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TNO report

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Modelling consumer decisions towards sustainable energy technology

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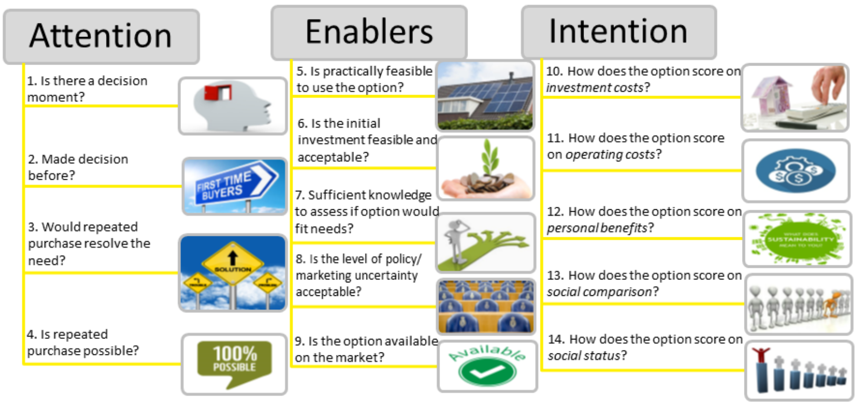

Since April 1st ECN and TNO have joined forces.

Summary

Goal of this document

This report reflects the development of a consumer decision model to simulate the adoption of innovations. Goal of this document is to provide a description of the model in order to discuss the model with policy makers and providers of innovations. A second goal is to find developers of similar models in order to discuss the model with, and make a comparison. The ultimate goal is to support the development of policy and strategy in regard to the adoption of sustainable energy technology.

Enhancing the adoption of innovations by consumers

ECN part of TNO has developed a consumer decision model which aims to help policy makers and companies stimulate effective diffusion of innovations (e.g. electric vehicles, or solar panels). The model focusses on the decision making process of the consumers who will have to adopt a product to reach a desired goal, for example the climate goals. Hereby providing support in overcoming the difficulties that 1) at the moment innovations that are essential for the transition towards sustainable energy are adopted at a slow pace, 2) human determinants that go beyond the “homo economicus” are often missing from models that are used to calculate market uptake, and 3) psychological models (that do include psychological determinants) are often difficult to quantify into for example market share.

Combining psychological determinants with quantification

The model has been dubbed CODEC which stands for COnsumer DEcisions Comprehended. The model is based on different theories which include: behavioral economics including the concepts of mental accounting and delay discounting, the Consumer Decision model; the Integrative model of Behavioral Prediction; and Rogers adopter categories.

The model treats the adoption of an innovation by an individual as a purchase by a consumer looking to fulfil a need or solve a problem such as: buy a new car when the old one has broken down, with different possible solutions (product options). The model results show a product’s market share development over time, and the barriers for full scale adoption. In order to create this market share and identify barriers, the model balances determinants stemming from several psychological models and theories, including habits, factual barriers, social processes, and irrationalities in the consumer decision processes. In the model these determinants are represented by fourteen questions in three phases (see Figure 1): 1) Attention, which is about whether people are engaging in decision making (e.g. for how many consumers is there a decision moment?), 2) enablers, which is about whether people would be able to buy the product (e.g. how many consumers could pay for this innovation?), and 3) intention, which is about whether consumers would like to buy the product (e.g. does the innovation provide status?). The model calculates which percentage of the target group (e.g. the Dutch population above 18 years of

age) will buy the innovation in a certain year, taking the fourteen questions into account.

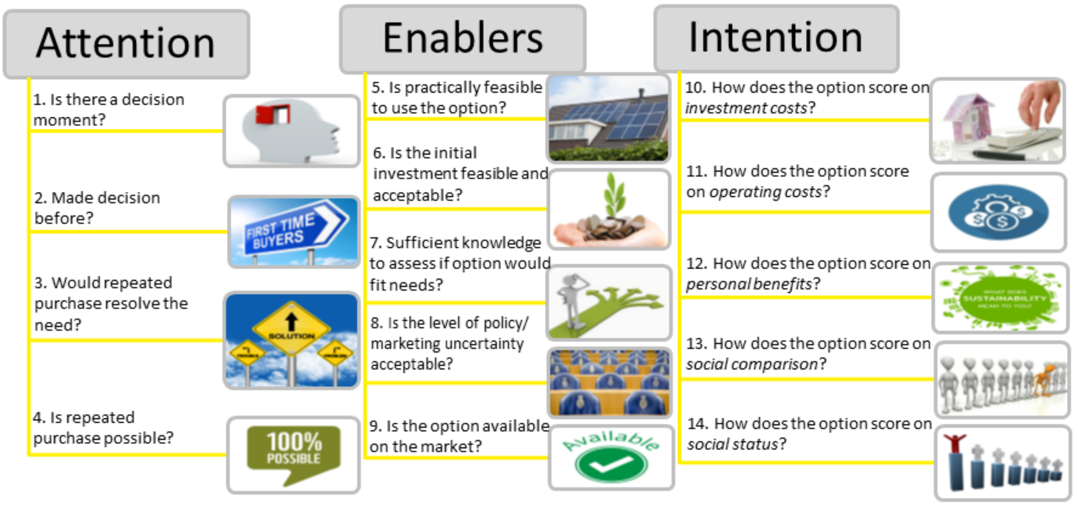

Figure 1. Visual of the CODEC model. Each question is quantified in order to calculate market share, and can be a barrier to reaching a 100% market share for each choice option.

The different steps of applying the model

A first step in using the model is to define the decision which is perceived by the consumer, for example “I need a new car. Which one should I buy?” in the case of the uptake of electric vehicles. The second step is defining the complete set of alternatives that a consumer perceives in the context under research. For example when looking at the adoption of electric vehicles other options are other types of cars (fossil fuelled, hydrogen, etc.). A third step is to look at how the model should be adapted to the product or service that should be adopted. This is important since not all innovations are the same. For example, for solar panels it is important to know if people have a suitable roof, while this is not important when looking at electric vehicles. The fourth step is to find input for the model for all fourteen questions. When suitable data is lacking, (expert) assumptions have to be made. The input is used to calculate market shares for the different choice options for consumers, over a certain period in the future. It can be seen as fallows: after each question a percentage of the target group will be dropped until, for that year, the percentage that is likely to buy a product option is left. The last step is to perform an uncertainty analysis on the outcomes. After the analysis the results are interpreted: what is the projected market share under the current conditions, and which determinants (questions) are the main barriers preventing further uptake? It is also a possibility to compare different policies.

The CODEC model was applied in two case studies: the decision to buy solar photovoltaics (solar PV), and to the decision to buy an electric vehicle. Results indicate that CODEC is able to simulate market share. For 2005-2015, the model outcomes were calibrated on the practical realisation of PV systems on private dwellings according to the background data for the Dutch National Energy Outlook (ECN, et al., 2016). What CODEC adds to the forecasts already provided by the

National Energy Outlook is that in CODEC it is possible to compare different forms of providing a specific subsidy.

A more realistic view on the uptake of innovations

Main advantages of the CODEC model are that it enables :

a) quantitative projections of innovation uptake in competition with other choice options,
b) while taking into account the difference between habitual and conscious behavior (attention to the innovation),
c) factual (dis)enablers to performing the behavior (also factual enablers, such as the availability of a suitable roof for solar PV),
d) and 'irrationalities' in the consumer decision process: perceived (dis)enablers (thinking the roof is unsuitable for solar PV), subjective cost-benefit evaluations, and social influence.

These advantages result in more realistic projections about the uptake of innovations and provides – in comparison to economic optimization models – additional quantitative insights to industries and policy makers about possible measures to improve the diffusion of innovations. In addition, the model is able to demonstrate how policy interventions may impact each step in the consumer decision making process and how this affects the adoption rate. The model can handle combinations of interventions, for example an information campaign plus a subsidy, and demonstrate which steps in the decision-making process will be affected in what way. The model shows which additional interventions could aid the adoption rate.

Model limitation

A couple of issues were identified with the current version of the model that need to be resolved:

- For some determinants of the model there was a lack of suitable data, which makes it necessary to make certain assumptions, increasing the uncertainty of the outcomes. To overcome this problem a consumer survey could be developed to gather the information that is required for CODEC.
- Some determinants included in the model are most likely not interdependent of each another. To enhance the model this should be taken into account.

The last chapter of this report lists some recommendations for improvement of the model.

Contents

1 Introduction

Human behavior is an essential element in innovation adoption
Will battery or fuel cell electric cars eventually take over the market or will the combustion engine remain dominant? Will there be solar photovoltaic panels on every roof in ten years' time, or will most home owners be reluctant to buy them? In the end, the choice is up to car buyers and home owners. Therefore, it is not sufficient to perform technical and economic analyses to project future developments in energy technology innovations, such as alternative powertrains and photovoltaics (PV). It is also important to take consumer behavior into account. To look at how consumers make decisions. For them "innovations" are products and services that do, or do no fulfil a need.

Innovative energy technologies have major benefits for the energy system and for society as a whole. However, initial benefits to individual consumers are not that obvious. Lack of consumer demand as well as high initial costs of innovations are major barriers for large-scale technology adoption. To accomplish large scale up-take of new energy technologies, both industry and policy makers must identify and tap into additional benefits of these products as perceived by different types of potential consumers. This requires insight in consumer (information) needs and demands, and how policy and marketing instruments can tap into these needs and demands.

Policy is often based on models that do not account for human determinants
The current models that are used to calculate the effects of policy for the energy transition, in the National Energy Outlook (in Dutch NEV; NEO, 2017), do not take human behavior into account, since they are based on economic theory. The development of the model described in this document are inspired by this lack of human behavior.

Identifying and effectively addressing consumer needs requires a better understanding of consumer decision making than can be provided by economic theory. In economic theory (Lunn, 2010), consumers are assumed to (a) always seek to maximize benefits and minimize costs; (b) be fully informed about available alternatives for any particular behavior as well as the objective advantages and disadvantages of these behaviors; (c) make accurate cost-benefit calculations, and (d) are not socially influenced but only seek to maximize individual gains and minimize individual losses (Lunn, 2010). However, behavioral economics research (e.g. Kahneman, 2011; Thaler & Sunstein, 2009), has shown that (a) consumers are change-averse and will stay as they are unless they feel an urgency to change; (b) the human mind is a 'cognitive miser', meaning that consumers will take as little time and effort for the decision process as they can get away with. Even in 'elaborate' decision making the consumer is likely to compare only a small number of options, on a low number of features, using simple rules of thumb; (c) consumers are not good with numbers. Even when trying to calculate costs and benefits, their thinking is subject to bias. For example, consumers are more strongly averse of risks than motivated by possible gains; and (d) consumers are social beings. Rather than listening to 'objective' information or to experts, most of them will listen to the opinion of people who are like them and whom they like, and they model their behavior consciously as well as unconsciously.

Whereas each of these insights by itself is not new, there are still few quantified models that include both predictors of innovation uptake from economic theory and predictors of innovation uptake from psychological theory on consumer decision making (the authors of this paper have not yet come across these kinds of models). Our assumption is that such a combined model results in more realistic projections of the uptake of innovations, and provides – when compared to traditional economic optimization models – additional insights to industries and policy makers about possible measures to accelerate the diffusion of innovations.

Consumer Decisions Comprehended
This report introduces a quantitative consumer decision model for innovation adoption dubbed CODEC: COnsumer DEcisions Comprehended. CODEC is a quantitative simulation model that has been developed to understand and predict the market uptake of technological innovations in the realm of sustainable energy consumption, such as solar panels and electric vehicles. The model treats the adoption of an innovation by an individual as a purchase by a consumer looking to fulfil a need or solve a problem. The model is a technology adoption model in which consumer behavior is modelled as a process of attention, evaluation of alternatives, and decision-making. It was, as explained above, developed to add to the models underlying the National Energy Outlook. The model is based on several psychological theories (as will be described in Chapter 2).

CODEC aims to help policy makers and companies to obtain a quantitative estimate of the market share (of different alternatives) and to identify barriers to overcome in the diffusion of innovations. The model is thus developed with three aims: 1) to combine human determinants (factors) with a quantified economic model, 2) to be better able to realistically predict projected market share, and 3) to provide actionable insights to policy makers and the providers of innovations (products) to accelerate the diffusion of innovations.

Reading guide
The aim of this report is to provide a basis for discussing the model with parties who are interested in applying the model to a particular problem. A second goal is to discuss the model with experts in (social simulation) modelling, and compare the CODEC model to other models. To this end, the focus of the paper is on how the model works, why it works as it does, and how it processes data from various sources. After describing the theoretical background and basic principles of the model (Chapter 2), we demonstrate the application of the model on two cases. In the first case, we explore the possible developments in sales for different innovative car types from the moment of market introduction (Chapter 3). In this case, we show how CODEC can be used to compare various options on the market. In the second case we examine how various reform options for the Dutch PV policy may impact consumer decisions to buy solar photovoltaics (Chapter 4). In this case, we show how CODEC can be used to estimate the effects of policy and marketing interventions. Finally, challenges and venues for further research and model development are discussed (Chapter 5).

- ➔ Do you want to know more about the theoretical underpinnings of the model? Read Chapter 2.
- ➔ Do you want to know how the model works, or can be applied? Read Chapter 2 and/or 4.

2 The CODEC Model

In this chapter we first describe the theories and models underlying CODEC (2.1). Second, we describe the type of decision that can be studied using CODEC (2.2). Third, we describe the final model structure, demonstrating how the introduced concepts are translated into the model (2.3). The final section (2.4) contains a brief discussion of policy and market interventions, and how they may impact innovation uptake, and how CODEC can reckon with this.

2.1 Theoretical Basis

In this paragraph the theoretical basis for the CODEC model is described.
We start with some assumptions from behavioral economics regarding consumers on which the CODEC model is inspired (2.1.1). Next we describe the basic framework: the consumer decision model. This model describes the steps that consumers (unconsciously) take to come to a decision. This model acts as the spine of CODEC (2.1.2). In 2.1.3 we describe how the integrative model of behavioral predictions adds determinants to the consumer decision model. Followed by the inclusion of modelling the choice between different (product) option that consumers perceive to fulfil a need (2.1.4) and the theory behind how people determine if a product is “expensive” (2.1.5, mental accounting). Last, we describe the time dimension and how the decisions of different adopter categories differ from each other when innovations are involved, compared to product that are not new to consumers (2.1.6).

2.1.1 Basic assumptions regarding consumers

CODEC combines determinants from expected utility models with insights from behavioral economics (Kahneman, 2011; Thaler & Sunstein, 2009), psychology, and marketing, to introduce an alternative to the increasingly criticized neo-classical concept of the ‘homo economicus’. CODEC seeks to model and quantify consumer characteristics and decision making processes that affect the adoption of new products and innovations, based on the following key insights:

- *Consumers are change-averse. If change does not seem urgent consumers will stay as they are (status quo bias: Kahneman, Knetsch, & Thaler, 1991). This defies the assumption that consumers are always seeking to maximize benefits and minimize costs.*
- *Consumers have limited cognitive capacity. For this reason, they will take as little time and effort for the decision process as they think they can get away with. Even in 'elaborate' decision making the consumer is likely to compare only a small number of options, on a low number of features, using simple rules of thumb (bounded rationality). This defies the assumption that consumers are fully collecting information about alternatives for any particular decision (Kahneman, 2011; Thaler & Sunstein, 2009).*
- *Consumers have difficulties processing numbers. When trying to calculate costs and benefits their thinking is subject to bias. For example, people are more strongly averse of risks than motivated by possible gains (prospect theory; Kahneman & Tversky, 1979). This means that losses outweigh gains: a product that is more expensive than what a person is used to will be perceived as a bigger loss than if the product would be the same amount cheaper. Furthermore, immediate financial benefit is perceived to be more valuable than exactly the same benefit a while later (discounted utility; Chapman, 1996), or even a higher benefit a while later (hyperbolic discounting; Laibson, 1997). Finally, consumers do not treat money as "fungible" (interchangeable) but attach labels to it, such as "household money", "clothing money", or "holiday money" to control their expenses on these budgets (mental accounting; Thaler, 2008). This defies the assumption that consumers are rational actors in the way defined by economic theory.*
- *Consumers are social beings. Rather than listening to 'objective' information or to experts, they listen to the opinion of people who are like them and whom they like, and they imitate their behavior consciously as well as unconsciously (Aronson, 2007). This defies the assumption that consumers are fully independent decision makers.*

2.1.2 Basic framework of CODEC: the Consumer Decision Model

The five general steps of decision making

The basic framework of CODEC is modelled after the Consumer Decision Model (Engel, Blackwell, & Miniard, 2001), since we wanted to treat the adoption of an innovation by an individual as a purchase by a consumer looking to fulfil a need or solve a problem. The Consumer Decision Model provides a basic framework to which newer findings regarding human behavior can be added. The model which was developed in the field of consumer psychology and marketing, describes consumer (purchase) decision making as a conscious process consisting of five steps (see Figure 2). First, the moment of 'need recognition' when a consumer perceives a difference between current state (for example, a broken cell phone) and desired state (a working cell phone). Second, the search for information about solutions to the problem. Third, an evaluation of found alternatives. Fourth, the final choice, and fifth, evaluation of the outcome.

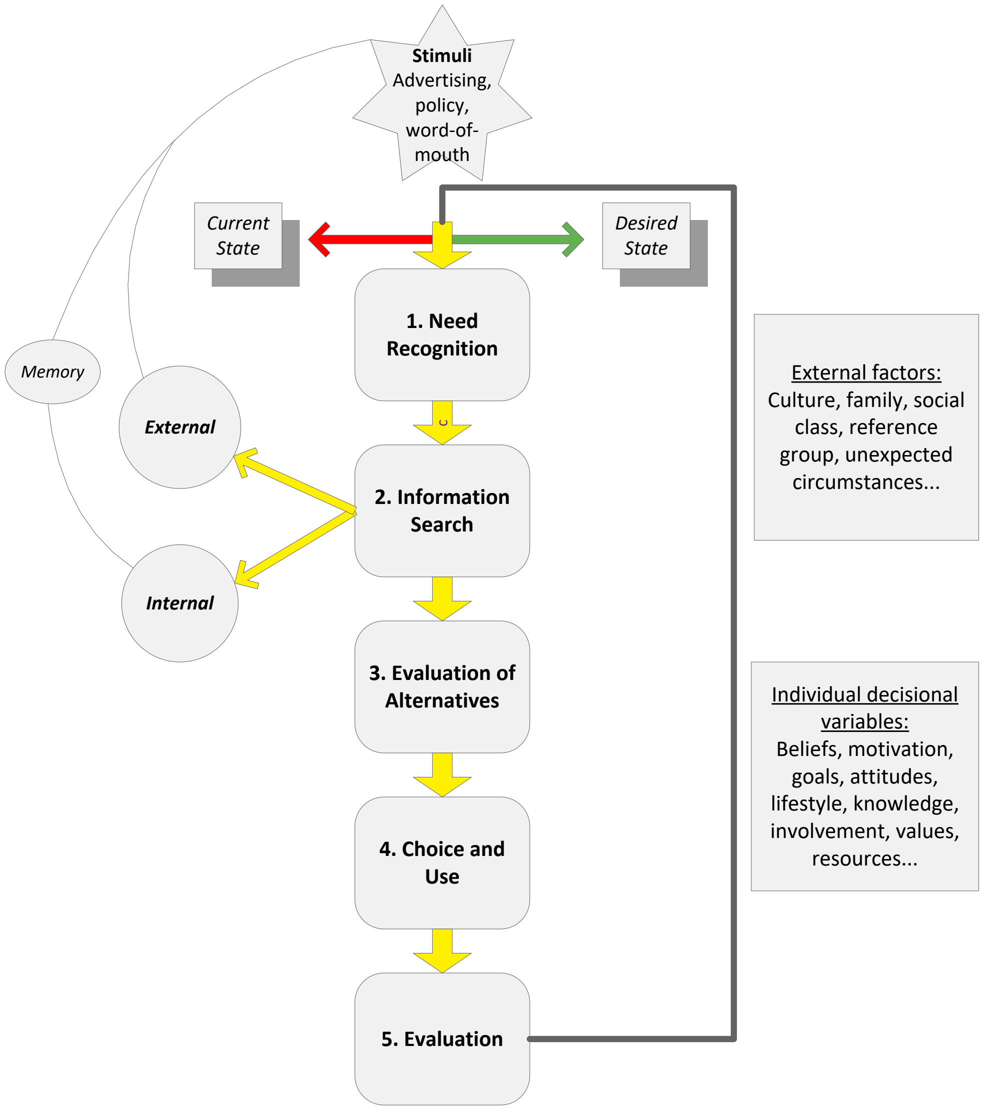

Figure 2. The Consumer Decision Model (Engel, Blackwell, & Miniard, 2001).

The Consumer Decision Model clearly describes the steps in a consumer decision process, which is useful for CODEC. However, unlike CODEC, the Consumer Decision Model is descriptive and not quantitative. To model the steps in the Consumer Decision Model, CODEC requires that the ‘consumer decision’ that follows from need recognition (step 1) is defined in such a way that it results in a set of behavioral alternatives (step 3) that is both finite and complete, to ensure that for every possible behavioral alternative the likelihood that it is chosen can be calculated. CODEC is applicable to any decision that fulfils these requirements.

Limited, extended, and routinized problem solving
The five steps are different for different types of problem solving. The extensiveness of the information search phase and subsequent phases of the Consumer Decision Model depends, amongst others, on whether it concerns a repeated purchase. In that case, a consumer has previous experience and memories of that experience to rely on, and external search of information (such as advertisements, or experiences of others) will be more limited than when the purchase has never been made before. Another important determinant of the extensiveness of information search is the type of purchase. Figure 3 provides some examples of purchase types for which people engage in either extended or limited problem solving. Generally, the more important (i.e., expensive, risky) a purchase, the more extensive the information search and comparison of alternatives will be (Assael, 1995). For less important purchases for which alternatives are (perceived as) highly similar, such as groceries, people typically engage in limited problem solving.

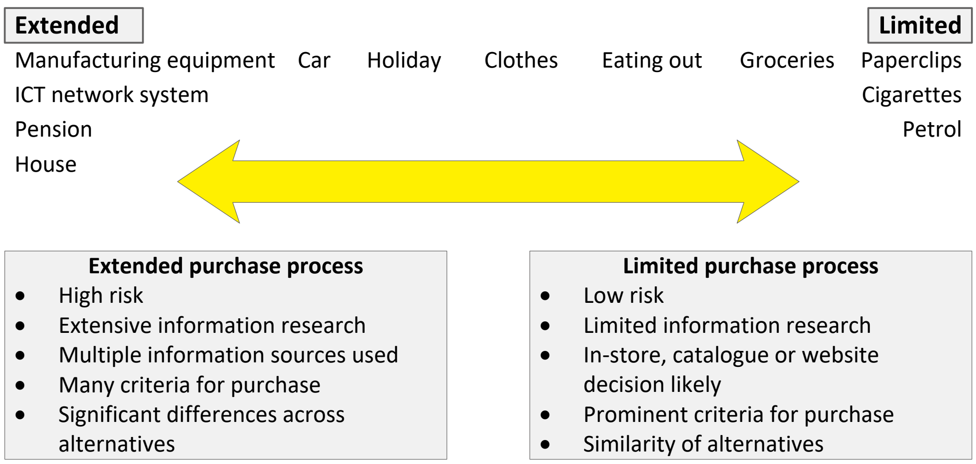

Figure 3. Purchases with extended or limited problem solving based on Engel, Blackwell, & Miniard (2001).

In addition to limited and extended problem solving, a third decision type called ‘routinized problem solving’ (Table 1) is sometimes identified separately in marketing literature (Engel, Blackwell, & Miniard, 2001). Any type of habitual purchase that does not require thinking fits this description. Typically, these are repeated purchases of relatively low-cost consumer products, such as paperclips. Problem solving is only required if the preferred brand is not available and the consumer is forced to select a different option. This situation is typical for groceries, where a preferred brand may be out of stock which forces consumers to switch to another brand.

Table 1. Characteristics of consumer problem solving approaches (Loudon & Bitta, 1993).

	Extensive Problem Solving	Limited Problem Solving	Routinized Problem Solving
Purchase Involvement Level	High	Medium	Low
Problem Recognition	Complex	Semi-automatic	Automatic
Information Search and Evaluation	Extensive	Limited	Minimal
Purchasing Orientation	Shopping	Mixed	Convenience
Post-Purchase Processes	Complex	Limited	Very Limited
	Loyalty if satisfied	Inertia to Purchase	Habit
	Complaint if Dissatisfied	Brand Switching if Dissatisfied	Brand Loyalty

In line with the Consumer Decision Model, CODEC distinguishes between extensive, limited, and routinized problem solving strategies. Since we expect that different people will approach the decision to buy an innovation with different varieties of problem solving. As stated at the beginning of this chapter, CODEC assumes that people are change-averse and have limited cognitive capacity. What determines which type problem solving takes place? Consumers will only take effort to engage in extensive problem solving either when forced by circumstances or because they are no longer satisfied with the current solution to their problem. Therefore, for all types of decision making we assumed that if the consumer needs to make a decision, if the consumer has made the choice before, and if it is possible to simply repeat that behavior to satisfy the underlying need, the consumer will opt for this. Only if the current product no longer fulfils the consumers' needs, or if simple repeated purchase is not possible (as, for example, happened with incandescent light bulbs), the consumer enters the process of comparing alternatives with the old product as comparison. Finally, if the behavior is entirely new (for example buying solar panels), orientation of options will follow without comparison to the old product or situation. As the Consumer Decision Model (Figure 2) demonstrates, this orientation will be the most extensive since in this case no information is readily available from memory. It is therefore important to distinguish between purchase processes with or without a previous purchase as a comparison. How exactly this distinction impacts consumer attention to various behavioral alternatives will be explained in 2.3.1, where the "attention" part of the CODEC model is described.

2.1.3 Determinants influencing the decision making process: The Integrative Model of behavioral prediction

One limitation of the Consumer Decision Model is that the influence of decisional determinants (what influences the decision?) on the decision process is not well specified. To specify these determinants for use in CODEC we relied on expectancy-value models from social psychological literature, predominantly the Integrative Model (IM) of behavioral prediction (Figure 4; Fishbein & Yzer, 2003). We chose this model for it is the leading psychological model explaining behavior an integrated different older behavior models. The IM states that behavior is predominantly influenced by the intention to perform that particular behavior, but this relationship is moderated by environmental constraints (e.g., intending to buy an electric vehicle but having no access to charging facilities) and skills and abilities (e.g., intending to buy an electric vehicle but not having a driving license).

Behavioral intention, in turn, is predicted by three determinants: beliefs about the personal advantages and disadvantages of the behavior (attitude), beliefs about how the behavior is viewed by others in society (social norms), and beliefs about one's capabilities to execute the behavior (self-efficacy). All other influences on human behavior one could think of are treated as 'external' or 'distal' determinants, of which 'past behavior' has proven a strong predictor of future behavior (Ajzen, 2011). The model thus provides some determinants of behavior.

This simplification of human behavior has been subject to criticism (Ajzen, 2011), but the authors have always argued that the model is open to adding new determinants if they substantially increase the explained variance in behavior. Rather than focusing on adding new determinants, however, most research inspired by IM (and its precursors, the Theory of Planned Behavior and the Theory of Reasoned Action) has been focused on improving the operationalization of the three current phases. Furthermore, variations of the model have been designed to explain a particular behavior type, such as the Technology Acceptance Model (TAM; Venkatesh et al, 2003). A quantitative integration and review of research using the Theory of Planned Behavior up to the end of 1997 showed that the model explained about 27% of the variance in behavior and about 39% of the variance in intention (Armitage & Conner, 2001). The relative weight of the three main predictors – Attitude, Social Norm, and Self-efficacy - depends on the behavior type. Unfortunately, due to, amongst others, measurement issues (e.g., the difference between self-reported and actual behavior) and conceptualization issues (particularly with the social norms part of IM and Theory of Planned Behavior), it is difficult to draw a general conclusion about the weight of each of these predictors based on available studies. In the CODEC model we chose to derive the weighing factors, as much as possible, from data sources. If this required data is unavailable, the possibility of collecting additional data has to be considered. If no data are available, expert judgments have to be made, leading to lower reliability of the outcomes.

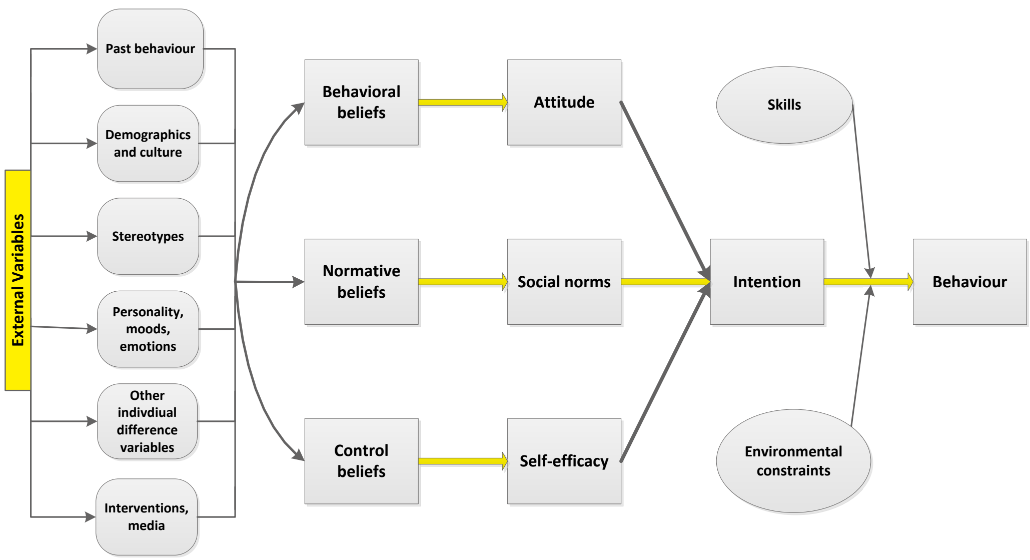

Figure 4. The Integrative Model of behavioral prediction (Fishbein & Yzer, 2003).

2.1.4 Competition between behavioral options

While the IM is more specific about determinants of behavior than the Consumer Decision Model and has quantified their predictive validity, the IM does not take into account that consumers compare various behavioral options before making a decision. Instead, the IM focuses explicitly on one behavior, that has to be specified in terms of action (e.g., buying), target (e.g., solar panels), context (e.g., for my privately owned roof), and time (e.g., within this coming year). All determinants in the IM must be defined and measured by exactly the same measurement scale, the so-called principle of compatibility. In CODEC, we choose to include multiple behavioral options, each of which is scored on a set of weighing factors based on the Attitude and Social norms phases in the IM. Perceived enabling determinants (self-efficacy) and factual enabling determinants (skills and environmental constraints) are also included in CODEC, but in a different phase of the model. We explain this in 2.3, where we will demonstrate how the model structure exactly links to the IM.

2.1.5 Mental accounting & Delay discounting

Important determinants in regard to beliefs about the personal advantages and disadvantages (attitude) are the financial costs of an innovation. To simulate how consumers evaluate an option's investment costs and operating costs, which are an vital determinant in the decision to invest in a product, we use the theory of Mental Accounting (Thaler, 2008). People do not always buy an innovation if they can afford it. They will think about whether they will find the price attractive or reasonable. There are several mechanisms that have an influence on whether people find something reasonable. Here we describe mental accounting and delay discounting.

2.1.5.1 Mental accounting

Consumers do not treat money as "fungible" (i.e., replaceable by another identical item; mutually interchangeable) but attach labels to it, such as 'household money', 'clothing money', or 'holiday money' to control their expenses on these budgets or accounts. This so-called mental accounting (Thaler, 2008) is a combined theory which consists of two elements: How budgets are allocated, and how costs and benefits of a financial decision are valued.

Allocation of budget
The allocation of budget in mental accounting is not based on total costs of ownership. People divide or 'frame' their budget into categories. For example, when buying a car, people allocate a budget that they want to spend on a new car. A small number of alternatives will be evaluated to see which car offers most value for money within the budget. When buying a car, many people are less precise in calculating the operating costs such as insurance, fuel, or maintenance. Rather than labelled 'operating costs' such costs are typically categorized in separate mental budgets, at least with most of us. For example, fuel goes under 'household expenses' while car insurance is part of 'insurances' and maintenance is in 'unforeseen'.

Value of costs and benefits
When applying mental accounting, people value options relative to a specific reference. In the CODEC model we assumed that the investment costs of the presently owned option is used as reference to evaluate the price of other options.

Figure 5 illustrates the way people value differences (loss or gain score) against a reference price. This figure demonstrates the basic principle of Prospect theory (Kahneman & Tversky, 1979; Kahneman & Tversky, 2013). Where the x- and y-axes meet, the reference option has an arbitrary score of 50. If an alternative option is cheaper, let's say minus 10 percent, it gets a higher score of 60. The larger the difference with the reference option, the higher its score. The effect, however, is not linear. If an option costs 10 percent less compared to the reference type, the score increases with 10 points. If the option is 20 percent cheaper, the score will not increase by 20 points but by 18 points.

Furthermore, the effect is asymmetrical for gains and losses. If an alternative option is 10 percent more expensive than the reference option, this has a stronger effect on the loss score compared to a 10 percent gain. This effect is called loss aversion. In literature a loss aversion factor of 2,25 percent is found (Tversky & Kahneman, 1992). A 10 percent loss will thus decrease the score with 22,5 points to 27.5, compared to an increase with 10 points to 60 in case of a 10 percent gain. For a 20% loss the score will decrease extra to 9.5 : 50 - (18*2.25=40.5) = 9.5.

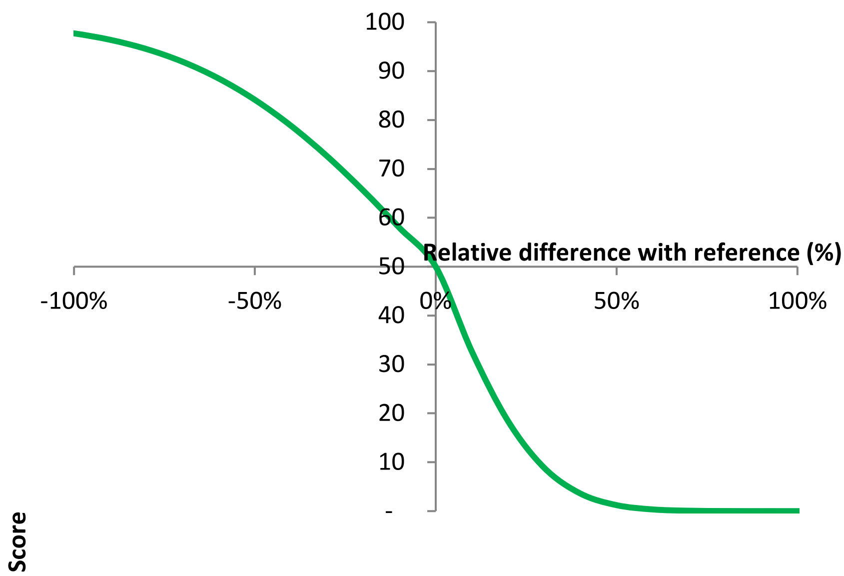

Figure 5. Relative valuation against a reference following Prospect theory (Kahneman, 1984).

To simulate the effect of framing costs into different mental budgets, CODEC distinguishes between investment costs and operating costs. Although we mentioned that people do not include those operating costs very well in their decision making, this could be a mechanism for policy makers to focus at. Both cost phases are valued relative to the costs of the presently owned option according to Prospect theory. For cars, an example looks as follows:

When a consumer wants to buy a car, the currently owned car serves as a reference. Assume the replacement of the present car with exactly the same type of car will cost 20.000 Euros. If an alternative car A costs 18.000 Euros, the difference of a 2000 Euros or 10% is seen as a gain and leads to a score of 60. Another car B is available for 16.000 Euros, representing a 20% gain versus the present car, so this car scores even better; 68 points. Alternative car C costs 22.000 Euros, representing a 10% loss, leading to a score of 27,5. Alternative car D costs 24.000 Euros, representing a 20% loss, leading to a score of 9.5.[1]

Reference Car	Option A	Option B	Option C	Option D
20.000	18.000	16.000	22.000	24.000
50 points	60	68	27,5	9,5

As discussed the operating costs of a car are often labelled in a different frame. The same scoring mechanism used for investment cost must be repeated for operating cost as well. If we use the same example but now for operating cost. The operating costs for the reference car are 4.000 euros annually. Option A has similar operating costs resulting in score 50. Option B has 20% higher operating cost leading to a score of 9,5 option C has 10% lower and option D 20% lower operating cost, which respectively lead to a score of 60 and 68.

Reference Car	Option A	Option B	Option C	Option D
4.000	4000	4.800	3.600	3.200
50 points	50	9,5	60	68

To combine the two scores, we have to weigh the different elements. For this example we use an equal fifty-fifty weighing. As you see in the table below. Option A scores highest with 55 points. All the other alternatives score worse than the reference car. Economically option C and D both can be considered as an investment with a profitable payback time of 5 years. But because of mental accounting the cars are not considered an attractive alternative for most people.

Weighing	Reference Car	Option A	Option B	Option C	Option D
50% investment	50	60	68	27,5	9.5
50% operating costs	50	50	9,5	60	68
Weighted score on economic effects:	**50**	**55**	**38,75**	**43,75**	**38,75**

2.1.5.2 Delay discounting
For some products, such as solar panels or floor insulation, there are expectations about returns on investment. For these products, the concept of delay discounting is needed to explain behavior. Delay discounting can be defined as the depreciation of the value of a reward related to the time that it takes to be released (Matta, Gonçalves, & Bizarro, 2012). People have the tendency to value rewards in the short term more, than in the longer term. Delay discounting has the effect that it is more effective to give people a direct reduction of investment costs than to give a similar reduction with a delay, even if returns on investment in the end are similar - or even if they are eventually higher (hyperbolic discounting; Grüne-Yanoff, 2015).

2.1.6 The time dimension: diffusion of innovation

Both the Consumer Decision Model and IM lack the time dimension: both models explain determinants influencing a purchase at one specific point in time for one

[1] As discussed a gain of 20% leads to 18 points because of the non-linear way people value price difference. The same is true for losses, but because of loss aversion the negative scores need to be multiplied by a factor 2.25. This leads to the following equation: 50 (the reference point) minus (18 * 2.25) = 9.5.

individual, but not how a new product will gain a particular market share through time. In his well-known book ‘Diffusion of Innovations’, Rogers (2003) describes innovation diffusion as “the process by which (1) an innovation (2) is communicated through certain channels (3) over time (4) among the members of a social system.” An innovation is “an idea, practice, or object that is perceived as new by an individual or other unit of adoption.” Innovation diffusion theory holds that innovation does not take place in a vacuum, but within a social system in which actors are socially influenced through largely unconscious mechanisms such as modelling and identification.

Rogers (2003) conceptualizes five main steps in the innovation-decision process. As Table 2 shows, these steps are highly similar to the steps described by the Consumer Decision Model, even though the latter is designed specifically for explaining decisions while the former is designed for explaining diffusion of both material and non-material innovations (e.g., ideas, practices). The steps are: (1) knowledge of an innovation, i.e., knowing it exists and have some understanding of what it is used for (= information search); (2) persuasion, i.e., developing a positive or negative attitude towards the innovation (= evaluation of alternatives); (3) decision to adopt or reject the innovation (= evaluation of alternatives and choice), (4) implementation and actual use of the innovation (= use), and (5) confirmation of the decision, i.e., seeking reinforcement of the decision already made (= evaluation). The previous decision may be reversed if the consumer is, for example, exposed to conflicting messages about the innovation. We explain how these steps are included in CODEC in 2.3.

Table 2. Steps in the innovation-decision process in the Diffusion of Innovations theory versus the Consumer Decision Model.

Diffusion of innovations	Consumer Decision model
1 Knowledge of an innovation	1 Information search
2 Persuasion	2 Evaluation of alternatives
3 Decision to adopt or reject	3 Choice
4 Implementation and use	4 Use
5 Confirmation of the decision	5 Evaluation

Rogers’ consumer segmentation on degree of “innovativeness” or openness to an innovation is shown in Figure 6. The diffusion of innovations model assumes that “innovativeness” as a trait is normally distributed within the population, over five segments or “adopter categories”. Each of these adopter categories has particular features that distinguish them from other adopter categories, not just socio-demographically but also in terms of underlying values and motivations. The first adopter category consists of people who enjoy being the first to do so – the innovators (2,5%). The second category consists of people who enjoy being one of the first to pick up the innovation, but to whom it is also important to be seen as first-movers and who readily share their experiences and knowledge with the innovation with others in their social network – the early adopters (13,5%). This is why the s-shaped diffusion curve in Figure 6 "takes off" at about 10% to 25% adoption. At this point, interpersonal networks become activated. Innovators are often typified as cosmopolites with weak local ties, while Early adopters are typified as localites who are seen as opinion leaders in their local community.

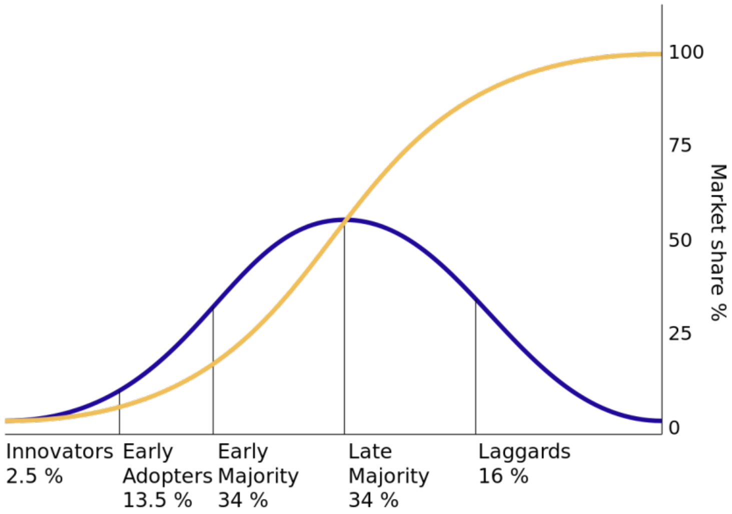

Figure 6**.** Diffusion of innovation (Rogers, 2003).

The third category consists of people who see that the innovation is gaining popularity in their social environment. They are acquainted with one or more early adopters who share their experience, and then decide to adopt the innovation too – the early majority (35%). The fourth category – the late majority (35%) - consists of people who do not want to be ahead of others, but who also do not want to lag behind. They adopt the innovation the moment they observe that at least half of the people around them have adopted the innovation too. The fifth category – the laggards (16%)– are the last to adopt the innovation. Some of them will not adopt the innovation until no other options are available to them. This category is the least well described in Rogers' model, despite its size. Generally, the first phases of innovation diffusion receive the most scholarly attention, the main question being why some innovations take off while others fail to do so.

The rate of adoption (s-curve) depends on the perceived attributes of an innovation. Adoption rate is positively influenced by: (1) its relative advantage over other options; (2) compatibility with past experiences, existing values, and needs; (3) trialability, the degree to which an innovation may be experimented with before committing to it; (4) observability, the degree to which the results of an innovation are visible to others. Adoption rate is negatively influenced by (5) complexity, the degree to which an innovation is perceived as difficult to understand and use. As Table 3 shows, these five main predictors of adoption rate within a population are highly similar to the predictors of individual purchasing intentions and behavior in the IM, where advantages or disadvantages and compatibility link to attitude phase, trialability and complexity to the self-efficacy phase, and observability to the social norms phase.

Table 3. Determinants of the adoption rate in the Diffusion of innovations model versus the Integrative Model.

Diffusion of Innovations	Integrative Model
Relative advantage	Attitude
Compatibility	Attitude
Trialability	Self-efficacy
Complexity	Self-efficacy
Observability	Social norms

An underdeveloped aspect of the diffusion of innovations theory is that there is little quantitative information about the relative weights of the scores on these determinants for different adopter categories. Based on the differences between the categories as described by Rogers (2003), we developed the following set of hypotheses.

Note that at present, the set of hypotheses as displayed below in Figure 7 has not yet been operationalized in CODEC, partly because of lack of empirical data to feed into the model and partly because the abovementioned hypotheses were not all developed at time of working on the case studies presented in chapters 3 and 4. Up to now, the operationalization of Rogers' model has been limited to reproducing the S-curve using the determinants investment costs, operating costs, social status and social comparison, whereby each choice option is scored on these determinants and the impact of these scores is the same for all adopter groups.

Attitude: Relative advantage and Compatibility
How an innovation is perceived regarding Relative advantage and Compatibility (Attitude) will presumably be of relatively high relevance to the early majority and late majority (see Figure 7), whose decision making will be based on utility and practical benefits rather than on 'being the first'.

Self-efficacy: Trialability and Complexity
How an innovation is perceived regarding Trialability and Complexity (Self-efficacy) will presumably be of relatively low relevance to innovators, who are the most venturesome and least risk-averse of all adopter groups and who are generally assumed to be highly educated, enhancing chances of experiencing more self-efficacy. Laggards are the most risk-averse of all adopter groups and are expected to tend to opt for innovations with low complexity.

Observability: Social Comparison and Social Status
Regarding Observability, we challenge Rogers' statement that higher visibility of an innovation means higher adoption rate is similar for all adopter categories. We hypothesize that a highly visible innovation may negatively impact the adoption rate among early adopters because, rather than learning about the benefits of an innovation from others, they want to be the opinion shapers who define the benefits and share their experience with others. In contrast, how an innovation is perceived regarding Observability will be irrelevant to innovators, because they simply want to be the first to adopt an innovation and do not need to see that others have already adopted the innovation. Observability will be of high importance to the early and the late majority, who adopt new products and ideas only after others have done so and they were able to see the advantages. Laggards are assumed to adopt only when they are forced to do so, not because of social influence. Laggards are assumed to

be the least wealthy of all adopter groups, and for that reason the innovation may even not become within reach of this group until it is offered with a discount, for example because it has been surpassed by a new innovation. Rather than perceived Observability, low risk and low costs appear the main drivers for this group.

To visualize the hypothesized weight of Observability on each of the five adopter categories, we decided to split this determinant into two phases: Social Status and Social Comparison. We define Social Status (giving) as the degree to which an innovation is perceived as granting the owner a reputation as first-mover. The better the reputation of an innovation, the more attractive the innovation will be to innovators and early adopters, while other adopter categories are indifferent to a positive reputation of an innovation. We define Social Comparison as the degree to which an innovation is perceived to be adopted by others. The higher the Social Comparison, the more attractive the innovation will be to the early majority and late majority, while innovators and laggards are indifferent to adoption of an innovation. For early adopters, perceived Social Status will be of great importance to their decision to adopt. However, in contrast to innovators, they are not entirely insensitive to Social Comparison. If they do not sense that the innovation will be acceptable to others, they will not be keen on taking opinion leadership.

Costs: Investment costs and Operating costs

Next to attitude, self-efficacy and observability thee different adopter categories also differ in the costs they will find acceptable for an innovation. To accommodate modelling the impact of investment and operating costs of an innovation in CODEC, we also formulated hypotheses about the weight of these determinants per adopter group. Rogers (2003) describes innovators as relatively wealthy while laggards are assumed to be the least wealthy. By lack of empirical data, we therefore assume that the importance of costs as a decision criterion in innovation adoption will be lowest for innovators and highest for laggards, with other adopter categories scoring in between.

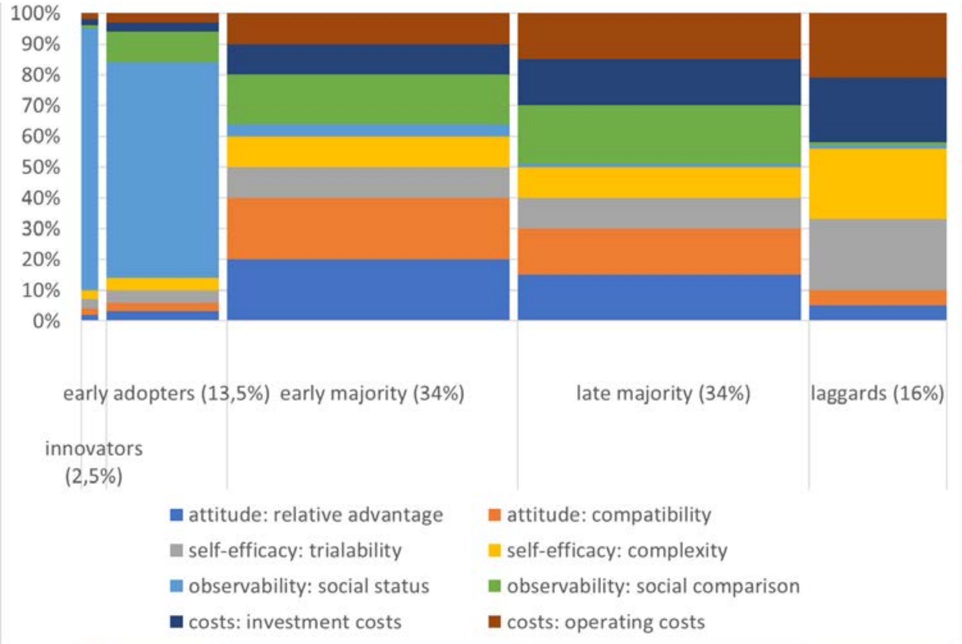

Figure 7. Weight of perceived innovation attributes by adopter category.

To reproduce the S-Curve in the CODEC model, we defined the expected development in scores on investment costs, operating costs, social status, and social comparison for each choice option. We assume that these determinants will differ most for the different adopter categories, especially the first three categories. We assume that the group of innovators (2,5%) will purchase the innovation because they derive their social status from being the first to own the product, regardless the price. Social status is the main driver of this group's behavior. However, to get within reach of subsequent adopter groups, the costs of the innovation will have to decrease at a certain pace. Assuming this will happen, the innovation comes within reach of adopter groups who are driven by social comparison. As the market share of the innovation increases, so does its visibility in the market, resulting in an increasing social comparison score. This makes the innovation attractive for adopter groups who imitate the behavior of innovators and early adopters. At the same time, the score on social status for that particular option declines.

2.2 Defining the decision and decision-specific consumer segments

Before moving on to the final model structure, we first discuss the type of decision the model can be applied to and the importance of defining the target groups, and limit the set of choice options.

2.2.1 Defining the decision

CODEC requires that the 'consumer decision' that follows from need recognition is defined in such a way that it results in a set of behavioral alternatives that is both finite and complete. CODEC is applicable to any decision that fulfils these requirements. Therefore, the first step in model application is to provide a precise definition of the decision and a complete list of behavioral alternatives that consumers facing this decision can choose from.

To define the decision we adhere to the same principles as the IM. That is, the decision should be specific in terms of action (in this case: buying), target (for example, solar panels), context (for example, for private use, on privately owned roof), and time (for the sake of modelling, a year is a good time period).

When the decision is defined as a purchase decision, it is nearly always possible to define a complete list of behavioral alternatives. Moreover, by applying consumer segmentation, the number of alternatives per segment or segment can be reduced to include only the 'likely' options that particular segment will choose from given, for example, constraints on income in a particular consumer segment. Target segments can for instance be home owners versus renters, or people with high or low income levels, etc.

Purchase decisions for new products are initially marked with a high degree of uncertainty that decreases over time, when market share increases and supporting policies are in place. For these new types of products, consumers engage in extended problem solving instead of engaging in routinized behavior. In principle, however, CODEC is applicable to any of the behavior types described in 2.1.1, including routinized and limited problem solving.

Since the basic structure of CODEC is based on consumer decision models for purchase behavior, the present version of the model focuses on the adoption of material innovations such as electric vehicles, solar panels, or heat pumps. It is a topic for further investigation whether CODEC may be suitable for application to behavior that does not involve a purchase (e.g., the decision to join an energy cooperative) or to decision processes that involve comparison of both material and non-material options (e.g., choosing between different modalities of transport versus making lifestyle changes to reduce need for transport). The present structure of CODEC may have to be modified to model such social innovations, this requires further investigation and discussion.

2.2.2 Defining the decision makers and their behavioral options

When the decision has been defined, it is important to specify the decision maker or target group the model will focus on and the set of behavioral options this target group can choose from. The definitions of the decision, decision makers, and behavioral options are interrelated. For example, the decision to invest in solar photovoltaics (PV) can be made by home owners, but not by those who rent their home. In that case the decision maker is the housing cooperative or private landlord. The decision criteria as well as the choice options look different for home owners than for instance for housing cooperatives. For example, while to home owners the size and orientation of their own roof will be main criteria in PV system selection and their set of options will consist of single-roof solutions, housing cooperatives will have to consider the orientation and size of whole blocks of buildings and their set of options will consist of block solutions. In sum, the definition of the target group(s) (segments) and the considered options are interrelated and both are linked to the definition of the decision.

As stated before, modelling a decision process with CODEC requires a finite as well as complete set of behavioral options the decision maker can choose from. If the definition of the decision is such that such a set cannot be created, either the definition of the decision should be changed or the model should only consider target groups for whom the choice options can be reduced to a finite and complete set. As the case studies in chapters 3 and 4 will show, the definitions will partly depend on the main question that needs to be answered by the study and partly on pragmatic considerations such as data availability.

2.3 Final model structure

Based on the theories and models described in 2.1, CODEC distinguishes between three types of determinants that influence the innovation adoption rate, three different phases: attention to an innovation and its competing options (attention), qualification of each option as a possible choice (enablers), and the weighing of the pros and cons of each option (intention) leading to a choice to adopt or reject the innovation. These phases, the steps they consist of, and how the market share of different options is calculated from these steps, are shown in Figure 8. Each step will be described in detail below. Although for the sake of clarity the steps are numbered, it must be noted that the order in real-life decision making can be different. This, however, does not make a difference to the model output.

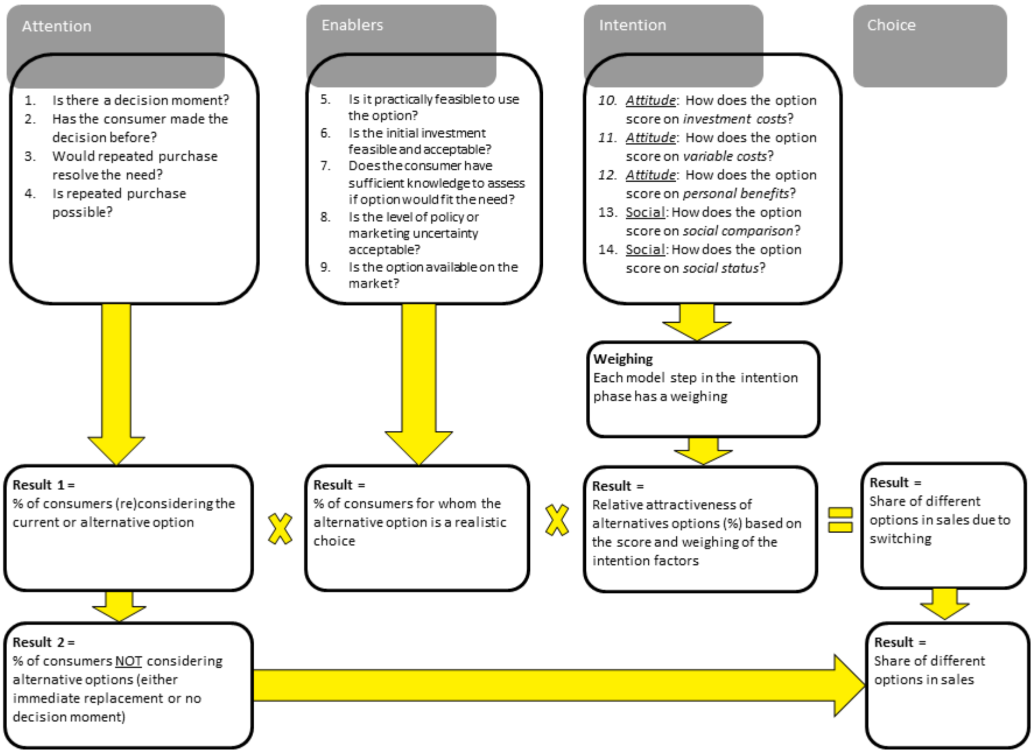

Figure 8. The general model structure of CODEC.

2.3.1 Attention

As explained in 2.1, consumers are change-averse and neither able nor motivated to fully inform themselves about available choice options and their features to make a decision when trying to solve a problem, for example ”buy a new car because the old car has broken down”. Therefore, consumer behavior depends to a large extent on routines. As long as people are satisfied with their present situation, they are unlikely to look for alternatives even if these alternatives would significantly improve wealth, health, happiness, or all of these.

This limited cognitive capacity influences their attention to new options on the market. Therefore, the model starts with analysing the likelihood of choice options getting attention. For each of the choice options (for the example “buy a new car” this includes fossil fuelled cars as well as electric cars and hydrogen cars) included in the model, the likelihood is estimated that the choice option will get noticed. The calculation results in a percentage of consumers that may be open to the innovation at some point within a specified timeframe, for example within one year.

As displayed in Figure 8 and which is detailed in Figure 9, the model starts establishing how many consumers experience a decision moment at a particular point in time. For those who do, it is checked if they have made the decision (e.g. buy a car) before, since previous experiences are powerful predictors of future behavior. For example, for electric vehicles this can be done by looking at how many people already own a car. Knowing from academic research that people prefer to repeatedly (and unthinkingly) purchase a product similar to that they have purchased before it is then estimated for how many consumers simply replacing the current option by a similar option, would resolve their need. For example, in the case of electric vehicles: if people owned a fossil fuelled car, at the moment, another fossil fuelled car would still resolve their need, unless these cars are for example banned from city centres. The final step is to check if repeated purchase is possible. For example, if fossil fuelled cars are banned, consumers cannot routinely buy them. There are thus three possible routes through the model: 1) routine behavior, when people have made the decision before, a similar option would resolve their need, and this option is still available on the market (nothing changes); 2) re-orientation on options with the old option as comparison, when people have made the decision before but when the option does no longer resolve their need and/or the option is not available on the market; and 3) orientation on options without old behavior as comparison, when people have not yet made the decision before. This process is described in more detail below.

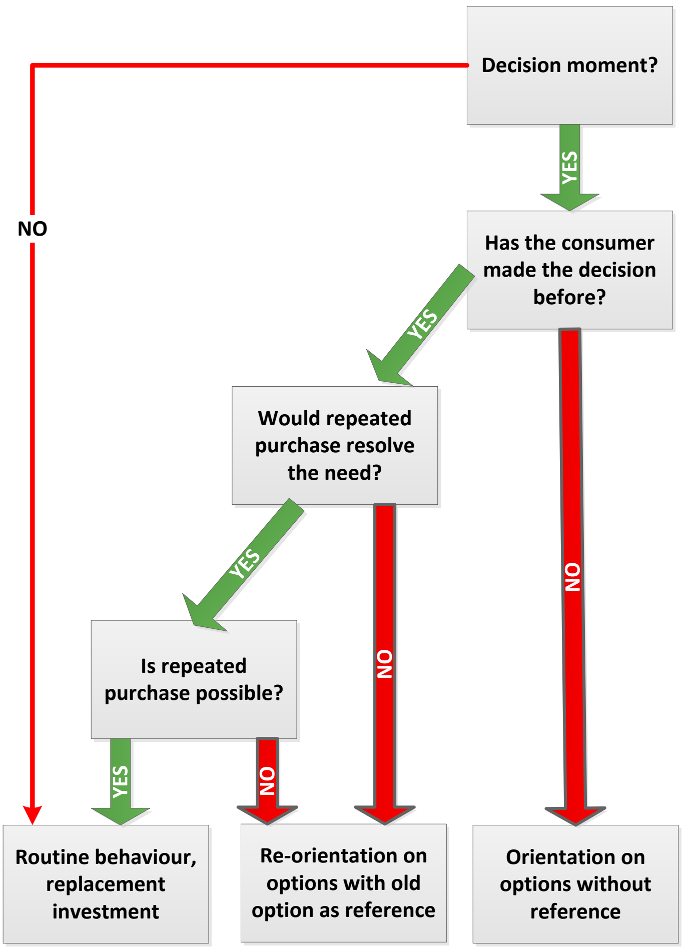

Figure 9. Orientation on alternatives as influenced by previous experience, need fulfilment, and product availability.

The model’s ability to take competition between different choice options into account and to differentiate between familiar and unfamiliar behavior is of major importance for making realistic predictions about innovation uptake. Innovation adoption requires new behavior patterns that have to compete with existing behavior patterns, which most consumers will initially keep preferring even if the innovation comes with clear advantages (Rogers, 2003). For this reason, it is important to distinguish between consumers who have previous experience with a particular purchase, such as buying a car, and those who do not, and hence will not have 'past behavior' as comparison. Another reason why this distinction is important is that those who seek to influence consumer preferences (policy makers or advertisers) need to employ different strategies depending on familiarity with the behavior. Each of the steps in the Attention phase is explained below, with the numbers corresponding to Figure 11 in which the entire model is depicted. The steps are taken for each (consumer) segment.

- *Is there a decision moment for the consumer? / How many (which percentage) of the consumers is facing a decision moment (to solve a problem)?*

A decision moment arises when the consumer experiences a discrepancy between the current situation and the desired situation. This results in need recognition. For example, when I am happy with my car as a mode of transport, but my current car for whatever reason no longer fulfils my needs, I will be open to alternative cars on the market. The decision will be: buy another car. As explained in 2.2.1, the definition of the decision is very important, because it determines which alternative options will be considered to fulfil the underlying need. For example, if I need my car to get from home to work every day, and suddenly it breaks down, I have to make another decision first: replace the car (at that moment, I will be open to alternative cars and the decision will be 'buy an alternative car'), or find alternative means for travel (at that moment, I will be open to different transport modes). In that case, the decision will be: Choose a transport mode to get from home to work every morning. Although this may involve a purchase, depending on the travel options (an alternative car, train tickets, a bicycle) this decision is too complex for CODEC since there are multiple sets of different options to choose from. Similarly, a decision such as 'how to improve energy efficiency in my home' would be too complex, since there are too many options. The model can, however, predict the uptake of particular technologies such as in-home displays, heat pumps, insulation, and other purchases that could fulfil the underlying need to improve energy efficiency. If a decision moment is absent, either because there is no need recognition or because the need can be fulfilled by a routine purchase, the consumer will not enter a decision making process and nothing changes.

The outcome of this step is a percentage of consumers facing a decision moment.

- *Has the consumer made the decision before? / How many (which percentage) of these consumers has made the decision (to buy the option) before?*

If someone has to make a particular choice for the first time, routines are obviously not established yet. The more often a choice has been made, the more strongly past experiences and routines will influence the present decision. Buying LED lights for example to replace incandescent or halogen bulbs will require information search the first time, but becomes a routine once the consumer knows which type to buy. The next purchase will require only routinized problem solving. Buying an alternative with a previous one as comparison is different than buying your first car ever. Buying your first car requires extended problem solving, but for repeated car purchase the information search is likely to be less extensive. For example, you already know which brands are most suitable to your needs in regard to e.g. price range, looks, and quality.

The outcomes of this step are (1) a percentage of consumers for whom the decision is new, and who will enter the phase of orientation on available options without comparison to 'previous' behavior; (2) a percentage of consumers who have made the decision before, and for whom the current option is thus the comparison option. These consumers enter the third step of the attention phase.

- *Would repeated purchase resolve the need of the consumer? / For how many (which percentage) of these consumers would a repeated purchase of the option resolve the need?*

The consumer has previously recognized a need, has resolved it with a purchase, but is now facing a decision moment. Reasons may vary. For example, the previously purchased product may have reached the end of its life cycle. Or the product has not performed as expected, and the consumer is no longer satisfied with how the product fulfils his or her need. The model assumes that if repeated purchase of exactly the same product will resolve the need, people will opt for this (because they are change-averse).

It must be noted that a 'repeated purchase' in CODEC is defined as 'buying the same product type again'. To CODEC, product updates do not matter. Photovoltaics, once chosen, remain the same, regardless if panels bought in twenty years' time look different or perform better (the innovation is electricity production at one's own roof). An electric vehicle remains an electric vehicle regardless the brand (the innovation is the powertrain), a smartphone remains a smartphone regardless brand or model version (the innovation is in the functionality of the smartphone). CODEC has not been designed to deal with differences between brands, or with minor differences within brands between versions of what is essentially still the same product with the same functionality. However, CODEC is able to make distinctions between products within different price ranges, targeting different consumer segments.

The outcomes of this step are (1) a percentage of consumers who intend repeated purchase, and who will therefore move to the fourth step; (2) a percentage of consumers for whom repeated purchase would not fulfil their need, and who will therefore enter the phase of orientation on available options with (negative) comparison to the 'previous' behavior.

- *Is repeated purchase by the consumer possible?*

Particularly because the model focuses on innovations, it should be checked if the current option is still available. After all, innovations may push existing options from the market, especially when supported by policies prohibiting old options. CODEC assumes that if the old choice option is still available, it will be the preferred choice option because it is most familiar to consumers. If the old choice option is no longer available, consumers are forced to choose from the available alternatives, but the attributes of the old choice option will still serve as a positive benchmark. This distinguishes this group of consumers from the group who enter the orientation phase because they were dissatisfied with how the current option fulfilled their need. For this group, the attributes of the old choice option will serve as a negative benchmark, but nevertheless the option serves as “fall-back” if orientation on alternative options does not result in a more satisfying option. At the moment, however, CODEC does not distinguish between consumers who enter the orientation phase because they are dissatisfied with the current option and consumers who enter the orientation phase because the current option is no longer available.

The outcome of this step is either that all consumers will make a repeated purchase or, if repeated purchase is not an option, all consumers will enter the phase of orientation on available options with (positive) comparison to the ‘previous’ behavior.

The output of the attention phase is a percentage of consumers who will consider to change from their present option to another option within a specified timeframe, for example one year. This percentage is not per option (as are the percentages in the “enablers” and “Intention” phase), since all these consumers will be engaging in weighing the different product options that apply to the problem they are trying to solve (e.g. buy a new car when my car is broken).

2.3.2 Enablers

Once the consumer has entered the process of evaluating alternatives, CODEC makes an estimate for each choice option of the percentage of the consumers who would feel able to use the option. This phase in the model is called the ‘enablers’ phase. Options are compared on enabling and disabling determinants such as the initial investment costs, required knowledge and skills, and practical feasibility of using the option. If, for example, a consumer depends on the car to bridge the distance between home and work of 200 miles every day, an electric vehicle will only be an choice option if the consumer can charge it at the workplace. Even then, the consumer may reject the option for personal reasons, such as ‘range anxiety’. In case of PV, the investment costs can be a hurdle, or doubt whether the roof is suitable for PV. These examples show that the model includes both factual enablers (the roof can be suitable or not, the range can be sufficient or not) and perceived enablers (one may believe the roof is not suitable and therefore not explore the PV option further, or one may not trust the reported range of an EV). Factual and perceived enablers may also contradict: One may think the roof is unsuitable while in fact it is.

These examples also show that determinants concerning the ‘fit’ between the innovation and the consumer are partly product-specific. CODEC therefore includes a limited set of general determinants (see Figure 11), which is adaptable to specific purchases. The steps are taken for each (consumer) segment and each choice option.

- *Is it practically feasible to use the option? / For how many (which percentage) of the consumers is it practically feasible to use the option?*
  - *Factual feasibility – fit between needs and product properties, e.g., for how many people is the EV range sufficient given home-work distance? Or how many home owners have a roof that is suitable for PV?*
  - *Perceived feasibility – does the consumer believe that the range will be sufficient (range anxiety)? Or does the consumer believe that the roof is suitable? How many consumers do believe that the range will be sufficient?*
- *Is the initial investment feasible and acceptable? / For how many (which percentage) of the consumers is the initial investment feasible and acceptable?*
  - *Feasibility – can the consumer afford the option? How many consumers can afford the option?*
  - *Acceptability – is the consumer willing to spend the required sum on the option? How many consumers are willing to spend the required sum on the option?*
- *Does the consumer have sufficient knowledge to assess if the option would fit the need? / How many of the consumers (which percentage) have sufficient knowledge to assess if the option would fit the need?*
  - *Factual knowledge – does the consumer have a correct understanding of relevant product features such as the costs, the way it works, or the service provided? How many consumers have enough factual knowledge?*
  - *Perceived knowledge – does the consumer feel he or she is knowledgeable enough about the product to purchase it? How many consumers feel like they have enough knowledge?*

    Here, it must be noted that in studies using the aforementioned Integrative Model (IM) or similar expectancy-value models, knowledge is supposed to influence behavior via attitudes and behavioral intention. The impact of (perceived) knowledge is thus mediated by these determinants, and is generally found to be weak or even non-existent. Most of the studies on the knowledge-attitude-behavior link have been conducted in the context of health behavior change and health promotion. The general finding is that the impact of knowledge is generally positive, however, since knowledge is only a weak and indirect predictor of eventual behavior, behavior can never be expected to change as a result of information campaigns only. Information campaigns are but one instrument that policy makers or media planners may use to influence behavior. It must always be part of a mix of instruments, and it must be chosen only in those situations where a positive behavioral effect can be expected. To enable examination of the influence of knowledge, it is included as a determinant in CODEC. Moreover, CODEC distinguishes between factual and perceived knowledge to allow the model to work with any consumer data that may be available regarding the target behavior at a particular point in time. While factual knowledge may be an even weaker predictor than perceived knowledge, if this is the only information that is available in existing data sources we assume it is better to include this in the model than to include nothing.

- *Is the level of uncertainty (of the policy and/or commercial arrangements for stimulating the option) acceptable? / For how many (percentage) consumers is the level of uncertainty (of the policy and/or commercial arrangements for stimulating the option) acceptable?*

This is an entirely perceptual determinant. For innovations often subsidy arrangements or other forms of financial stimulation are provided for a certain period. Consumers may have the feeling subsidy or pricing arrangements are ever changing and therefore it would be a risk to invest in an innovation since the innovation may not be profitable when the arrangements end.

- *Is the option available on the market?*
  this is an entirely factual determinant. Because the model deals with innovations, initially the availability of particular options may be limited. Availability should improve in time, but this depends on development in demand and supply, which in turn depends on the investment cost of the product, which should decrease when the market share increases (i.e., the innovation overcomes the valley of death).

The output of this phase is a percentage of consumers who feel able to invest in the option (percentage per option).

Some remarks on why perceived knowledge and perceived feasibility are placed in the Enablers phase

Initially, it was envisioned that the Enablers phase would only hold information about the objective ‘fit’ between product and consumer, and that the Intention phase would be about the perceived fit (separation of facts and beliefs). In the present CODEC model, however, the Enablers phase combines both perceived and factual enablers of the target decision. When looking at the IM more closely, this makes sense.

The relationship between de IM and CODEC is depicted in Figure 10. The determinants Skills and Environmental constraints on the right end address factual barriers between the intention to perform a certain behavior and the actual performance of that behavior. The determinant “Self-efficacy” addresses perceived control over performing the behavior and has a direct effect on the intention to perform the behavior[2]. It would therefore make sense to include self-efficacy in the Intention phase of the CODEC model, and put Skills and Environmental constraints in the Enablers phase. However, in some versions of the IM, self-efficacy also directly influences behavior. This means a different rationale can be followed as well, one that in this case better suits the logic of the CODEC model.

The concept of self-efficacy was the last addition to the IM and its role has always been different than the role of the determinants Attitude and Social norms. In the precursor of the IM, the Theory of Planned behavior, self-efficacy, or perceived behavioral control as it was then called, was added to the model as a determinant of both behavioral intention and behavior. The rationale for including perceived behavioral control as a predictor of behavior, in addition to intention, was twofold: Firstly, when holding behavioral intention constant, greater perceived control over the behavior will increase the likelihood that enactment of the behavior will be successful (Armitage & Christian, 2003). Secondly, the stronger perceived control reflects actual control, the stronger perceived behavioral control will directly influence behavior. Therefore, perceived behavioral control simultaneously acts as a proxy measure of actual control and as a measure of perceived confidence in one’s ability (Armitage & Christian, 2003).

Therefore, in CODEC, self-efficacy is placed in the Enablers phase with direct relation to behavior along with skills and environmental constraints (Figure 10, dotted lines), while attitude and social norms are placed in the Intention phase of the model (solid lines). The Intention phase is discussed in the next paragraph.

[2] Scientifically, this is not entirely correct. Some scholars distinguish between self-efficacy and perceived behavioural control as two distinct clusters, with self-efficacy referring to perceived ease/difficulty of the behaviour and perceived control referring to perceived controllability/personal control over the behaviour. However the conceptual basis for this distinction is still in development, (Rhodes & Courneya, 2003). To CODEC, however, this distinction does not matter, and self-efficacy and perceived behavioural control are used as synonyms.

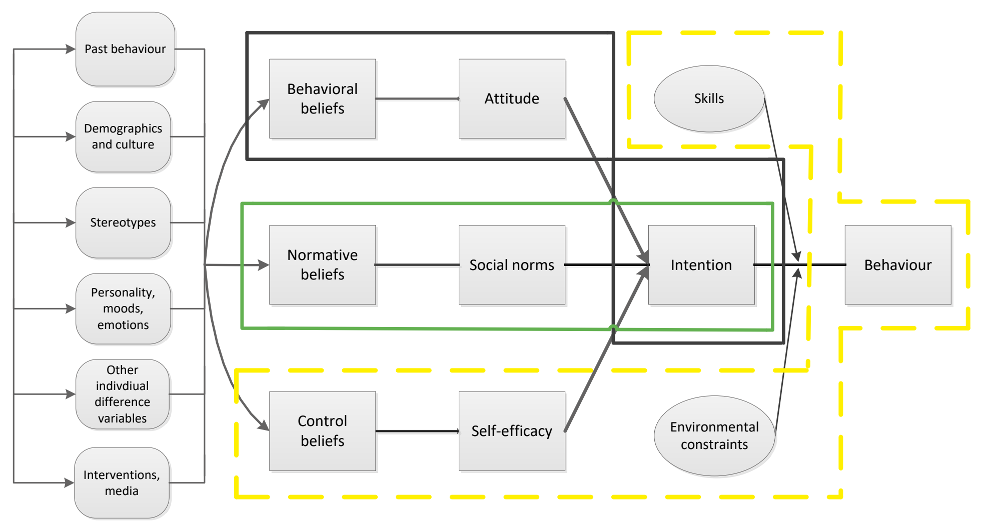

Figure 10. How the CODEC structure is derived from the Integrative Model of Behavioral Prediction (IM).

2.3.3 Intention

As already stated in the Enablers phase, consumers do not just use factual or ‘objective’ evaluation criteria for evaluating options such as performance and cost development. Consumers are not good with numbers, which influences how they weigh monetary costs and benefits, and their decisions are socially influenced. Similar to the IM (Figure 10), the Intention phase of CODEC distinguishes between two types of ‘subjective’ evaluation determinants: Attitudinal determinants and Social determinants. Their conceptualization, however, is somewhat different than in the IM. Regarding Attitudinal determinants, CODEC distinguishes between financial benefits of buying the option and personal benefits of buying the option. Regarding financial benefits, CODEC distinguishes between the investment costs of the option and the operating costs of the option to facilitate application of Thaler’s (2008) theory of Mental Accounting in section 2.1.5. Regarding the social determinants, CODEC distinguishes between social comparison and social status to fit the diffusion of innovations theory (Rogers, 2003).

As displayed in Figure 8, the Intention phase thus consists of a set of determinants that are scored and weighed for each option. Similar to the Enablers phase, CODEC is open to additional determinants but the five determinants below are included in the basic model. The steps are taken for each (consumer) segment and each choice option.

Attitude determinants: Investment costs and operating costs

- *How does the option score on investment costs? / For how many (which percentage) of the consumers are the investment costs of the option acceptable?*
  Following the principle of mental accounting in section 2.1.5, the investment costs and the benefits of that investment often fall with in a different 'mental budget' than the operating costs (i.e., the fixed, variable and semi-variable costs that come with owning and using the product). Therefore, investment and operating costs are included as separate determinants in the model.
- *How does the option score on operating costs? / For how many (which percentage) of the consumers are the operating costs of the option acceptable?*
  This determinant takes into account how the alternatives score on operating costs, which include the fixed, variable, and semi-variable costs that come with owning and using the product. Operating costs may vary considerably between choice options. For example, an electric vehicle has lower monthly fuel costs than a vehicle with a gasoline internal combustion engine.

Attitude determinants: Personal benefits

- *How does the option score on personal benefits? / For how many (which percentage) of the consumers are the personal benefits of the option important?*
  Personal benefits may include all kinds of considerations, including subjective evaluations of the contributions that owning the product will make to wealth, to health, and to well-being, for example by satisfying personal values (e.g., environmental protection, hedonism, independence).

Social determinants: Social comparison and social status

- *How does the option score on social comparison? / For how many (which percentage) of the consumers is reputation of the option important?*
  This determinant takes into account that people look at other people to infer what is proper behavior – both consciously and unconsciously.
- *How does the option score on social status?/ For how many (which percentage) of the consumers is uniqueness of the option important?*
  This determinant takes into account that people can (un)consciously behave in a certain way or purchase certain goods to set themselves apart from "the mass".

For the consumers that reach this phase in the model, each of the abovementioned determinants 10 to 14 is weighed to decide whether these benefits are sufficient to continue to purchase of this product option. This weighing is explained below. Consumer that do not choose for this product option, it is calculated which option they would choose. This way for every product option a market share is calculated.

Each behavioral choice option or product receives a score on each of the abovementioned determinants 10 to 14. Option A can, for example, have a high score on investment costs but a low score on social comparison, whereas option B scores high on both determinants. Next, for every choice option, the five model questions (10-14) of the Intention phase are weighed by 'weighing factors' for choosing between the options. The weighing factors thereby decide which model steps of the Intention phase are decisive in the final decision making. Finally, by multiplying the scores of the five model questions (10 -14) with their accompanying weighing factor, and by scaling the likelihood back to a total of 100%, one receives the eventual likelihood of purchase for the different purchase options. Both the scores and the weighing factors are derived, as much as possible, from existing theory and data sources. If the required data is unavailable, the possibility of collecting additional data has to be considered. If neither theory nor data are available, expert judgments are being made – see the case studies in Chapters 3 and 4.

The output of this phase is a percentage of consumers who will invest in a particular option (percentage per option).

Similar to the Enablers phase, the Intention phases takes into account both factual and perceived fit between option and consumer needs. This is an important asset of the model because it more closely resembles the purchase process in real life, where the eventual choice for a particular option does not logically follow from the fit between consumer needs and enablers. For example, an option may be too expensive for a consumer when considering his or her savings account, but the consumer may decide to purchase anyway and fund it with a loan. The other way around, an option can perfectly fit someone's budget but may be perceived as unacceptably expensive.

The model derived from this theoretical basis is depicted in Figure 11. The application of the model will be described in Chapter 3 and 4.

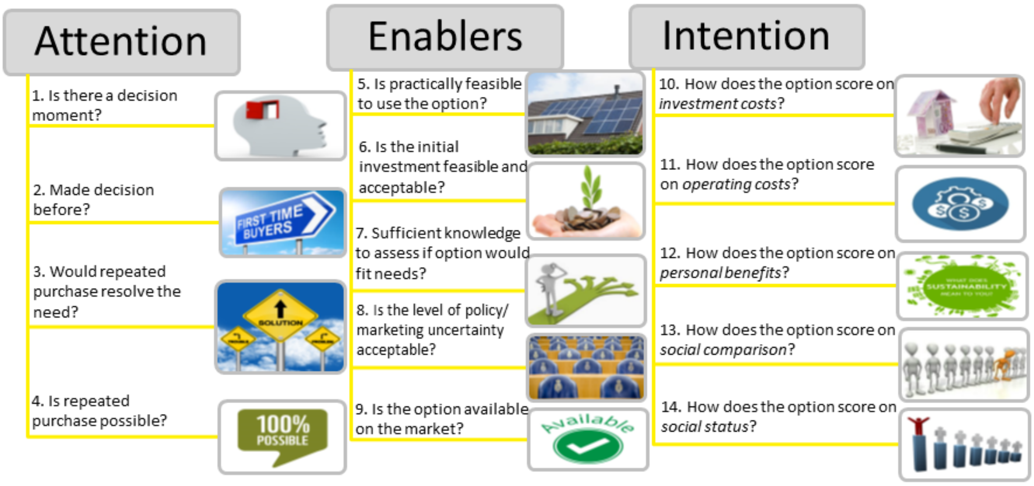

Figure 11. The CODEC model with the 14 questions (determinants).

2.4 Interventions

The model is developed with the goal of comparing different combinations of interventions directed at consumers, for example an information campaign plus a subsidy, and demonstrate which steps in the decision making process will be affected in what way. Indeed, the model structure enables modelling of the possible effects of (combinations of) interventions to influence consumer choices. What would aid the model is an instrument that supports the user of the model, such as policy makers, design the mentioned combinations of interventions. This instrument is not yet developed, however we have found some valuable building blocks that we will build on in future work.

The influencers behind these interventions may be policy makers, manufacturers and providers of products and services, public institutions, NGOs, etcetera. Each group has access to its own, slightly different, set of instruments that is suitable to impact one or more phases at a time in the decision making process. For example, national policy may affect the accessibility of options in the Enablers phase by subsidizing particular options, while manufacturers may affect the accessibility of options by discounts, attractive loans, or lease contracts. Each type of sender has limits in what phases they can influence effectively. National policy instruments are limited when it comes to influencing the ‘attention’ phase, because information campaigns cannot be tailored to particular consumer segments. In marketing, however, segmentation is a core activity, providing manufacturers with much more refined possibilities to define and target particular groups of prospective innovation adopters.

Effective intervention design to influence (steps in) the consumer decision making process has been extensively studied in the realms of health promotion, policy design, and advertising and marketing, however attempts to combine insights from these research areas are scarce. In this paragraph, we will describe the main insights from each field. In a later version it is our ambition to become more familiar with these fields, including the limits of each perspective, and attempt to arrive at an integrated approach to intervention design. We conclude with a list of research topics that are relevant to explore further in relation to CODEC.

2.4.1 Health promotion and behavior change

Health promotion encompasses all activities (educational, social, political, etcetera) facilitating health behavior change. For example, changing the societal norm on smoking from being normal to non-smoking being normal took several decades of educating, campaigning, lobbying, restrictive policy making, and offering multiple methods to help to people who could not quit on their own. While it is known that the interplay of these instruments has eventually contributed to a norm shift in society, effects of single instruments and their contribution to the instrument mix are difficult to assess.

Generally, a good instrument mix should target all steps in the behavior change process, which is why it is important to know which instruments are supposed to impact which steps. For example, behavior change cannot be an expected as a direct result of a mass media advertisement. However, well-designed mass-mediated messages may stimulate first small steps in the process of behavior change, such as further information seeking (Brunsting, 2007).

Most behavioral models explaining and predicting behavior change consist of three key concepts or constructs: Motivation, Opportunity, and Capacity or Ability. These elements can also be found in CODEC and the underlying theoretical framework, the Integrated Model (IM). Intervention design, as a result, focuses on increasing motivation, opportunity, or capacity/ability, depending on where the ‘bottleneck’ for effective performance on the behavior is located. To identify this bottleneck, inquiries with the target group are necessary. Common instruments to collect this data are (a combination of) interviews and surveys, though observation may in some cases also be possible. Once it is known which steps are problematic for which target groups (e.g., lack of knowledge in low educated groups, low self-efficacy in adolescent groups, etcetera), interventions can be designed targeting specifically those steps with those target groups.

A well-known intervention planning model designed specifically for health behavior is the Intervention Mapping[3] approach. Intervention Mapping is a protocol that describes ‘the iterative path from problem identification to problem solving or mitigation’. The protocol includes six steps comprising several tasks (see Figure 12). Completing all the steps leads to a blueprint for designing, implementing an evaluating an intervention.

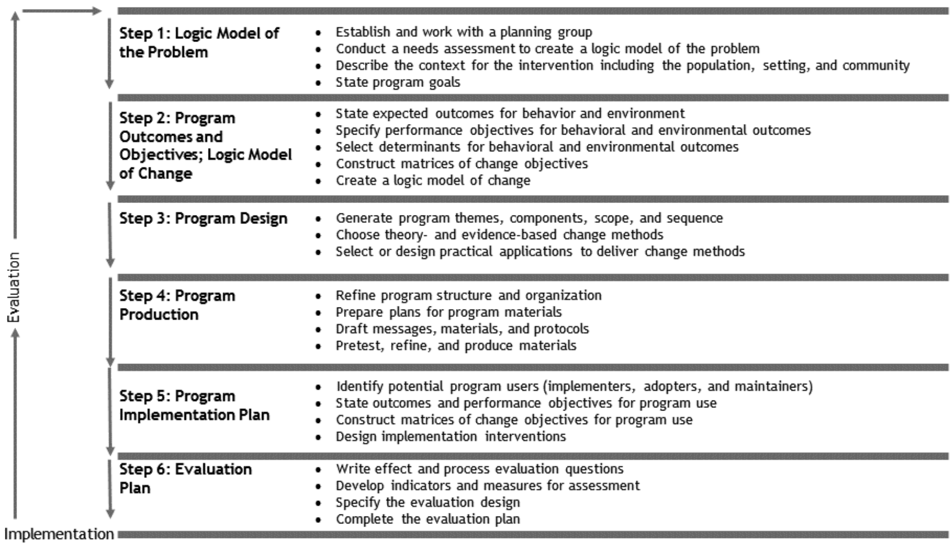

Figure 12. The six steps of intervention mapping, derived from interventionmapping.com

A more recent and more integrated approach is the Behavior Change Wheel (Michie, Van Stralen, & West, 2011). The Behavior Change Wheel was developed from 19 frameworks of behavior change. It consists of three layers (see Figure 13). The hub identifies the sources of the behavior that could prove fruitful targets for intervention. It uses the COM-B ('capability', 'opportunity', 'motivation' and 'behavior') model. This model recognises that behavior is part of an interacting system involving all these phases. Interventions need to change one or more of them in such a way as to put the system into a new configuration and minimise the risk of it reverting.

Surrounding the hub is a layer of nine intervention functions to choose from based on the particular COM-B analysis one has undertaken. The outer layer, the rim of the wheel, identifies seven policy categories that can support the delivery of these intervention functions.

[3] https://effectivebehaviourchange.com/; https://interventionmapping.com

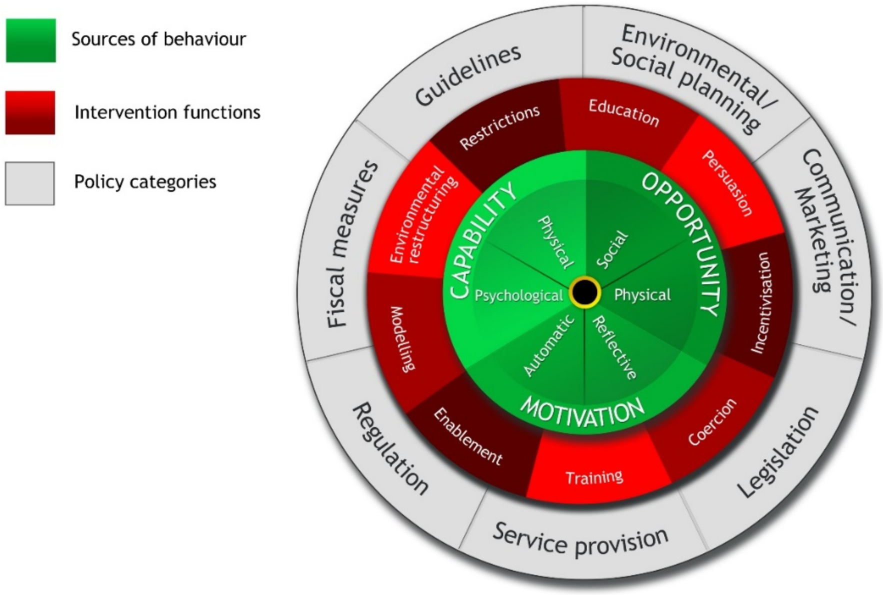

Figure 13. The Behavior Change Wheel (derived from www.behaviorchangewheel.com)

2.4.2 *Policy instruments and behavior change*

In the past decade, behavioral insights teams and 'nudging' networks have been established across countries and at the European Commission in order to facilitate the application of insights from behavioral economics and psychology in different policy areas. The most well-known of these networks is the UK Nudge Unit, or the Behavioral Insights Team UK (BIT UK). The rise of Nudge Units has resulted in more attention from policy makers to behavioral influence tools and models, most of which have not specifically been developed for designing policy interventions. A recent overview of behavioral models in use at various departments in the Dutch government contains seven different tools.[4] While it is beyond scope of this text to describe, compare and discuss all of these tools, there is one that we would like to mention specifically: The instrument planner[5] (Egmond, 2010).

The instrument planner was developed by RVO before the rise of Nudge Units and now seems to have been replaced by the Behavior Change Wheel of Michie et al. (2011). The reasons why we still like to describe it here, are (1) its focus on policy instruments that can be used in interventions, and (2) it linking behavioral determinants to these interventions in a simple and straightforward manner, which serves our aim to briefly and systematically describe the basic principle of theoretical and empirically based instrument planning.

Assuming that behavior is a function of the collective influence of Motives, Enablers, and Reinforcers, the instrument planner asks the user 12 questions to estimate for a particular behavior which determinants are most important to that behavior in a

4 https://www.communicatierijk.nl/documenten/publicaties/2017/11/23/tooloverzicht-bin-nl
5 https://sme.nl/instrumentplanner/html/start.htm

specific target group. Users are thus asked to estimate the impact of various determinants on the target group's behavior, based on actual data or expert judgment. Then, the instrument planner calculates the relative importance of various determinants, and provides advice about which instrument are the most appropriate to influence this specific behavior, of this specific target group, at this point in time.

2.4.3 Advertising research

Interestingly, academic research concerned with studying effects of so-called 'commercial communication' (advertising, branding, marketing, and media planning) has developed independently from research on effects of non-commercial communication that attempts to stimulate, for example, healthy behavior or prosocial behavior. As Brunsting (2007) describes, this is a missed opportunity since both fields offer complementary insights.

Brunsting (2007) states that a central question in advertising research is which determinants stimulate information processing. In particular, advertising research focuses on the question what features of advertisements may motivate people to pay attention to them and appreciate the advertisements. Based on the results of such research, it is determined what an attention-getting and likeable advertisement should look like. Instead of changes in beliefs resulting from exposure to an advertisement, which is central to research based on behavioral prediction models, attention to the advertisement and attitude towards the advertisement are the most often used measures of effectiveness in advertising research. With this approach advertising research especially provides useful insights in the effects of execution characteristics on the first stages of the persuasion process.

2.4.4 Research Issues for CODEC

Above we described various interventions from a number of fields (health, policy and media), but there will be more interventions coming from different fields that can be added to this. In the next phase of developing the CODEC model we want to add which interventions can be useful and applied to each of the CODEC steps. In addition we want to add an overview of which instruments have the most and which have the least impact on consumer decisions, for example using a ranking. Moreover it would be very insightful to find out and add how combining different instruments affects the final outcome: will interventions strengthen each other, or maybe diminish the overall effect? As a next step we would like to test a case in which different interventions are part of the research question.

3 Application 1: Car buyers' uptake of electric vehicles

3.1 Introduction

Chapter 2 was focused on the theoretical basis and the general structure of the CODEC model. In this chapter we will explain how the general model structure was applied to the passenger car market to obtain expected market shares of passenger cars with alternative innovative powertrains.

The text of this chapter is an adapted copy of the text in a confidential report by ECN (Weeda & Tigchelaar, 2012), produced as a commercial assignment for a car manufacturer. Although the majority of data used for the study are not country specific, both the composition of the car fleet used as starting point for the study and the projections for total annual car sales are based on Dutch market data. Therefore, the results of this study are basically only valid for the Netherlands. In addition, in this case the lease market was not included. In this report, however, our main interest is in showing how the model was applied and how suitable the model has been to create market share graphs for different powertrains. Because the study dates from 2012, and the market for electric vehicles has developed rapidly since then, the study itself would have to be updated to be of interest to readers who would like to see model results for the present market situation.

After describing the application of the general CODEC model to the uptake of electric vehicles, and hereby to the market of passenger cars with innovative powertrains (3.2), we describe the model generated output of the expected number of car sales, stock of cars, and the market shares of cars with different powertrains (3.3). Subsequently, we provide conclusions (3.4). Finally, we discuss how suitable the CODEC model has been to provide a valid and reliable graph of the expected ramp-up of sales of Electric Vehicles (EV), and alternative powertrains, from the moment of market introduction (3.5).

3.2 Applying the general CODEC model to the EV case study

In order to apply the general CODEC model structure to this case study, several questions had to be answered:

- Which decision do we want to simulate with the model? (3.2.1).
- What are the choice options and related consumer segments? (3.2.1).
- Do we have to adapt the general model structure for the case study? (3.2.3).
- How do we operationalize the CODEC model steps? (3.2.4).
- Do we need to make an uncertainty analysis to express uncertainties in the model results? (3.2.5.).

3.2.1 Defining the decision in the EV case study

This study focuses on the decision to "buy a new (not an occasion) passenger car" (within a particular year). Alternative transport media, such a buses, trains or a bike are out of scope of the decision.

3.2.2 Choice options and related consumer segments in the EV case study

As described in 2.2.1, the set of behavioral alternatives or choice options has to be exhaustive and the number of options should be limited to a workable number. All choice options that the target group has, should be included in the model.

The case study focuses on consumers who currently own a car and who choose from options in the market of first-hand cars. New cars with innovative powertrains are likely to be sold to people who have already bought a car at least once before, and the second hand market for innovative powertrains was and is currently negligible. Thus, we exclude first-time car buyers as well as buyers in the second-hand car market from the analyses.

According to the BOVAG (2011) and the European Commission (EFAO, 2017), cars are classified in groups from A to N based on the size and investment cost of the car. Based on this information, three market segments were defined that are displayed in Table 4: small (A&B), medium (C&D) and large (J&K).

Table 4. Relation between car model segments in CODEC and the equivalent Dutch car segments in the market.

Car model segment CODEC	Equivalent Dutch car segment	Description vehicle segments
Small	A B	Sub-mini or Small, e.g., Toyota Aygo, Fiat Panda Mini or City, e.g., Peugeot 207, Opel Corsa
Medium	C D Proportional share of other segments*)	Compact or Lower Family, e.g., VW Golf Medium-sized or Upper Family, e.g., Ford Mondeo
Large	J K Proportional share of other segments*)	Medium MPV, e.g.,. Renault Megane Scenic Upper MPV, e.g., Chrysler Voyager

*) The following segments are proportionally divided over the segments Medium and Large: E (Luxury medium-sized or Executive), F (Large or Lower Luxury), G (Sporty models or Lower Sports), H (Supercars or Upper Sports), I (Large luxury or Upper Luxury), L (SUVs or Lower Utility), M (Upper SUV or Upper utility), N (Vans or Commercials) and O (Other or Non-classified).

For each of these car segments, consumers can choose from five powertrains (that is, in theory – in practice, some combinations between car model and powertrain are unlikely – we will return to this point later in section 3.2.4:

- *Gasoline internal combustion engine (ICE)*
- *Diesel-ICE*
- *Plug-in Hybrid Electric Vehicle (PHEV)*
- *Battery Electric Vehicle (BEV)*
- *Fuel Cell Electric Vehicle (FCEV).*

Based on the car model segments (small, medium and large) and the alternative powertrains, we have identified in fifteen different consumer segments (3 car models X 5 powertrains).

For each powertrain and car segment, BOVAG (2011) and CBS (2011a) annually specify the number of cars in the Netherlands by powertrain. These datasets were used to define the current composition of the car fleet. The datasets include both the numbers of cars in personal ownership and the cars in ownership of companies (lease cars). Because the "*car stock specified per powertrain"* was not split into personal ownership and lease cars, the total stock of passenger cars was used as an input of the model.

3.2.3 Deviation from the CODEC model structure

The general model structure, consisting of fourteen model steps, was explained in section 2.3. The application of the CODEC model to electric vehicles did not require adaptation of the model structure, however the operationalization of several model steps deviated from how the operationalization was intended in the design of the CODEC model (see 3.2.4). In some cases, this is due to new insights gained between working on the EV study and working on the theoretical basis underlying the CODEC model. In other cases, it is due to lack of suitable data. In the discussion section we will elaborate on this whether this operationalization was valid.

3.2.4 Operationalization of CODEC for the EV case study

The basic CODEC model structure (see 2.3, Figure 8) was operationalized for the case study of EV. In the operationalization of the model steps, there was some deviation from the general model.

Table 5 provides an overview of how the model steps were operationalised in the case study of EV. The table also shows the actual model input, which literature sources were used for the operationalization, and finally, a judgment of the data quality of these literature sources.

Table 5. Overview of the operationalization of the CODEC for the case study EV for the three phases Attention, Enablers and Intention.

Model steps	Operationalization	Model input	Literature sources	Data quality[1]
		Attention		
• *Is there a decision moment?*	Number of car owners that is considering to buy a new car.	Varying from 5-14%; the decision moment percentages are different per type of powertrain and per year.	BOVAG (2011), CBS (2011a)	☺
• *Has the consumer made the decision before?*	Focus on consumers that have bought a car before, and are replacing their car, not buying an additional one.	100% replacement	Basic assumption	☺
• *Would repeated purchase resolve the need?*	Percentage of car owners per option that is (still) satisfied with present option and therefore will not switch to another powertrain.	Lack of sufficient empirical data. Bandwidth of 50% to 90%; 70%, of the car buyers is not considering to switch to a different powertrain.	No empirical data available; expert assumption	☹
• *Is the current option still available?*	It is assumed that the present option is still available and that buyers can opt for a repeated purchase.	100% availability current option	Basic assumption	☺
		Enablers		
• *Is it practically feasible to use the option?*	5a. The most important differences between powertrains are the ranges these cars can drive.	Share of target group for which the range of a specific powertrain is sufficient. Based on (a) a range demand distribution curve in which we plotted the share of car buyers and their minimal range demand and (b) driving range development of the different fuel options.	(a) Grid-4-Vehicles (2011), CBS (2011b) (b) McKinsey, (2011)	☺
	5b. Percentage of target group for which fuel infrastructure is available.	For ICE gasoline and diesel powertrains, the fuel availability is constant (100%). The fuel availability for PHEV increases linearly towards 58% in 2050 and for BEV and FCEV the fuel availability linearly increases towards 2050, respectively 56% and 100%.	ECN (2011), Grid-4-Vehicles (2011)	☺

Model steps	Operationalization	Model input	Literature sources	Data quality[1]
• *Is the initial investment feasible and acceptable?*	This step was not modelled in this case study since in this (older) version of the model, investment costs were not included in the enablers phase, only in the intention phase.	-	-	-
• *Sufficient knowledge to assess if the option would fit the need?*	Operationalized as being aware of the existence of alternative powertrains instead of having sufficient knowledge about the product	Linear increase of awareness in first four years after introduction (innovative powertrains): 2012: 0%, 2013: 25%, 2014: 50%, 2015: 75%, 2016: 100%.	No empirical data used; expert assumption	☹
• *Is the uncertainty of the policy (or commercial arrangements) for stimulating the option acceptable?*	Policy interventions were not operationalized in CODEC applied to the EV case study because at the time there was no policy regarding EV, only for the lease market, which was out of scope.	-	-	-
• *Is the option available on the market?*	The option must be up for sale if it is to be selected and demand should not exceed supply.	An S-curve to simulate a gradual market introduction based on (a) car model sales, (b) market size of car model segments and (c) expert judgment.	(a) Autoweek (2011), (b) BOVAG (2011) CBS (2011b) (c) Expert judgement	☺
Intention				

Model steps	Operationalization	Model input	Literature sources	Data quality[1]
• *How does the option score on investment costs?* (financial)	Initial investment costs (car price) for different option, relative to present car including loss aversion penalty.	Investment cost projections of passenger cars with a different powertrain and modelling the theory of Mental Accounting, as described below.	McKinsey (2011), Thaler (2008) based on Kahneman and Tversky (1979)	☺
• *How does the option score on operating costs?* (financial**)**	Operating costs for different options, relative to present car including loss aversion penalty based on Mental Accounting.	Variable cost projections of passenger cars with a different powertrain and modelling the theory of Mental Accounting, as described below.	McKinsey (2011), Thaler (2008) based on Kahneman and Tversky (1979)	☺
• *How does the option score on personal benefits?* **(non-financial)**	Not operationalized in CODEC applied to the EV case study, because at time of writing this determinant was not yet defined in the basic model structure.	-	-	-
• *How does the option score on social comparison?* **(non-financial)**	The larger the market share of a specific powertrain, the larger the score on social comparison until the effect of saturation comes into play.	Social comparison of gasoline and diesel powertrains are assumed to be constant (1.00). For the innovative powertrains, the score increases from 0.09 to a range of 0.16 – 0.82 depending on the market share of the particular powertrain.	Rogers (2003), expert assumption	☹/☺
• *How does the option score on social status?* **(non-financial)**	The larger the market share of a specific powertrain, the lower the score on social status until the effect of saturation comes into play.	Environmental friendly cars have additional social status at first. The social status of diesel and gasoline passenger cars, start decreasing in 2030 from a score of 1.00 to 0.95. In contrast, the social status of the alternative powertrains stayed at 1.00.	Rogers(2003), expert assumption	☹
Weighing (model steps Intention)				
Weighing	Factors to weigh the relative importance of different determinants influencing **intention**: financial and social determinants. Personal benefits were not operationalized and hence not included in the weighing.	Large uncertainty no empirical data. Assumption made that financial determinants are more important than social determinants.	Assumption, uncertainty analysis.	☹

[1] *A happy face means that the model input is underpinned by a valid literature source or a basic valid assumption (this is an assumption that follows from logic or from choices made in regard of e.g. the scope), a sad face means that we had to make assumptions by lack of appropriate empirical data which should be substantiated in further research.*

Below, we will elaborate on the information shown in Table 5**.**. The numbers between brackets in the text correspond to the model step numbers.

Attention
To estimate for which share of the *car owners* (2) there is a *decision moment (1)*, we looked at car stock statistics per powertrain for the period 1986 - 2011 (BOVAG, 2011; CBS, 2011a). Cars are on average replaced every four years, but there is a large variation. Some cars are replaced after one year, others after 8 years. In order to prevent a too optimistic number of yearly car replacements, we based the amount of car replacements on the yearly average change of the car fleet of the last 8 years.

Central to the CODEC model is that consumers will at some point switch from one powertrain to another. If all car buyers were *satisfied with their current car and its powertrain (3)*, none of the car owners would change to a different fuel type because repeated purchase would resolve the need. If car owners are dissatisfied with their current powertrain, chances are that they switch to another powertrain. At the time of research, however, there was no empirical data to determine what percentage of car owners is dissatisfied with their present powertrain and is therefore considering an alternative powertrain. Therefore, we have made an expert assumption. We assumed that a percentage of 70% of car owners will not switch, with a bandwidth of 50%-90%.

We assumed that all powertrain options remain available until 2050. All car buyers will therefore *be able to replace (4)* their present car by a new one with the same powertrain and consumers will therefore not be forced to look for alternatives.

Enablers
A main impact of changing to an alternative powertrain in terms of *practical feasibility (5a)* is the difference in driving range. Electric cars in particular have a much shorter range compared to conventional gasoline or diesel cars. Although the distance of over 90 percent of all trips in the Netherlands by car is less than 50 kilometres (Grid-4-Vehicles, 2011; CBS, 2011b), people expect a longer range of their car. The range criterion is not based on average distance, but on more incidental longer trip-distances. By combining data of car ranges that consumers perceive as sufficient (Grid-4-Vehicles, 2011) and range development of the different powertrains (McKinsey, 2011), it was possible to project the share of car buyers who perceive the range of specific powertrain types to be adequate.

The uncertainty of availability of hydrogen filling stations and electrical charging points is a second indicator of *practical feasibility (5b)*. Availability of required energy infrastructure is part of the “chicken and egg” dilemma, especially in the case of hydrogen. The CODEC applied to the EV case study has an input of equations which describe the share of the population (or market) for which the required energy infrastructure is available as a function of associated cars in the fleet. For FCEV, the equation has been derived from the Dutch hydrogen roll-out study THRIVE (ECN, 2011). In the case of BEV, results from the European Grid for Vehicles (2010. p20-21.) project were used to derive a relation between share of population for which the required energy infrastructure is available, as a function of cars in the market.

The *feasibility of the investment (6)* was not modelled in this case study since in this (older) version of the model, investment costs were not included in the enablers phase, only in the intention phase.

Consumers must be aware of the existence of alternative powertrains in order to be able to buy one. Therefore, the step *'sufficient knowledge' (7)* in the CODEC model for the EV case study was operationalized as "awareness" of the option, measured with the question whether respondents had heard of an option. In a survey on battery electric vehicles in 2011, it was found that nearly all respondents have heard about electric cars; only 9 out of the 1,899 have not (Grid-4-Vehicles, 2011. p16.). Seventy percent of the respondents have even heard "a lot" about electric cars and/or have seen (or think they have seen) an electric car in real life. Given that at the time of the survey BEV were just available of the market, we assumed a quick linear increase in awareness to 100% in 2016.

This operationalization deviates from the current definition of "sufficient knowledge" in the basic model structure, in which a distinction between factual and perceived knowledge has been made. At time of working on the EV case study, this distinction had not yet been added do the model. However, even if it had been, it would have been a challenge to find data on perceived and factual knowledge of powertrains and we would probably have had to make do with the Grid-4-Vehicles survey as a data source anyway.

The possible impact of *policy uncertainties (8)*, was not operationalized in CODEC applied to the EV case study because at the time there was no policy regarding EV, only for the lease market, which was out of scope.

Cars with different powertrains will not be *available* (9) immediately. The introduction of hybrid cars started with the introduction of the Toyota Prius, but it took some time before other brands and other car models became available with a hybrid powertrain. At first only a few brands offered hybrid cars and only particular car models were available, but eventually more car producers followed to supply PHEV cars for more car model segments. Based on car model sales and the market size of the car model segments (Autoweek, 2011; BOVAG, 2011; CBS, 2011b) we were able to draw an S-curve for the availability of PHEV. The market size of the car model segment (e.g., A/B or C/D) determines the saturation point of the S-curve (demand should not exceed supply). The steepness of the S-curve is based on the increased PHEV car model sales (i.e., more brands sell PHEV and hybrid powertrains become more common for the different car model segments). Based on the S-curve for PHEVs and expert judgements, S-curves for the availability of BEV and FCEV were created. We also took into account that not all car segments may be equally suited for a particular powertrain. For example, we assumed that fuel cell technology is most suited for driving long distances, for which people will use relatively large cars. Fuel cell technology seems a less logical choice for small cars, which are generally used for short to medium distances. The reverse may be true for Battery electric vehicles, given their relatively small range. Unlikely combinations of powertrain/car segment were thus excluded from the list of choice options (see 3.3).

Intention
As explained in 2.3.3, intention to buy a particular option is the result of weighing five determinants in the basic CODEC structure: investment costs, operating costs, personal benefits, social comparison, and social status. In this version of the model, however, we did not operationalize the score on *personal benefits (12)*. At the time of research, several publications were available on personal motives to purchase innovative vehicles. Such motives may include a desire to contribute to sustainability, or to be independent from fossil fuel suppliers. However, we had not yet decided on the best way to include such information from existing studies in the model. Therefore, in this case study, it was decided to leave out the operationalization of personal benefits.

Data on the *investments costs (10)* and *operating costs (11)* of different powertrains were combined with the theory of mental accounting, which resulted in different scores for alternative powertrains (Table 5). As noted earlier, this way of reasoning is based on the concept of Mental Accounting of Thaler (2008), which is in turn based on Prospect Theory by Kahneman and Tversky (1979). See 2.1.5 for more background on the calculation method in the model. We used McKinsey's (2011) scenarios as input for investment costs and operating costs of different powertrains.

Besides the financial attractiveness of the powertrain options, the decisions of consumers are to a large extent influenced by decisions of other people. To simulate this, we included a '*social comparison score' (13)* that is related to the share of a powertrain in the total fleet. For both the diesel and gasoline car, the social comparison is at its maximum score of 1.00 because these are standard powertrains. The score of social comparison for the innovative powertrain increases in the shape of an S-curve. If the market share of that particular powertrain increases, the score of social comparison increases. At the same time, if more consumers will have an innovative powertrain, the *social status (14)* decreases. We modelled the effect of *social status* in a limited way by assuming that the social status of diesel and gasoline passenger cars starts decreasing in 2030 from a score of 1.00 to 0.95, while the social status score of innovative powertrains was set at a constant value of 1.00.

Weighing
To combine the scores of the model steps in the intention phase, each of the scores on the five intention determinants is weighed with a factor. These weighing factors were based on expert judgements. The total of the weighing sums up to 100%. Financial indicators have been given a greater weighing factor than the non-financial indicators. Between the two financial indicators, investment costs were assumed to be more important than operating costs, because these costs are immediate while operating costs are future costs (delay discounting). Between the two non-financial indicators, social comparison was assumed to have more weight than social status. The weighing factors shown in Table 6 and Figure 13. Because they are based on expert judgment, we have used uncertainty boundaries for all weighing factors (see 3.2.5).

Table 6. The values of the weighing factors used in the CODEC model applied to the EV case study model.

Weighing	Used	Lower boundary	Upper boundary
Non-economic versus Economic (% weighing social)	30%	15%	60%
Investment costs versus Operating costs (% investment costs)	75%	38%	100%
Social comparison versus Social status (% social comparison)	75%	38%	100%

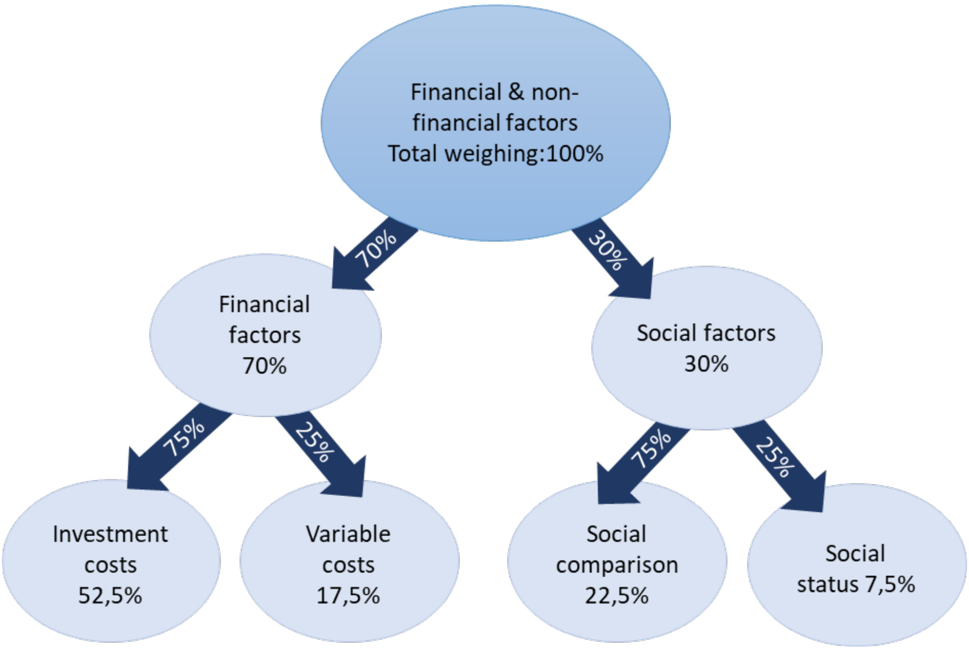

Figure 14. The values of the weighing factors used in the CODEC model applied to the EV case study model.

3.2.5 Uncertainty analyses: Monte Carlo

How the powertrains in cars will transform in the coming decades is, to a large extent, uncertain. Alternatives like Battery Electric Vehicles (BEV) and Fuel Cell Electric Vehicles (FCEV) have only just entered the market. The actual market uptake in the coming decades will depend on future innovations and changing circumstances such as policy and charging infrastructure.

As discussed, assumptions were made in the model for the different parameters. To judge the extent to which the main outcomes depend on these assumptions, uncertainty analyses have been conducted. A simple way to execute such an analysis would be to change one input variable to see the effect on the end result. Although this clarifies the effect of this single input, it does no justice to the complexity of multiple uncertainties that influence the outcome simultaneously. Individual uncertainties cannot be simply added up, because some uncertainties are reinforcing each other while others reduce each other's effect. Therefore, it is better to analyse the combined effect of different uncertainties.

To analyse the combined effect of different uncertainties, in this case study a monte Carlo analyses was executed. Special software[6] allows to vary multiple inputs within pre-set uncertainty boundaries at the same time. The software recalculates the outcomes multiple times, depending on the settings for example 100 or 1000 or many more times, each time with a different setting of input variables (between the uncertainty boundaries). This results in many possible outcome values, on which a probability distribution can be based. With this method it is possible to give a confidence interval of the model outputs: given the uncertainties of the assumptions made in the model, how certain can we be of the outcomes of the model?

In the results section (3.3) we will show the market shares for 2010-2050 for the different powertrains, including lower and upper uncertainty boundaries, based on the Monte Carlo analysis. In the discussion section (3.5) we will show the results of the uncertainty analysis on the defined lower and upper boundaries for each weighing factor.

3.3 Model output and EV case study results

The previous paragraphs focused on the application of the CODEC model to the case study of EV. The intended output of the CODEC model applied to the EV case study was as follows:

1. *Projected number of passenger car sales on the first-hand market;*
2. *Fleet of passenger cars in the Netherlands;*
3. *The expected market shares per powertrain between 2010-2050.*

The model successfully provided these intended outputs, which we will present below. It is important to note, however, that these outputs are projections characterized by uncertainty boundaries. In 3.5 we will reflect on the robustness of the model output.

As shown in Table 7 and in Figure 15, the model proofed suitable for providing the demanded output of yearly car sales and market shares between 2010-2050 for the different powertrains. The 5% - 95% uncertainty boundary was based on the Monte-Carlo analysis as explained in 3.2.5.

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[6] In this case @risk software was used to do the analyses.

Table 7. Output of the CODEC model applied to the EV case study: the number of yearly car sales with a 5%-95% uncertainty boundary. Given that for the year 2010 statistic data was used, there is no range of car sales.

Number of yearly passenger car sales in the first-hand market (x1000)	FCEV	BEV	PHEV	ICE-gasoline	ICE-diesel
2010	0	0	0	381	102
2020	0 (0 - 0)	0 (0 - 1)	1 (0 - 4)	380 (336 - 470)	231 (189 - 344)
2030	6 (2 - 26)	1 (0 - 3)	4 (1 - 18)	384 (331 - 505)	262 (210 - 403)
2040	32 (12 - 97)	1 (0 - 9)	12 (4 - 45)	368 (310 - 511)	275 (219 - 425)
2050	58 (23 - 147)	5 (1 - 29)	28 (11 - 90)	327 (263 - 500)	271 (215 - 436)

As Table 7 shows, the yearly car sales for BEV started to increase between 2010 – 2020, but for FCEV the yearly car sales start only to increase significantly after 2020. This is because after 2020 the barriers in the *Enablers phase*, mainly the fuel availability and whether the powertrain is available for sale on the market, become lower for FCEV. On top of that, initially BEV were more affordable than FCEV, but from 2030 on the investment costs for a BEV and FCEV are similar.

Important disablers for BEV are the limited car range and a relatively low availability of BEV on the car sale market. For the latter we assumed that BEV is well suited for relatively small cars (the A/B and C car segments) and not for the larger car segments (D and J/K). Moreover, since the rollout status of electric charging stations is linked the number of BEV car sales, the fuel availability stays a significant barrier for BEV until 2050 (i.e., the chicken and egg problem). These aspects result in a relatively low market share of BEV as displayed in Table 7.

Essential enablers for FCEV are the attractive car range and a well expected ample availability of hydrogen fuel stations, which increases from 1% in 2017 to around 75% in 2030. Accordingly, the market share of FCEV is relatively larger than for BEV. However, we assumed a limited car availability for FCEV since fuel cell technology is mostly suited for relatively large cars that regularly drive longer distances (no FCEV technology available for the A segment).

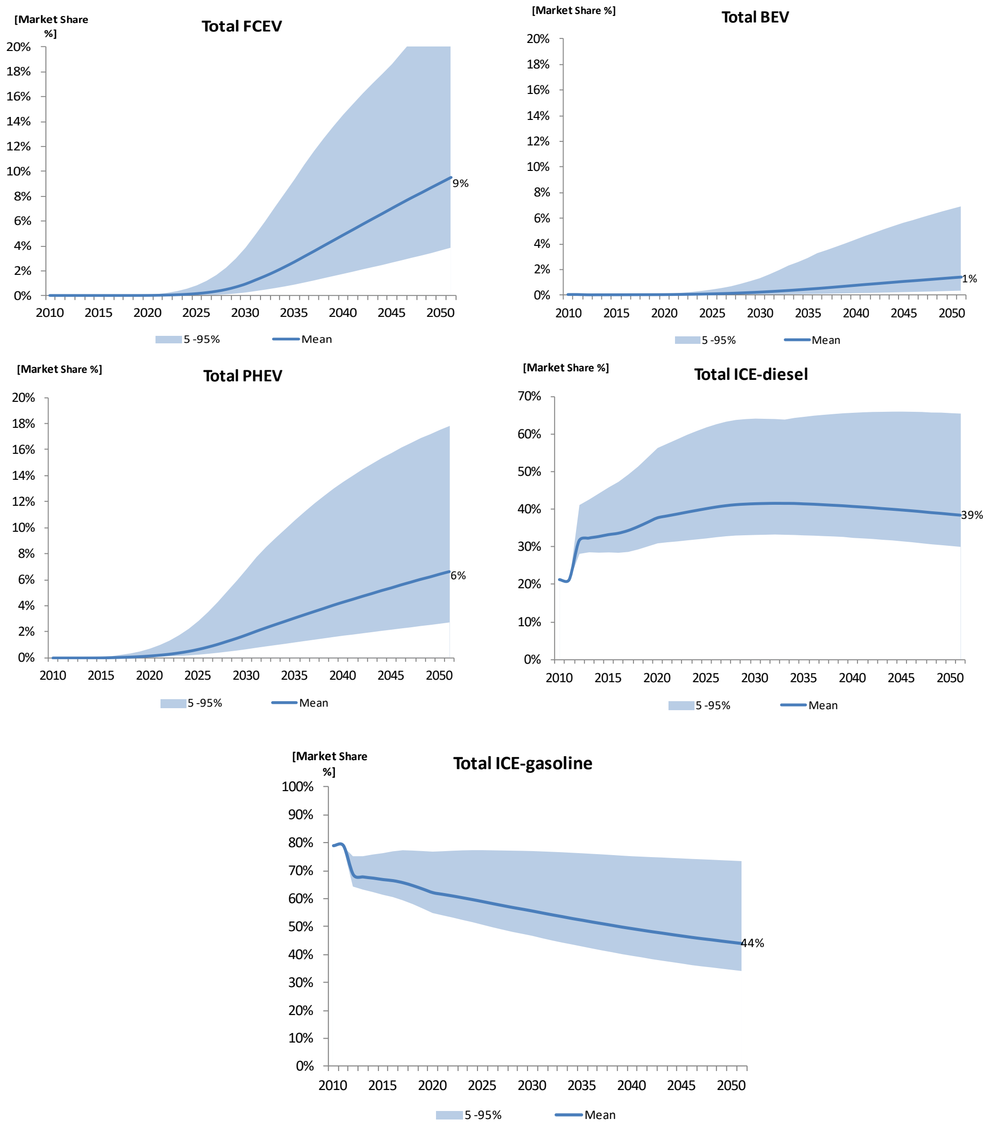

Figure 15. The market shares for 2010-2050 for the different powertrains. The market share graphs include a 5-95% uncertainty boundaries. The total market share, with a deficiency of 1% due to rounding, adds up to 100%.

3.4 Conclusion on the application of the model

The CODEC model has been applied to the case study of EV, or more correctly to the market of innovative types of powertrains. Based on this application we can draw the following conclusions on the usability of CODEC model:

- The model was able to evaluate competitive alternatives like consumers are doing in practice in their purchase process, and the model was able to show why a particular option has a relatively lower market share than another option.
- The model gave us projections of car sales (until 2050) of alternative (innovative) powertrains.
- Based on the Diffusion of innovations theory (Rogers, 2003), we expected S-curves for the number of car sales and market shares for the innovative powertrains when approaching 100% market share. As shown in Figure 15,

the graphs of the market shares of PHEV, FCEV and BEV are characterized by a curve which does not resemble an S-curve yet. The market shares do not approach 100%.

- Using the model, we were able to assess the relative influence of the model steps on the actual market shares.

In contrast to economic models, CODEC includes the social perception and behavior of consumers. Applying the model is supposed to result in more realistic projections of the uptake of alternative powertrains and should provide – in comparison to economic optimization models – additional quantitative insights to industries and policy makers about possible measures to improve the diffusion of innovations.

However, as mentioned throughout this chapter several times, consumer perception and behavior is intrinsically difficult to quantify. By lack of suitable data to serve as input to the model, we were required to make assumptions and include uncertainty boundaries. In the next section we will reflect on the EV case study results, the CODEC model structure, modelling simplifications, operationalization issues and (un)certainty of the assumptions made.

3.5 Discussion

In this section, we will address the model output and EV case study results (3.5.1), the general model structure (3.5.2), operationalization issues and data availability (0), uncertainty analysis of the weighing factors, and uncertainty of the assumptions made (3.5.4).

3.5.1 Model output and EV case study results

The EV case study was commissioned and conducted in 2012. When comparing the EV case study results with more recent statistical car data (Table 8), we can now conclude that our projection of the number of yearly car sales in 2020 of BEV and PHEV (Table 7) was too low. In the period 2013 – 2016, roughly 3000 BEV passenger cars were annually registered and this number of annual registrations is still increasing. In contrast, the model output showed that in 2020 approximately 1000 BEV will be sold. If the current statistic trend continues, this is a notably low projection.

Table 8. Number of car registrations per type of powertrain (BOVAG, 2017). FCEV matches with hydrogen in the literature source.

	Number of car registrations (#)						
	2010	**2011**	**2012**	**2013**	**2014**	**2015**	**2016**
ICE - gasoline	364,054	374,811	323,370	264,586	248,693	258,679	274,731
ICE - diesel	98,675	156,834	142,807	103,557	105,014	129,773	72,356
PHEV	21	36	1,217	16,952	11,833	39,763	18,545
BEV	122	861	828	2,619	2,911	3,193	3,988
FCEV	-	-	-	1	2	19	7

This discrepancy between projections and current findings is mainly due to the data input of the model, which is outdated in some respects, and of which the quality is not always optimal:

- *The lease market is a specific market segment that differs strongly from the first-hand car consumer market. Nevertheless, in the present case study, we were forced to treat these segments as one because underlying data sources did not distinguish between them*
- *Policy interventions (i.e., a low additional tax liability and other tax benefits) have had an significant impact on the increase of BEV in the lease sector. The (potential) impacts of these policy interventions were not included in the EV case study, because this was out of scope of the assignment.*
- *We made a relatively low estimation of the technological feasible car range of BEV based on McKinsey (2010), who stated that a BEV driving range in 2015 fits between roughly 120km and 200km. Accordingly, a driving range of 150 km in 2011 and 200 km in 2020, which stays constant towards 2050, was assumed in CODEC applied to the case study EV. However, more recently the ANWB (2017) stated an average BEV driving range of 221km. Also the Tesla Model 3 will have a driving range of roughly 325 km (EVD, 2017).*
- *The relatively low availability of BEV on the car sale market is a partly due to the assumption that BEV – because of their modest range- are mainly suited for relatively small cars (the A/B and C car segments) and not for the larger car segments (D and J/K). However, as the range of BEV is rapidly improving, more car producers and more car models in different car segments are now entering the market.*
- *The investment costs of the powertrain options were based on McKinsey (2010). Considering battery technology cost reductions due to economies of scale, the estimate of the investment costs of BEV could be outdated, however at the time, no recent information was available.*

Altogether, improving these model inputs will result in a larger amount of yearly BEV sales and a higher market share which is probably more in line with current statistical data.

On top of findings for BEV, the yearly car registrations of PHEV (Table 8) peaked in 2015 just before the fiscal benefits were lowered (CBS, 2017b). If we would have included the effect of this policy intervention in the operationalization, the model output would show a higher number of PHEV car sales. Assessing whether this is the case for BEV and PHEV would require a reapplication of the model to the case study of EV.

Updating the data input of the model will improve the quality of the case study results. However, rather than updating the present case study results, our aim is to discuss potential general model improvements, operationalization issues, and the robustness of the assumptions made.

3.5.2 General model structure

Weighing of indicators
After applying the CODEC model to the EV case study, we have identified one fundamental model improvement. This findingcame too late for this case to be implemented. The weighing of indicators predicting intention is currently equal for all consumer segments, while we hypothesize (see 2.1.9.2) that different weights will apply to different adopter groups as identified by Rogers (2003). For example, innovators will weigh financial and non-financial indicators differently than laggards. The general model structure can be improved by distinguishing between adopter groups. This is a general model improvement that not only applies to the case study of EV, but to all case studies conducted with CODEC.

Product differentiation and branding
Branding and product differentiation are important strategies impacting product preferences. Brands can also introduce innovations, like Tesla has done with a highly advanced BEV and Eneco has done with the smart thermostat (Toon). However, as explained in Chapter 2, CODEC focuses on the innovation (in this case, the powertrain) and not on competition between brands. Neither does the model take into account that innovations may actually “take off” due to the popularity of the brand that introduces them. The main reasons for this choice are (a) to reduce model complexity, and (b) we simply do not know how to model this yet. Further discussion of this point can be found in Chapter 5.

3.5.3 Operationalization issues and data availability

In the operationalization of the CODEC model we depend on the data quality of available literature sources: For some of the operationalised determinants, there was a lack of empirical data and therefore assumptions had to be made. Furthermore, some assumptions had to be made to reduce complexity of the model. Below we describe the assumptions made, and the robustness of these assumptions. For the weighing factors, a Monte Carlo uncertainty analysis was performed. The results of this analysis will be given in 3.5.4.

Below we discuss the assumptions made due to lack of data and how they may have affected the model output.

Attention phase
In the attention phase we made an assumption only in the operationalization of step *(3)* “*Would repeated purchase resolve the need?*”

- ***Step 3*** *“Would repeated purchase resolve the need?*
  At the time of research there was no empirical data to determine what percentage of car owners is dissatisfied with their present powertrain and is therefore considering an alternative powertrain. Hence, we assumed that 70% of the car owners stick to a similar powertrain. If we adapt the model input to 50% or 90%, there is a significant change in the final model output. The market share of BEV in 2050 is respectively twice as high or twice as low. The model requires an empirical underpinning, for example from survey data on dissatisfaction with the current powertrain, for this model step.

Enablers phase
In the enablers phase we made assumptions in the operationalization of model steps *(6) "Is the initial investment feasible and acceptable?"* and *(7) "Sufficient knowledge to assess if option would fit the need?"* All model steps in the Enablers phase have an equal impact on the percentage of consumers who feel enabled to invest in the option (percentage per option). If one of the model steps in the Enablers phase doubles, then the percentage of the consumers that feel enabled to invest in the option doubles as well.

- **Step 6** "Is the initial investment feasible and acceptable?"
  Of this step, only feasibility of the investment was operationalized. Operationalization of investment acceptability is a point for improvement. The focus of the EV case study was on consumers who already own a car and who consider buying a new, first-hand car. The investment costs for a car are assumed to be no barrier, to the extent that the new car costs the same as the old car. Alternative powertrains can be more expensive, so investment costs for a new car with an alternative powertrain may be a barrier for purchase. However, the investment costs of innovative powertrains will presumably decrease in time through technological development and economies of scale[7]. Altogether, this assumption will have probably a negligible effect on the model output.

- **Step 7** "Sufficient knowledge to assess if option would fit the need?"
  This step was operationalized as being aware of the existence of the alternative powertrain instead of the perceived knowledge about the product (e.g., costs, the way it works, or the service provided). Awareness, however, is a different concept than knowledge in information processing literature. Assumptions regarding awareness and knowledge significantly impact model results. In the present case study, an equal level of knowledge was assumed for all innovative powertrains. However, FCEV are less implemented than PHEV and BEV vehicles, so consumers are probably less knowledgeable about FCEV than BEV and PHEV. Furthermore, factual knowledge levels are unlikely to reach 100%, since there will always be people who are incapable of obtaining sufficient knowledge about different powertrains. Assuming differing levels of knowledge for the various powertrains (PHEV: 50% in 2015 to 90% in 2050, BEV: 40% in 2015 to 90% in 2050, FCEV: 30% in 2015 to 90% in 2050. IC-gasoline and IC-diesel a constant of 95%), the market shares of all innovative powertrains roughly decrease with 8%. It is hence worth the effort to collect data on the actual level of knowledge on various powertrains, since this would improve the model application in this case study.

Intention phase and weighing
In the intention phase we made assumptions for step *(12) "How does the option score on personal benefits?",* step *(14) "How does the option score on social status?"*, and the weighing factors.

  - **Step 12** "How does the option score on personal benefits?"
    This attitudinal determinant: personal benefits was not operationalized in

[7] The market for EV in the Netherlands will not have as much influence on the prices compared to the global market. Therefore there is no feedback between uptake and price in the CODEC model.

the EV case study mainly because we were unsure how to do this based on available data. In a reapplication of this case study, we would take time to find a solution to this issue. For application of the general model to any case study, it would be recommendable to develop a standardized measurement instrument for personal benefits that may be derived from adopting energy-related innovations.

- **Step 14** “How does the option score on social status?”
  In this study, social status was operationalized as a product feature instead of a feature of particular adopter categories. Rethinking the operationalization of this concept is the first point for improvement. The second point that requires attention is how to collect the data, or how to arrive at reliable assumptions, about the value of the social status determinant which can serve as input to the model. In the present study, it was assumed that the *social status* consumers derive from owning diesel and gasoline passenger cars will start decreasing in 2030 from 1.00 to 0.95. The social status derived from alternative powertrains will stay constant at 1.00. In an update of the case study, we should expect a faster decrease of social status of gasoline and diesel cars. Moreover, the social status for BEV, PHEV and FCEV can differ from each other. For instance, BEV are perceived as more innovative than PHEV. Moreover, the social status will also decrease when these powertrains become the standard. Considering the relatively low weighing factor of social status in the present case study, the impact on the model output of an incorrect assumption is relatively small. The weighing factors, however, are also a point of consideration.

- **Weighing factors:** “Which model steps of the intention phase are the most decisive?”
  In the operationalization of the weighing factors we experienced difficulty because there was no data available about how (car) consumers weigh the defined financial and non-financial factors. Defining the weighing values was therefore based on an expert assumption and not based on empirical data. To improve the case study results, empirical data on behavioral predictors of (innovative) car buying is required from which the weight of financial versus non-financial factors can be derived. The use of assumptions and its effect on the market share of FCEV was analysed by ECN (Weeda & Tigchelaar, 2012). This was only done for FCEV, because this had the particular interest of the car manufacturer for whom the study was conducted. In the next section (3.5.4) we will elaborate on this.

3.5.4 Uncertainty analysis: Monte Carlo

Figures 16, 17, and 18 show the uncertainty boundaries for each of the three weighing factors with a chosen lower and upper boundary on the market shares of FCEV’s. The uncertainty effect of the weighing factor of *investment costs vs operating costs* on the market share of FCEV is the largest. The error margins due to uncertainty in the other weighing factors are relatively small in terms of impact on the market share of FCEV. Moreover, as shown in Figure 16, the uncertainty boundaries around the market shares are relatively large.

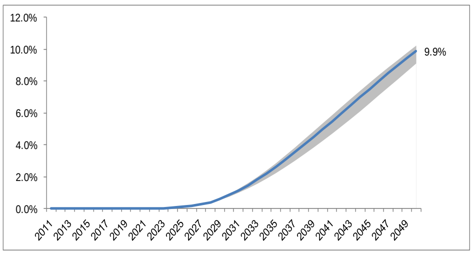

Figure 16**.** The uncertainty effect on market share of FCEV (y-axis) as a result of lower and upper boundary of the weighing factor *non-economic vs. economic*.

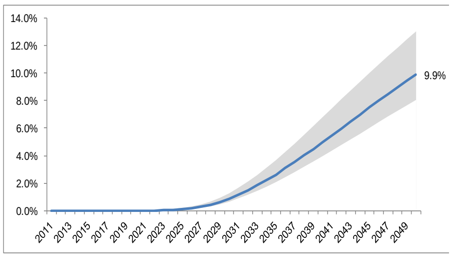

Figure 17. The uncertainty effect on market share of FCEV (y-axis) as a result of lower and upper boundary of the weighing factor *investment vs. operating costs*.

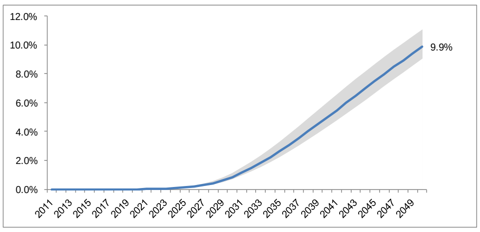

Figure 18. The uncertainty effect on market share of FCEV (y-axis) as a result of lower and upper boundary of the weighing factor *social comparison vs. social status*.

3.5.5 Conclusion

Consumer behavior is intrinsically difficult to quantify and measure. This is visible in the operationalization of the model steps in this case study. Particularly those steps focusing on non-observable determinants of behavior were difficult to operationalize by lack of (suitable) empirical data. This has a major impact since the model output is mainly sensitive to the indicators in the intention phase, which are considered most influential in the decision process. Getting the weighing factors right is therefore of major importance, since these are the most decisive in the actual decision. While the need for empirical data to improve the model is so obvious, and the data requirement for CODEC is very specific, we recommend development of a standardized survey to collect data in such a way that the data can serve as model input.

4 Application 2: home owners' uptake of solar photovoltaics

4.1 Introduction

In this chapter, we will explain how the general model structure was applied to the solar photovoltaics (PV) market in order to:
1. *provide a quantified estimation of the growth path of solar PV in the private housing sector for single family dwellings. The model provides the yearly growth of the installed capacity, as well as the cumulative installed capacity in the period 2006-2045.*
2. *understand how different types of policy interventions influence the decision-making process of home owners for solar panels.*

As a result of a large price decrease of solar panels and the Dutch net-metering policy (the so-called "Salderingsregeling"), the installed capacity of small-scale solar PV systems has increased strongly in the Netherlands (PWC, 2016). The net metering policy facilitates the feed-in of PV produced electricity in the electricity system and using that amount of electricity at any other moment. In other words, the electricity net serves as a storage system. Financially, the value of the produced electricity is equal to the consumer electricity tariff regardless whether the electricity is directly consumed or fed into the electricity grid and consumed at another moment.

Considering the current policy scheme and the large price decrease of solar panels in combination with the rising electricity prices (including taxes), the payback time of PV-systems will decrease significantly from 7 years in 2015 towards 4 years in 2020. Based on this this significant decrease in payback time, the Ministry of Economy Affairs has asked ECN Energy Transition Studies to evaluate different policy options as a basis for redesigning the net metering policy scheme. An important condition for this new policy scheme is a stable growth of the newly installed PV systems (ECN, 2017b). The growth of newly installed PV systems for households owning a single family dwelling was modelled by the CODEC model.

After describing the application of the general CODEC model to the case study of solar PV in the private housing sector (4.2), we describe model generated output of the expected solar PV capacity in the private housing market under various policy alternatives (4.3). Subsequently, we provide conclusions (0). Finally, we discuss how suitable the CODEC model has been to provide a valid and reliable graph of the expected solar PV installed capacity and whether the model provides insight in the effect of various policy interventions (4.5). For a more detailed description of the policy options studied, we refer to the publicly available report of the study (ECN, 2017b).

4.2 Applying the general CODEC model to the PV case study

In order to apply the general CODEC model structure to this case study, several questions had to be answered:
- Which decision do we want to simulate with the model? (4.2.1).
- What are the choice options and related consumer segments? (4.2.2).

- Do we have to adapt the general model structure for the case study? (4.2.3).
- How do we operationalize the CODEC model steps? (4.2.4).
- Do we need to make an uncertainty analysis to express uncertainties in the model results? (4.2.5)

4.2.1 Defining the decision in the PV case study

Since the focus of the study was on PV adoption under different policy regimes rather than on PV adoption in competition with other measures that consumers can opt for to improve household energy performance (such as wall, floor or roof insulation, an efficient central heating unit or double glass windows), the study focused on the decision to “install PV”, the only alternative choice option being “not install PV”.

4.2.2 Choice options and related consumer segments in the PV case study

As described in 2.2.1, the set of behavioral alternatives or choice options has to be exhaustive and the number of options should be limited to a workable number. All choice options that the target group has, should be included in the model.

To make a reliable estimate of installed capacity, electricity production and consumption, we first identified the most influential characteristics of dwellings in this respect: type of building (privately owned, own roof) x roof orientation (South or East/West) x size of property (big or small) x PV installed (yes/no) (ECN, 2017b).

- Type of building. Firstly, we distinguished between single family dwelling and multi-storey dwellings. Secondly, we distinguished between private property and rental. The model focuses on single family, privately owned dwellings, with a privately owned and maintained roof. The reason for this is twofold. Firstly, private properties currently constitute the biggest market for small-scale PV systems. Secondly, for privately owned roofs, a single-actor decision making process can be assumed, whereas this is not the case for jointly owned and maintained roofs. Another restriction is that the model focuses on existing dwellings. The growth curve of PV capacity does not include EPC[8]-dwellings (Energy Performance Coefficient).
- Roof orientation. The orientation of the roof is strongly related to the amount of electricity produced. We focus on South or East/West oriented roofs, because a house with a North oriented roof has no sufficient PV yield and therefore lacks an attractive business case (in theory, owners of such a roof can still opt for PV, but this is deemed unlikely).
- Property size. Big and small houses (larger or smaller than 150m^2) vary in terms of electricity usage and roof space, resulting in the installation of either a small or large PV system. We considered the following aspects:

[8] Newly built houses need to comply with the energy performance rules defined by the Dutch government (RVO, 2017).

  - *A system installed on a large house with a south oriented roof produces roughly 90% of the household electricity consumption.*
  - *The size of the PV systems installed on large east/west oriented roofs are equal to houses with large south oriented roofs.*
  - *Small houses will have a system installed half the size of that of big houses.*
- *The system sizes will differ in practice, but the chosen system sizes were confirmed in consultation with the PV-sector.*
- *Current and alternative option(s). We identified two different options: PV or no PV installed. We do not distinguish between types of PV systems, since (at present) solar PV-systems are practically homogeneous products.*

Incorporating these characteristics of dwellings resulted in eight consumer segments which are shown in Table 9.

Table 9. Segments for PV based on building type and size, roof orientation, and PV or no PV.

Type of building[1]	Living area (1) (m^2)	System size (2) (kWp)	Consumption (1) (kWh/jaar)*	Production (3) (kWh/jaar)	Direct consumption (2) (%)
1. Single family - private property – big – south – **PV**	< 150	4,5	4400	4301	25%
2. Single family - private property – big – south – **NO PV**	< 150	-	4400	-	-
3. Single family - private property – big – east /west – **PV**	> 149	4,5	4400	3446	35%
4. Single family - private property – big – east /west – **NO PV**	> 149	-	4400	-	-
5. Single family - private property – small – south – **PV**	< 150	2,25	3700	2151	30%
6. Single family - private property – small – south – **NO PV**	< 150	-	3700	-	-
7. Single family - private property – small - east /west - **PV**	> 149	2,25	3700	1723	40%
8. Single family - private property – small - east /west - **NO PV**	> 149	-	3700	-	-

(1) BZK (2015), CBS (2016).

(2) ECN expert judgement & market consultations (ECN, 2017b).

(3) Solar irradiation numbers, KNMI (2016). South orientation: 956 kWh/kWp; E/W: 766 kWh/kWp.

* In the net metering policy report (ECN, 2017b) we used for small and big houses respectively an electricity consumption of 3300 kWh and 4400 kWh. In a model improvement, based on BZK (2015), we adapted these values to respectively 3700 kWh and 4500 kWh.

The total stock of households and the distribution of this stock over the different segments is based is on statistical data:

- *The model has an input of the housing stock and the installed capacity of solar PV for the period 1980 – 2005 (BZK, 2015; CBS, 2016; ECN, 2017b; CBS, 2017c; PWC, 2016, Stichting Z.O.N., 2016).*
- *The distribution of the housing stock – type of house, roof orientation and size of house – is based on a sample measurement in 2012 (BZK, 2015).*

We assumed that the distribution (amount of dwellings) over the different segments stays equal. From the year 2016, we expected that all newly build single family dwellings will be automatically equipped with solar PV (the EPC-dwellings). We included an increase of the number of single family dwelling only until 2016. These are valid assumptions since the impact of external determinants (i.e., housing demolitions), which influence the distribution of the current housing stock of houses with and without PV, will be probably low and the scope of the model is simply on the current housing stock.

4.2.3 Deviation from the CODEC model structure

The general model structure, consisting of fourteen model steps, was explained in section 2.3. The application of the CODEC model to home owners' uptake of solar PV did not require adaptation of the model structure, however the operationalization of several model steps deviated from how the operationalization was intended in the design of the CODEC model (see 4.2.4). The main adaptation is that the principle of mental accounting has not been applied in the case study of PV, for reasons we will explain below.

4.2.4 Operationalization of CODEC for the PV case study

The basic CODEC model structure (see 2.3, Figure 8) was operationalized for the case study of PV. In the operationalization of the model steps, there was some deviation from the general model.

Table 10 provides an overview of how the model steps were operationalised in the case study of PV. The table also shows the actual model input, which literature sources were used for the operationalization, and finally, a judgment of the data quality of these literature sources.

Table 10. Overview of the operationalization of the CODEC for the case study PV for the three phases Attention, Enablers and Intention.

Model steps	Operationalization	Model input	Literature sources	Data quality[1]
		Attention		
• *Is there a decision moment?*	Number of households that own a single family dwelling and are considering to install solar PV.	Of the households without solar panels, 23% intends to install PV within three years. For households with solar PV, the lifetime of 20 years defines whether there is a decision moment.	(GFK, 2016)	☺
• *Has the consumer made the decision before?*	The model considers households that have already installed solar PV as well as households that consider to install solar PV for the first time.	For households with solar PV, the lifetime of 20 years defines whether there is a decision moment. This group of households can decide whether or not to replace their PV system	Basic assumption	☺
• *Would repeated purchase resolve the need?*	Percentage of households with solar PV that is (still) satisfied and will replace their solar PV system when the time comes.	Stock of households with PV: 92% reports they will replace their PV system when time comes, while 8% reports either they will not replace current system or 'don't know'.	(ECN, 2017b)	☺
• *Is the current option still available?*	If consumers replace their current solar panels, we assume a replacement with an equivalent product that is available on the market.	100% availability current option.	Basic assumption	☺
		Enablers		

Model steps	Operationalization	Model input	Literature sources	Data quality[1]
5. *Is it practically feasible to use the option?*	The practical feasibility implies for this case the practical feasibility of roofs of single family dwellings. Perceived feasibility was not operationalized.	82% of the rooftops of single family homes in the municipality Groningen are suitable for solar PV. We assumed that this percentage is representative for the Netherlands.	(Mapgear, 2016)	☺
6. *Is the initial investment feasible and acceptable?*	The purchase of solar PV may be obstructed by two phases: (1) not having sufficient savings and (2) the percentage of savings that consumers are willing to invest in energy performance measures.	The distribution of bank savings of homeowners, the investment costs of solar panels, and households' willingness to invest.	(CBS, 2017a), (ECN, 2017b p.38)	☺
7. *Sufficient knowledge to assess if option would fit the need?*	Operationalized as having sufficient perceived knowledge about the product solar panels. Factual knowledge was not operationalized.	In a survey conducted in 2017, 23% of the home owners report that insufficient knowledge is currently a barrier. Based on this we assumed a linear growth pattern for the number of people who perceive to have sufficient knowledge, from 50% in 2005 to 77% in 2017 and 95% in 2030.	(ECN, 2017a)	☺/☹
8. *Is the certainty of the policy (or commercial arrangements) for stimulating the option acceptable?*	For the various policy options, the policy certainty is different. A higher uncertainty about whether the investment will pay itself back before the consumer moves to another house will result in a higher barrier.	For the various policy alternatives, ECN assessed the percentages representing the barrier of policy uncertainty. In the study of net-metering, ECN (2017b, table 2&3) presents the barrier for households to whom the policy uncertainty is a barrier to invest in solar PV considering a low, medium or high policy uncertainty.	(ECN, 2017b)	☺/☹
9. *Is the option available on the market?*	The options in the case study of solar PV are twofold: no PV and PV. With a wide variety of solar PV sellers and no scarcity of solar panel materials, we assume that there will no barrier in terms of market availability.	100% market availability of solar panels.	Basic assumption	☺
Intention				

Model steps	Operationalization	Model input	Literature sources	Data quality[1]
10. *How does the option score on investment costs?* (financial) 11. *How does the option score on operating costs?* (financial)	Operationalised as the combination of investment and operating costs: the score on the payback time. Investment and operating costs are in the same mental budget for households. If the expected payback time is longer than the remaining time that households expect to keep living in a house, households will not invest.	These determinants do not include mental accounting for the investment and operating costs, but the payback time as financial indicator. Payback time was calculated based on solar PV system investment costs and the development of electricity prices. 50% of the house owners report that a payback time of 6,6 years is acceptable.	(ECN, 2017b p.38), (NEV, 2016), (ECN, 2017a)	☺
12. *How does the option score on personal benefits? (non-financial)*	Operationalized as having the personal benefit to contribute to a sustainable society and being independent of fossil fuels.	Houses with solar panels get a score 1.0 whereas houses with the lack of solar panels get a score of 0.0.	Survey data (ECN, 2017a)	☺
13. *How does the option score on social comparison? (non-financial)*	The larger the market share of households with solar PV, the higher the score on social comparison until the effect of saturation comes into play.	In respectively 2016 and 2020 we assumed that roughly 12% and almost 60% of the households have the opportunity to compare themselves with neighbours.	Rogers (2003), expert assumption	☺/☹
14. *How does the option score on social status? (non-financial)*	The larger the market share of households with solar PV, the lower the score on social status derived from having solar PV.	In 2016 social status is relevant to roughly half of the households with PV, whereas in 2020 this effect is roughly zero. Houses without PV do not feel a social status at all.	Rogers (2003), expert assumption	☺/☹
Weighing (model steps Intention)				
Weighing	Factors to weigh the relative importance of different determinants of **intention**: financial and non-financial determinants.	Two-thirds of the households decide whether or not to invest in solar PV based on financial aspects such as the payback time. One-third of the households report a high importance for non-financial determinants (sustainability and independency) and social determinants (social status or social comparison).	Expert assumption using (ECN, 2017a)	☹

[1] *A happy face means that the model input is underpinned by a valid literature source or a basic valid assumption (this is an assumption that follows from logic or from choices made in regarding e.g. the scope), a sad face means that we had to make assumptions by lack of appropriate empirical data which should be substantiated in further research.*

Below, we will elaborate on the information shown in Table 10. The numbers between brackets in the text correspond to the model step numbers.

Attention
This phase starts with a *decision moment (1)* for households whether to install or *replace (2)* solar panels. The reason why this decision moment arises – the discrepancy between the current situation and the desired situation – and the resulting need recognition, is different for PV owners and for first-time PV buyers. First-time orientation on PV might be driven by a felt need to lower the energy bill, to lower their use of fossil fuels, or to invest their money effectively. Households that have already solar PV and are considering a replacement, will base their decision mainly on their PV satisfaction level. The percentage of consumers who will buy PV for the first time and who will replace their current system is based on statistics of the installed capacity of solar PV (NEV, 2016), self-reported intention to invest in PV (GFK, 2016), and self-reported intention to replace the PV system in the future (ECN, 2017a). For households that do not have solar panels, 23% of this group intends to install PV within three years (GFK, 2016).

Based on whether the system still *fulfilled their need (3)*, home owners will proceed to direct replacement or they will reconsider. In a survey conducted by ECN (2017a), 92% of the home owners with a PV system reported that that they will replace their PV system at the end of its lifespan.

Solar panels are relatively homogenous products because the differentiation in features, benefits or quality are limited and sellers have to compete based on price and availability. The ‘standard sold PV panels’ will be improved over years due to technological developments, but in a specific year solar panels are perceived as relatively a homogeneous product. If consumers replace their current solar panel, we assume replacement with an equivalent product is possible. In other words, we assume that *‘the current option is still available’ (4)*.

Enablers
Houses with a thatched roof or a fragile structure that is not strong enough to sustain the weight of solar panels, are practically infeasible for the installation of solar panels. This barrier is calculated based on *practical feasibility (5)*. According to “de Zonnekaart” designed by Mapgear (2016), 82% of the rooftops of single family homes in the municipality Groningen are suitable for solar PV. We assumed that percentage is representative for the Netherlands. Shadow as result of trees or obstacles was not included in the analysis. Perceived feasibility was not operationalized.

The purchase of solar PV in terms of *investment acceptability (6)* may be obstructed by two phases: (a) having no sufficient savings and (b) the percentage of savings that consumers are willing to invest in energy performance measures. We assumed that an average household is willing to invest 35% of their savings in solar panels. We assume that this percentage is independent of the year of investment.

Not having *sufficient knowledge* (7) about solar PV may slow down or even obstruct the purchase of solar PV. Households may perceive insufficient knowledge about the financial aspects of installing solar PV, technical performances of the system, and about finding a reliable installer. In a survey conducted by ECN (2017a), 23% of the home owners reported that insufficient knowledge is currently a barrier for them. Based on this we assumed a linear growth pattern for the percentage of people that will (perceive to) have sufficient knowledge, from 50% in 2005 to 77% in 2017 and 95% in 2030.

In general, if consumers feel uncertain about the benefits of their purchase, the willingness to invest will decrease. For solar PV, the business case for households depends on the so called “Salderingsregeling” policy scheme. Households perceive a higher barrier when there is *uncertainty about the policy scheme (8)*, because the estimate of their benefits is unsolid. We defined *uncertainty* in this case as the uncertainty in payback time (in relation to the remaining time the household expects to keep living in their house) caused by:

- transition from the current towards the new policy.
- future policy changes for small-scale solar PV stimulation.
- fluctuations in the electricity commodity prices (including energy tax and storage renewable energy tax) and the extent to which the policy scheme is capable of dealing with this fluctuation.

For the various policy options, the policy certainty is different. If the uncertainty is higher, it is assumed that less households will invest (ECN, 2017b). More specifically, if the expected payback time is longer than the remaining time that households expect to keep living in a house, it is assumed that households will not invest.

Regarding *step (9) – is the option available on the market* – in this study, the only choice options are to install PV or not to install PV. It is assumed that these choice options are always possible.

Intention

As explained in 2.3.3, intention to buy a particular option is the result of weighing five determinants in the basic CODEC structure: investment costs, operating costs, personal benefits, social comparison, and social status. In this version of the model, however, *investment costs (10)* and *operating costs (11)* were combined into one single score of the option on payback time. Based on a market consultation and the study of PWC (2016), *the payback time* (*10 & 11*) is the main financial indicator to define the financial attractiveness of installing solar PV.

In this respect this case study deviates from the general model structure, in which the theory of mental accounting is applied to account for the fact that people treat investment and operating costs differently. The case of PV, however, is seen as an exception. In comparison to other possible energy conservation measures, the business case for PV is relatively straightforward to calculate for households. Households can calculate how many years it will take to earn back their investment through a lower annual energy bill, assuming of course that the same policy regime still applies (see step 8). Therefore, in this case, both the investment and operating costs will be in the same mental budget. Furthermore, the theory of loss aversion is not applicable since consumers only have two options in this case study: To invest, or not to invest, in PV.

The score on the payback time was calculated based on:

- PV system investment costs (ECN, 2017b p.38)
- Development of electricity prices (NEV, 2016).

The year of payback is when the investment costs are break-even with the yearly lower electricity bill. The interest rate is set as 0%. Whether households accept a specific payback time is based on survey data in which 50% of the households accept a payback time of 6,6 years (ECN, 2017a).

Besides being able to reduce the energy bill, households also experience *personal benefits (12)*. Households are willing to invest in solar PV to be independent from energy producers and to contribute to a better environment (GFK, 2016; ECN 2017a). Households with a ‘green heart’ will feel more motivated to install solar panels. Consumers who want to be independent of fossil energy providers, have an aversion to gas and oil of the Middle East or Russia, or simply prefer to be self-supporting in terms of energy, also do not only focus on the financial aspects in their decision-making process.

Households experience *social comparison (13)* when considering to install solar PV. If a household has a solar PV system, a neighbouring household may sooner feel a need for one too. If households see that solar PV has its practical applicability, the influence of perceived barriers to install solar PV will also decline. In respectively 2016 and 2020 we assume that roughly 12% and almost 60% of the households have the opportunity to compare themselves with neighbours.

In contrast to social comparison, the social status of PV to households will decrease earlier and quicker than social comparison. As a result, the mean and standard deviation have lower values. In 2015 roughly half of the households with PV will derive social status from having PV, whereas in 2020 this effect is roughly zero. Households without PV do not feel a social status at all.

Weighing

To combine the scores of the model steps in the intention phase, each of the scores on the five intention determinants is weighed with a factor. The total of the weighing sums up to 100%. Economic determinants form the largest part of the considerations. The weighing of the four indicators is based on survey outcomes (ECN, 2017a) and visualized in Figure 19.

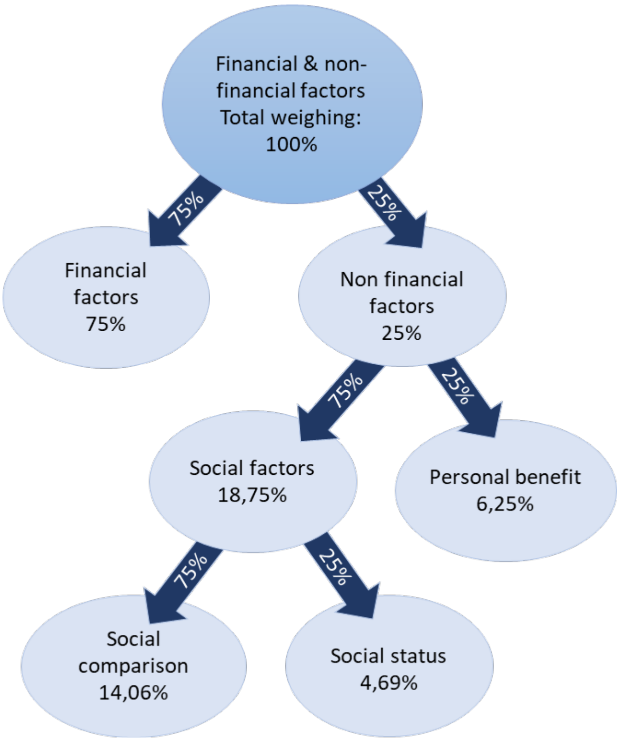

Figure 19. The values of the weighing factors used in the CODEC model applied to the PV case study.

4.2.5 Uncertainty analyses: Monte Carlo

For case study of EV (see Chapter 3) we conducted a Monte-Carlo uncertainty analysis to be able to discuss the robustness of the estimated weighing factors. For the solar PV study this was out of scope. However, we did an uncertainty analysis on the assumed values concerning policy uncertainty that was addressed in model step 8 by defining uncertainty boundaries (ECN, 2017b, p53-57). Furthermore, when inserting data for the operationalised determinants of the CODEC model for solar PV it was sometimes necessary to make an assumption because of a lack of empirical data. The robustness of these assumptions, i.e., the effect on the model output if the value of a particular determinant is 10% larger of smaller, will be addressed in the discussion Chapter.

4.3 Model output and PV case study results

The previous paragraphs focused on the application of the general CODEC model to the case study of solar PV. The intended output of the CODEC model applied to the PV case study was as follows (ECN, 2017b):

- The cumulative installed capacity [MW] of solar PV for home owners (Figure 20).
- The yearly solar PV production by home owners in [TWh] or [PJ] (Figure 21).
- The amount of PV systems yearly installed, including replacements and new systems (Figure 22).

The growth pattern of continuing the present net metering policy (policy options A and A1) shows the highest installed capacity [MW] (Figure 20), the highest yearly production of home owner solar energy [TWh] (Figure 21), and the highest number of installed systems per year (Figure 22). This is a result of the still decreasing payback time of solar PV systems. When comparing the other policy options (B, C and D), the investment subsidy (policy option D) illustrates the highest growth path because the investment barrier is lowered. According to the principle of delay discounting, it is more effective to give people a direct reduction of investment costs (D) than to give a similar reduction with a delay, even if payback times in the end are similar - or even if they are eventually higher! (hyperbolic discounting). Thus the preference of option D over options B and C can be explained with this concept. Option D is less attractive than options that more closely resemble the present policy situation, which is explained by the fact that consumers are change-averse.

Based on these case study results we can draw conclusions about the applicability of the CODEC model to simulate the decision process of consumers and to obtain projections for PV under various policy scenarios.

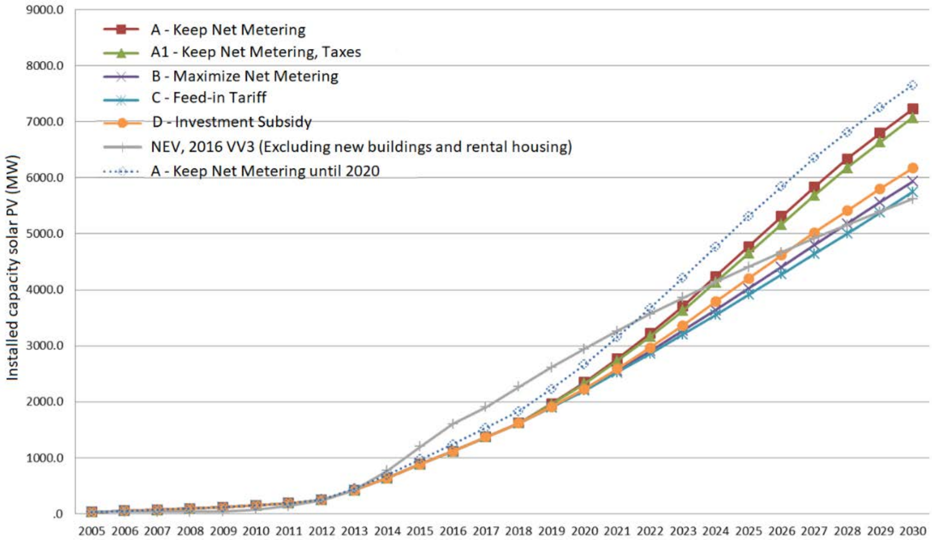

Figure 20. The installed capacity solar PV for the home owners sector (ECN, 2017b), until 2030 since data are available until 2030.

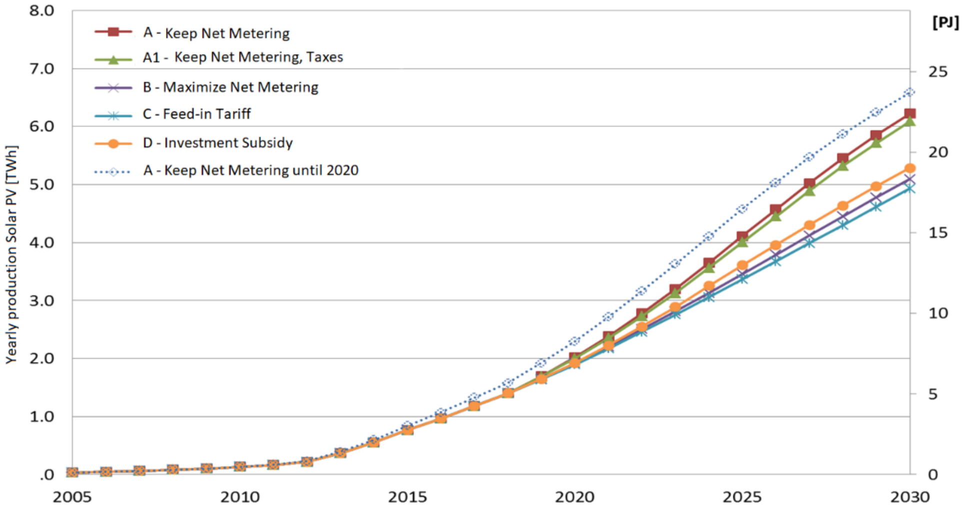

Figure 21. The yearly production of solar PV for the home owners sector (ECN, 2017b), until 2030 since data are available until 2030.

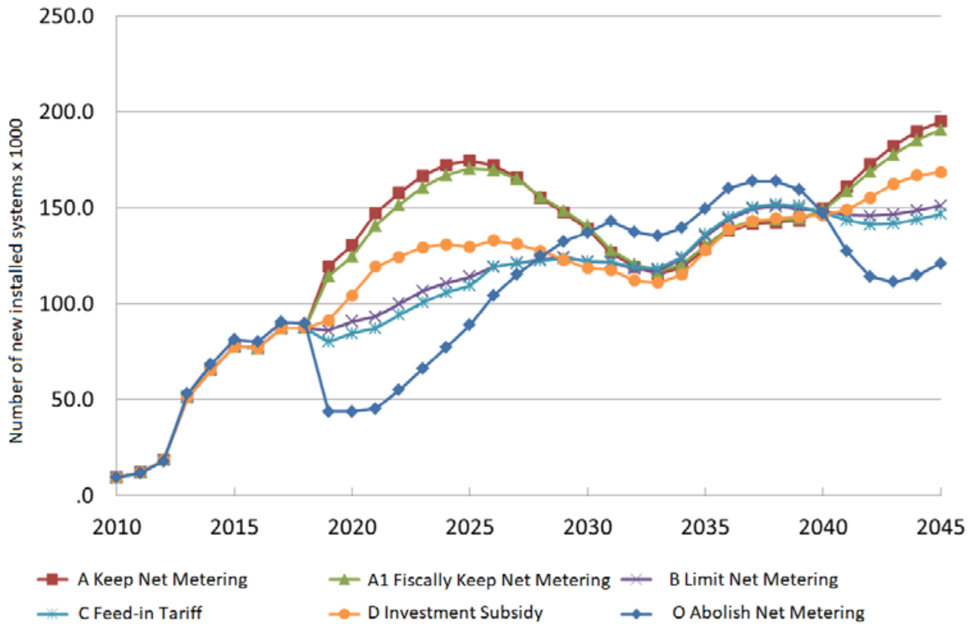

Figure 22. The number of solar PV installed in a specific year until 2045 (instead of 2030), in order to be able show the effects of the replacement cycle of 15 year (ECN, 2017b).

4.4 Conclusion on the application of the model

The CODEC model has been applied to the adoption of solar PV by households owning a single family dwelling. Based on the application we can draw the following conclusions:

- The model was able to simulate how households evaluate the alternative options of a roof with a solar-PV system and without.
- The model gave us projections of the cumulative installed capacity [MW], electricity production [TWh], and number of yearly installed solar PV systems. Starting in 2006, ending in 2045, the CODEC model applied to the PV case study starts with its simulation and provides the output as shown in Figure 20. For 2005-2015, the model outcomes were calibrated on the practical realisation of PV systems on private dwellings according to the background data for the Dutch National Energy Outlook (ECN, et al., 2016).
- Based on the Diffusion of innovations theory (Rogers, 2003), we expected an S-curve for the installed capacity and electricity production when 100% market share is reached. As shown in Figure 20 and Figure 21, the graphs of the cumulative installed capacities and solar PV electricity production are not characterized by a S-curve. This makes sense since the graphs do not yet reach 100%.
- The model facilitated to put a focus on and to analyse the decision making process of consumers. More specifically, the relative influence of the model steps on the actual installed capacities can be assessed. For instance, using the model, we can demonstrate the impact of lowering the investment barrier on installed PV capacity.
- The model was able to demonstrate how policy interventions may impact each step in the consumer decision making process and how this affects the adoption rate. The policy options had an impact on the payback-times,

the investment barrier, and policy uncertainties. On the latter, we conducted an uncertainty analysis on which we will elaborate on in the next paragraph.

Applying the model results in realistic projections of the uptake of PV so far, and provides – in comparison to economic optimization models – additional quantitative insights to industries and policy makers about possible measures to improve the diffusion of innovations. Nevertheless, consumer perceptions and behavior are intrinsically difficult to quantify and we needed to make assumptions and include uncertainty boundaries. In the next section we will reflect on the PV case study results, the CODEC model structure, modelling simplifications, operationalization issues and uncertainty of the assumptions made.

4.5 Discussion

In this section, we will address the model output and PV case study results (4.5.1), the general model structure (4.5.2), and operationalization issues and data availability (4.5.3).

4.5.1 Model output and PV case study results

There are no discussion points regarding the model output and PV case study results. As concluded earlier, the model output matches with the statistical numbers, demonstrating the model's practical applicability.

4.5.2 General model structure

Apart from the recommendation to apply different weighing factors for different adopter groups, which has already been mentioned in 3.5.2, the PV study did not give rise to any more suggestions for fundamental changes in general model structure.

4.5.3 Operationalization issues and data availability

In the operationalization of the CODEC model we depend on the data quality of available literature sources. For some of the operationalised determinants, there was a lack of empirical data and therefore assumptions had to be made. Furthermore, some assumptions had to be made to reduce complexity of the model. Below we describe the assumptions made, and the robustness of these assumptions.

Below we discuss the assumptions made due to lack of data and how they may have affected the model output.

Attention phase
In the attention phase we made assumptions for the first and the fifth model step.

- ***Step 1*** *"Is there a decision moment?"*
  GFK (2016) reports the percentage of home owners that is considering to install solar PV within the next three years. Actually, we needed data about the percentage of home owners that is considering to install solar PV within the

next one year. However, better data was not available and for this reason we used GFK's reported data. As a result, the model output could be a too optimistic estimation of the installed capacity. After, all, intention to install solar PV within one year is probably lower than intention to install solar PV within three years. It is recommended that data are obtained, for example through a survey, about intention to install solar PV within one year.

The possibility of early replacement of a PV-system because a household prefers a newer PV-system with a significant higher yield is not included in the model. Nevertheless, this effect is probably in practice negligible, unless at some point people are effectively motivated to do early replacement by advertising and marketing.

- ***Step 5*** *"Is it practically feasible to use the option**?"***
  Households may perceive their roof as unsuitable for PV while it actually is (ECN, 2017a). This perception determinant was not included in the PV case study. However, the more people who will have PV installed on their roof, the higher the level of comparison and this will probably increase knowledge and decrease incorrect perceptions of households. We expect, therefore, that not including this aspect does not significantly affects the model output.

  We assumed a constant percentage of factually suitable roofs. At a given moment, almost all suitable houses will be equipped with solar panels and as a result the share of households with a suitable roof and without solar-PV will decrease. This effect will not play a significant role until 2030, although a dynamic percentage for the practical feasibility could be an improvement of the model in general.

Enablers phase
In the enablers phase we made assumptions for the seventh and eighth model step.

- ***Step 7*** *"Sufficient knowledge to assess if option would fit the need?"*
  In this step, only perceived knowledge was operationalized, not factual knowledge. When data on perceived knowledge are available, preferably these are used. Data on factual knowledge are a good choice if data on perceived knowledge are not available. Only the 2017 data point was based on empirical data (ECN, 2017a). We assumed a linear growth pattern for sufficient knowledge, from 50% in 2005 to 77% in 2017 and 95% in 2030. If we still assume a linear growth pattern but alter the level of knowledge in 2030 to 85%, the installed capacity of solar-PV in 2030 decreases with approximately 3%. Consequently, the assumptions made for this model step have an insignificant effect on the model output and are therefore acceptable. Despite the relatively small effect, literature or data on knowledge development of technologies could be used to improve the operationalization of this step.

- ***Step 8*** *"Is the certainty of the policy (or commercial arrangements) for stimulating the option acceptable?"*
  The degree of policy uncertainty was quantified through expert assumptions in the model. This was a valid method, since we found a relatively small impact of altering the assumptions on policy uncertainty on the installed solar PV capacity (ECN, 2017b, p53-57, p30 Figure 16). The use of assumptions for this model step hardly had any effect on the model output.

Intention phase and weighing

In the intention phase we made assumptions in three model steps. Besides that, the data input for the weighing can be improved.

- ***Step 10 & 11*** *"How does the option score on investment and operating costs?"*
  We did not apply loss aversion as part of the Mental Accounting theory as described in the general CODEC model, because there were only two options to choose between: Install PV, or install no PV. For consumers, the payback time for PV on their roof is relatively easy to calculate. Therefore, they are unlikely to work with separate mental budgets for investment costs and operating costs in this particular case study. We consider working with payback time an acceptable way of operationalization.

- ***Step 13*** *"How does the option score on social comparison?"*
  Due to a lack of empirical data, we assumed that in respectively 2016 and 2020 roughly 12% and almost 60% of the households have the opportunity to compare themselves with neighbours. Assuming a higher value of social comparison, for 2016 and 2020 28% and 86% respectively, the installed capacity of solar PV in 2020 is then approximately 6% larger. Since this is a significant difference, it is recommended to collect data to underpin this model step rather than making assumptions.

- ***Step 14*** – *"How does the option score on social status?"*
  By lack of empirical data, we assumed that in 2016 roughly half of the households with PV will derive social status from this, whereas in 2020 this effect is roughly zero. Due to the relatively low weighing factor for *social status*, altering the score on social status does not have a large impact on the eventual model output. Thus, updating this model input, in the case the weighing factor for social status stays relatively low, will be not be a priority. However, as stated, the weighing factors themselves also need reconsideration.

- *Weighing factors – Which model steps of the intention phase are the most decisive?*
  The values of the weighing factors are based on an expert assumption using survey data (ECN, 2017a). However, the survey questions did not entirely have the suitable format to serve as a solid basis for these assumptions. What we actually need from respondents is an answer to the question: If you were to divide 100 points over these five determinants, how would you divide them? This would give us direct, self-reported, weighing factors. However, we know that people are unable to provide a reliable answer to the question "what motivates you" when asked directly – motivational determinants such as attitude, self-efficacy and social influence are so-called latent determinants (variables) which cannot be measured directly. Existing measurement instruments for these latent determinants are, however, not well suited for use with CODEC. It is therefore recommended to develop a standard measurement instrument, containing manifest determinants to measure latent determinants such that CODEC can take the data as input.

To conclude, after working on the PV case study, we arrive at the same main conclusion as for the EV case study. We have found, again, that particularly those steps focusing on non-observable determinants of behavior were difficult to operationalize. This has a major impact since the model output is mainly sensitive to the indicators in the intention phase. These indicators are considered most influential in the decision process. Getting the weighing factors right is therefore of major importance, since these are the most decisive in the actual decision. While the need for empirical data to improve the model is so obvious, and the data requirement for CODEC is very specific, we recommend development of a standardized survey to collect data in such a way that the data can serve as model input.

5 Discussion

CODEC (COnsumer DEcisions Comprehended) has been developed because of an observed need of both market players and policy makers to obtain a better understanding of consumer decisions regarding the adoption of sustainable energy technologies. CODEC has been developed and tested in the context of two cases: (1) Electric Vehicle adoption by car buyers, and (2) Solar Photovoltaics (PV) adoption by home owners. Although results have been documented and presented in various outlets, there was no document that fully describes the basic principles and method of CODEC, its applications this far, and what the model adds to the existing body of scientific insights on modelling consumer behavior. This paper aimed to fill this gap, and will hopefully serve to share and discuss CODEC with the community of practice (policy makers) as well as the community of science (developers of similar models), which will in turn stimulate and improve its further development and application. In this concluding chapter, we will summarize the current advantages and limitations of CODEC, and mention desired directions for future development that we will work on in the years to come.

5.1 Conclusions

CODEC adds human determinants to quantified models and economic determinants to psychological models
CODEC was designed with the primary goal of providing policy makers and market players with insight into the decision making process of consumers, in the context of the adoption of an innovation such as solar PV or an Electric Vehicle. More specifically the aim was to create a quantitative model that incorporates “rational”, as well as more “irrational” processes, hereby deviating from most models, that assume we are all “homo economicus”. It was found that this quantification was indeed possible: the different determinants that were distilled from theory could be quantified. However, not all required data was available while testing the model in the two cases.

CODEC is able to simulate market share
The goal of providing an accurate prediction of market shares was reached by testing accuracy in the case of the adoption of solar PV systems. For 2005-2015, the model outcomes were calibrated on the practical realisation of PV systems on private dwellings according to the background data for the Dutch National Energy Outlook (ECN, et al., 2016). What CODEC adds to the forecasts already provided by the National Energy Outlook is that in CODEC it was possible to compare different forms of providing a specific subsidy.

CODEC provides actionable insights
In addition, the results of the simulations were useful in the sense that the model was able to evaluate competitive alternatives and could explain why a particular option has a relatively lower market share than another option. Providing these reasons is important input to enhance policies or market strategy.

Lack of data causes the making of assumptions
Since in the two cases not all data regarding the fourteen questions was available, assumptions were made to fill some parts of the model. This means that several

determinants and weighing factors were more uncertain than others. The uncertainty analysis showed that the range of possible outcomes was quite broad. This means that the forecasts of the model has an uncertainty range, this range could be diminished by better data.

5.2 Improvements to current model version

Not all psychological or behavioral theories are easy to model quantitatively. In addition, incorporating too many elements could make the model overly complex. However, there are some improvements, based on the challenges we faced while working with CODEC, that we think would benefit the model.

5.2.1 Check the selection of determinants

The fourteen determinants (questions) that the model consists of are selected based on theories regarding decision making. It has not yet been tested if these determinants explain the market share sufficiently, or if the model would benefit from adding more determinants. In addition, in the current version of the model determinants of the model are independent. It has not yet been tested whether some determinants are dependent, meaning that one or more should be removed, or corrected for.

5.2.2 Develop a guidebook and standard survey to provide input for the model

In the described case studies, data to estimate the impact of some determinants or weighing factors was either absent or not entirely suitable. It is definitely possible to quantify these determinants, but it takes ample time and expertise to do so. Developing a standardized set of survey questions for these determinants would greatly improve case studies performed with CODEC. This is particularly important to improve the weighing factors in the intention phase, to which the model output is sensitive.

To use data on determinants of the target group’s behavior as input to CODEC, it has to be quantitative, and for some steps the data have to be collected in a slightly different format than theory would prescribe. This is a topic for further investigation and discussion. To conduct the case studies, we now had to resort to expert judgment to convert qualitative data, ideas or theories into input for the model steps, which is not a preferred method. To overcome these problems a guidebook and standard survey should be developed to help the user gather data which is (the most) suitable for the model.

5.2.3 Include more differences between adopter categories

In Chapter 2 we described that there individuals can be rated according to the manner in which they handle or are susceptible to innovations (Rogers, 2003). Based on this theory, in the current version of the model the scores on social status and social comparison have an equal weight for the entire research population in CODEC. In future development of CODEC, we would like to further develop the characteristics of the five adopter categories as well as the implications of these characteristics for (policy) interventions to help overcome the so called “chasm” which is described as the difficult step from early adopters to early majority (Rogers, 2003). We expect that more detailed knowledge of the 5 adopter segments will lead to better understanding of why ‘tipping points’ towards full scale adoption are reached for one innovation, but not for another, and what can thus be done to cross the chasm.

5.2.4 Test whether the model can deal with (policy) interventions and combinations thereof

Up to now we have only done one comparison of policy options and their effects on consumer choices (PV case in Chapter 4). In future applications of CODEC, we seek to (1) not only compare policy options, but also include a ‘no policy’ comparison scenario; (2) compare packages of different types of interventions (e.g. subsidy + information campaign), also extending to marketing (e.g. advertisements for new products, and attractive commercial arrangements to obtain them). The central question is: What is the (combined) impact of each of these interventions on the consumer decision process, and how can this impact be determined?

5.2.5 Explore the possibilities for extension of CODEC to other behavior types

Apply COCED to teams or organisations as decision makers
Up to now, CODEC has been applied to innovation uptake by consumers. It would be interesting to explore its applicability to innovation uptake by actors in professional environments. A main difference between decision making in households and decision making in professional environments is the involvement of multiple actors in the process of decision making. Decisions in professional environments, except for small enterprises, typically involves a team consisting of up to X persons, each with their own background and perspective (Larrick, 2016). The question is, does this matter for the decision-making process at large, or do there the same dynamics apply as to consumer decision-making?

Organizational decision making is also thought to be more ‘rational’ than consumer decision-making, presumably making economic models better applicable to these settings. Studies have shown, however, that rationality in organizational decision making is just as conditional as in households. Amongst others, it depends on the variety in information sources consulted and the weight each of these information sources is given in the decision. A decision taken based on the information of two people is far more rational than a decision taken based on the information of just one person, provided each person brings a different perspective to the table. The decision can be improved even further by bringing more perspectives to the table, provided that each is also given room to influence the decision-making process.

In sum, there appear to be no fundamental differences between organizations and households, and hence no theoretical reason why CODEC should not be applicable to both settings.

Apply CODEC to other types of behavior: habits and practices
Stated that CODEC can be applied to extended as well as limited problem solving and even habitual behavior. For example, buying light bulbs could be modelled just as easily.

However, it appears that CODEC is presently not applicable to non-material choices that would be interesting to have a better understanding of. What makes people join energy cooperatives? What makes people change their habits into less energy-consuming practices? Many of such behaviors do not (only) involve the purchase of goods, but require rather a whole new pattern of behavior a so called social practice that is gradually learned and extended[9]. How far can we go, with a model such as CODEC, in modelling this kind of societal change, since one of the prerequisites of using CODEC is that it is possible to define a full range of options for a given need.

5.2.6 Explore the inclusion of brands and marketing

As mentioned in Chapter 3, the EV case study, branding and product differentiation are important strategies impacting product preferences. Brands can also introduce innovations, like Tesla has done with a highly advanced BEV and Eneco has done with the smart thermostat (Toon). However, as explained in Chapter 2, CODEC focuses on the innovation (in this case, the powertrain) and not on competition between brands. Neither does the model take into account that innovations may actually “take off” due to the popularity of the brand that introduces them. The main reasons for this choice are (a) to reduce model complexity, and (b) we simply do not know how to model this yet.

For initial stages of innovation adoption, this choice can be justified. When focusing on energy innovations in general, there is initially just one supplier of the innovation, or several suppliers who all offer the same product. At a certain point, however, competition will arise. Initially, suppliers might compete on actual improvements to the innovation. However, the closest the market is to saturation, or the smaller the actual differences between products are, the more important branding and other marketing strategies will be in influencing consumer choices. We have already briefly touched upon this topic in 2.4, but more thinking is required on how to include such insights into CODEC. While incorporating effects of particular policies, marketing and sales strategies is already quite challenging, modelling the rise and maintenance of brand preferences is an even more difficult matter that is determined by an interplay of determinants, some of which have little to do with attractive pricing or actual instrumental advantages of particular products. In saturated markets, the main predictor may simply be the amount of promotion a brand can afford to make for itself to stay “top of mind”.

5.2.7 Explore interdependencies between model determinants

In the present version of the model the determinants are treated as being independent. The question is if that is realistic. For example, CODEC does not distinguish between consumers who enter the orientation phase because they are dissatisfied with the current option and consumers who enter the orientation phase because the current option is no longer available. One could argue that consumers who cannot find the option they were looking will prefer other options (more like the non-available option) than a dissatisfied consumer.

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[9] See for example: Oxford, Berg; Shove, E. (2010). "Beyond the ABC: Climate Change Policy and Theories of Social Change." Environment and Planning A 42: 1272-1285.; Shove, E. and Pantzar, M. (2005). "Consumers, Producers and Practices." Journal of Consumer Culture 5(1): 43-64.; Shove, E., Pantzar, M. and Watson, M. (2012). The dynamics of social practice: Everyday life and how it changes. London, UK, SAGE.

Another example is whether the “acceptability” in step six (Is the initial investment feasible and acceptable?) can be seen as independent from step ten and eleven (How does the option score on investment costs? How does the option score on operating costs?). A person that in step six answered being unwilling to spend the required sum on the option, will most likely also find the investment costs and operating costs too high.

5.2.8 Explore additional determinants influencing adoption

The present version of CODEC focusses on a specific set of contributing determinants stemming from several (psychological) theories. It may well be that others determinants, from different theories, could also contribute to adoption and should be included in the model. An exploration of different types of theories concerning innovation adoption is recommended to bring together the best of different worlds.

5.3 Other recommendations

5.3.1 Compare CODEC with other models

In order to establish CODEC’s weak and strong points it is necessary to compare CODEC and its results to other models that simulate decision making, such as agent based models CONSUMAT (e.g. Jager & Janssen, 2012) and FOUNTAIN (Beemster, Hof, Martens, Smit, Van der Vecht & Vonk, 2017; Beemster & Vonk, 2017; Smis, Bruining, Van der Vecht, Beemster & Vonk, 2017). In addition the model should be compared to economic models (such as from Acemoglu, Aghion, Bursztyn, & Hemous, 2012).

5.3.2 Apply CODEC to other case studies

By finding more cases to apply the model we aim to further validate the model, and investigate whether the above mentioned improvements have been valuable. In addition it aids the comparison to other models.

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