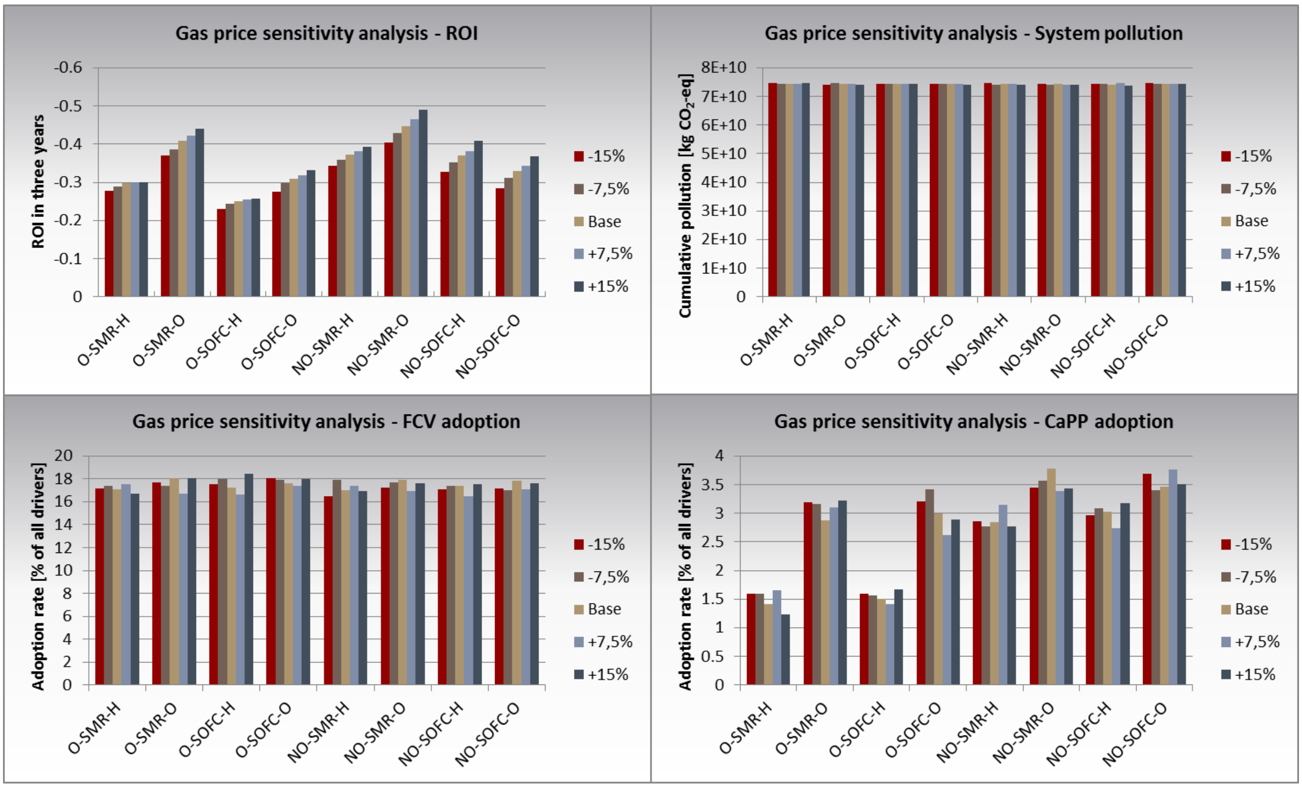

Figure I-2: Sensitivity plots for variation of the gas price.

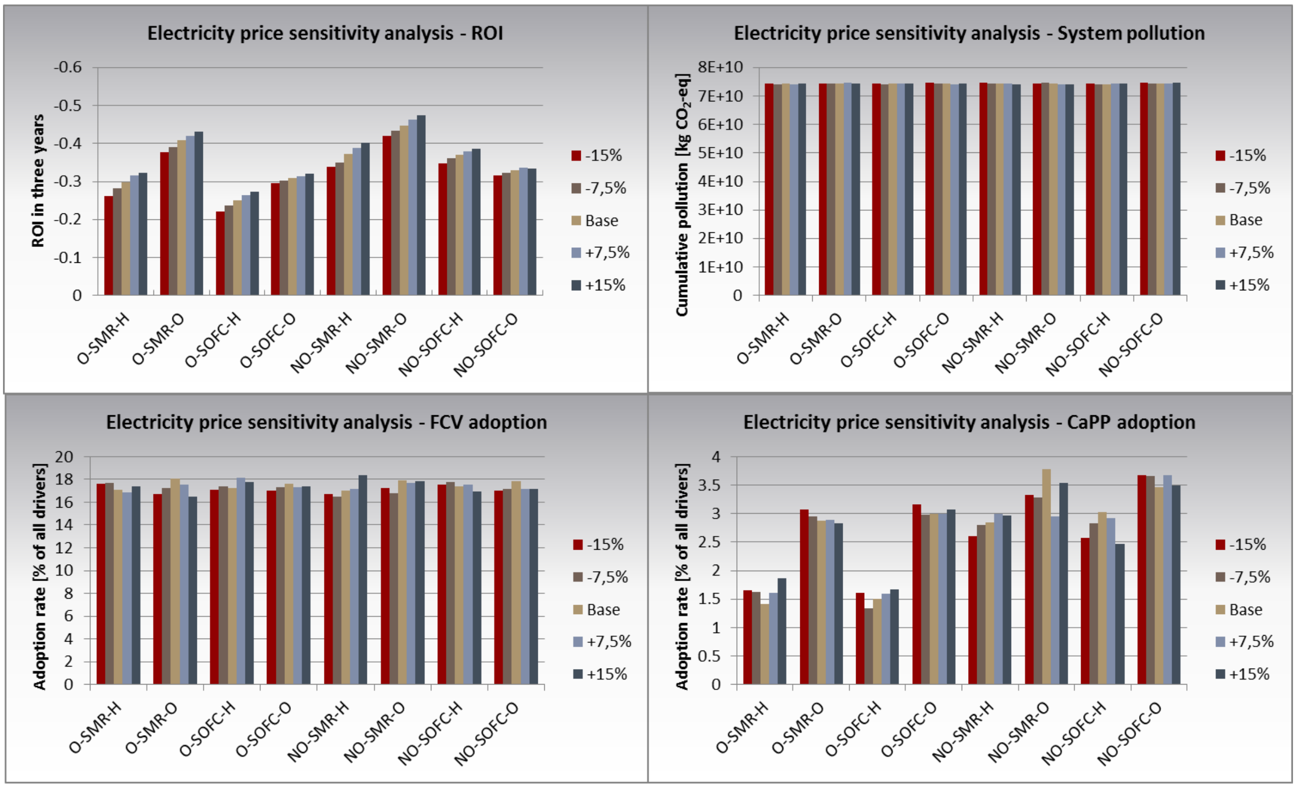

Figure I-3: Sensitivity plots for variation of the electricity price.