Impacts of social innovation on local energy transitions: Diffusion of solar PV and alternative fuel vehicles in Sweden

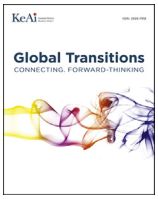
Citation for the original published paper (version of record):
Selvakkumaran, S., Ahlgren, E. (2020). Impacts of social innovation on local energy transitions:
Diffusion of solar PV and alternative
fuel vehicles in Sweden. Global Transitions, 2: 98-115. http://dx.doi.org/10.1016/j.glt.2020.06.004

Global Transitions 2 (2020) 98–115

Contents lists available at ScienceDirect

Global Transitions

journal homepage: www.keaipublishing.com/en/journals/global-transitions/



Impacts of social innovation on local energy transitions: Diffusion of solar PV and alternative fuel vehicles in Sweden

Sujeetha Selvakkumaran [a], [b], [*], Erik O. Ahlgren [a]

[a] Energy Technology, Chalmers University of Technology, Gothenburg, Sweden
[b] Energy and Environmental Systems Analysis, Sustainable Built Environment, RISE Research Institutes of Sweden, Sweden

ARTICLE INFO

Article history:
Received 12 March 2020
Received in revised form
12 June 2020
Accepted 26 June 2020
Available online 16 July 2020

Keywords:
Social innovation
Energy transitions
System dynamics
Simulation
Co-creation

ABSTRACT

Local energy transitions are gaining widespread attention through their contribution to sustainability, notably to climate change mitigation. Social innovation (SI) in local energy transitions have been scrutinized in multiple works, but the impact of SI on the local energy transitions is an under-studied field. The objective of this study is to put forward a method to model SI in local energy transitions. This is done using System Dynamics modelling (SDM) of the local energy transitions processes. The SDM method is to study a broad spectrum of socio-techno-natural phenomena, generally. In this study, SDM is used to capture the endogenous factors which underpin the transition processes. This study is based on two cases: solar photovoltaics (PV) diffusion in Skåne, and transition to alternative fuel vehicles (AFV) in Dalsland, Sweden. The transitions are modelled with the municipality actors providing input. Two simulation runs of the local transitions are executed, namely the Base run and No SI run. The Base run has the municipality actors' co-creation actions. Results show that the co-creation actions induce a significant increase in the diffusion of electric vehicles in Dalsland and higher diffusion of solar PV in Skåne. The main outcome of this study is a model to assess the possible impacts of SI on local energy transitions. Ultimately, we hope to contribute to methods of quantitatively assessing the impact of SI in local energy transitions.

1. Introduction

The response to the call for climate change mitigation in many countries has been at the grass-roots level, with local energy movements, citizen-lead movements and other varied movements leading to a revolution in the renewable energy uptake, supported by generous policies and interventions from governments.

Ref [1] defines social innovation (SI) as a new combination and/or new configuration of social practices in certain areas of action or social contexts, prompted by certain actors or constellations of actors in intentional targeted manner with the goal of better answering the problems of society. In a similar vein, a more comprehensive definition differentiating SI from technological innovation is proposed by Ref. [2]. Here, SI is characterized by it meeting neglected social needs, and the underlying image of social innovations combine functionalist and transformationalist aspects. Furthermore, they add that the primary impact is the well-being of the beneficiaries of social innovation, along with the actors involved. Thus, actor involvement and social processes are important in social innovation. Ref [3] notes that the differentiation between social and technical innovation lies in the intended result, that is while a technology is at the forefront of the technical innovation, in SI the social practices and processes are at the center. Another defining difference between social innovation and technological innovation is the immaterial structure of social innovation, which does not manifest as a technical artefact, but as new social practices. This is critical to understand in fields of practice which are technology-dominated, such as energy transitions. While in energy transitions, with a technological innovation lens the technology at the center of the innovation gets assessed, in the case

---

[*] Corresponding author. Energy Technology, Chalmers University of Technology, Gothenburg, Sweden.

E-mail addresses: sujeetha@chalmers.se (S. Selvakkumaran), erik.ahlgren@chalmers.se (E.O. Ahlgren).

Production and Hosting by Elsevier on behalf of KeAi

https://doi.org/10.1016/j.glt.2020.06.004

of social innovation, even with the technology being new for that place, for example solar PV in a household, the novelty could be the social practices and/processes spurring the transition on.

In a comprehensive review of social innovation, Ref [4] notes that the impact of social innovation on different social processes is often assumed to be positive in normative terms, without being rigorously proven so. The implicit presumption is that social innovation is good. This finding is also further supported by scholarly works such as [1,3,5-7], among others.

Nevertheless, there is the expectation that social innovation has the capability to address societal challenges related to poverty, social exclusion, environmental damage and sustainable development by complementing or supporting technical and market innovations [8]. Similarly, there is also the expectation that social innovation has empowering potential, even though there is no documented evidence of this [5]. Ref [9] postulates that social innovation has been instrumental in citizen-based activity associated with reducing emissions or increasing renewable energy production but also present the caveat that it is a contested concept, with no formal agreed-upon definition or universal method of measurement. Ref [1] goes on to say, even though social innovation is expected to solve society's wicked problems, a sustained and systemic analysis of its contents, and impacts is missing.

The social innovation in energy transitions has been recently studied extensively in multiple literature, whether be it in the form of community energy transitions in Europe [9], energy transitions through intermediaries [6], or social innovation in energy fields [10]. The impact of social innovation on energy transitions is not clearly defined or articulated in scholarly works dealing within the confines of this domain, as noted by Ref. [9]. In this study, in order to understand the impact of social innovation in local energy transitions, we must come to a common understanding of what social innovation actually is, especially within the confines of local energy transition. This also helps in determining the unit of social innovation that we are considering [1]. As detailed in Ref. [3] in relation to what can be considered social innovation, we consider the social practices and new activities carried out by the actors as the social innovation within the local energy transitions processes.

Ref [11] notes that local energy transitions are different from global energy transitions due to the disproportionate importance of local actors and local-specific contexts. This is especially vital when it comes to analysis of social innovation and its impact on local energy transitions, given the 'social' nature of social innovation.

So, the consensus is that, in scientific literature, 1. Social innovation in the field of local energy transitions is gaining significance, especially within the actor-lead/community transitions field, 2. But, social innovation's impacts on local energy transitions have not been measured, and 3. Such methods for measurements of impacts would need to consider local actors and novel social practices.

Thus, our objective is to propose a model to assess the impacts of certain social innovations in co-created local energy transitions and assess possible impacts of these social innovations. Moreover, the primary research question underpinning this study is: what are the possible impacts of social innovations in co-created local energy transitions? We answer this question by building a simulation model that represents the local energy transitions processes, and the social innovation actions associated with it. It is important to stress that this model is not meant to serve as a method for comprehensively quantifying all social innovation impacts on local energy transitions, but rather it takes a case-study approach and looks at the social innovation in two cases of co-created local green transitions.

To better understand the cases, the concept of co-creation is introduced here and the links between co-creation and social innovation are explained. Simply put, co-creation is creating something together with another person or entity. Co-creation is defined as the process of social innovation by Ref. [12]. According to them co-creation has four aspects, which are:

1. Co-creation's objective is to give lasting solutions to the parts of society that require it; a society which has needs and challenges.
2. Co-creation changes the social relationships between the stakeholders, in that it changes the context in which existing practices used to happen
3. For co-creation to give solutions that matter and are relevant to the society's needs, relevant stakeholders are involved in the design, implementation or adoption of an innovation for the society
4. And finally, co-creation is not just the production of innovation but also the process of producing that innovation. These four aspects pointed out show that co-creation and social innovation are connected concepts.

The synthesis of the above description shows that similar to SI, the purpose of co-creation is to give solutions to parts of society that needs it. Furthermore, this solution comes with various stakeholders involved in creating the solution, and the solution results in changes in existing social relationships between stakeholders. This is essentially the same as the definition of social innovation.

The rest of the article is organized as follows: Section 2 presents the two pluri-local case studies which form the basis of the study. Section 3 presents the methods and models used in this study, followed by Section 4 presenting the details of the findings. Section 5 presents the discussions and finally concludes.

2. The local energy transitions case studies

This section provides the details of the two local energy transitions case studies that are scrutinized in this study. These two case studies were part of an EU Interreg project titled "Co-creating local green transitions" which was carried out from 2016 to end of 2018. The details of the project can be found at [13]; and an in-depth explanation of the project is given by Refs. [14].

The first case study is based on Skåne, a county in southern Sweden, and its attempts to increase the diffusion of household solar PV among its single and double family dwellings. The county administrative body and the associated municipality actors have been engaged in activities to promote more solar energy and solar electricity in southern Sweden since 2012 [15]. One part of this strategy has been the community outreach program of solar study circles to encourage single and double family dwelling owners with solar PV to meet such house owners who did not yet own solar PV systems. Southern Sweden on average has the highest solar insolation in Sweden but still has quite considerable amounts of unrealized potential for harnessing solar insolation [16]. A more detailed description of the Skåne solar PV case can be obtained from Ref. [17].

The second case is based on the transition to alternative fuel vehicles (AFVs), specifically electric vehicles (EVs) and biogas cars, in the collection of five municipalities (or *kommunalförbund* in Swedish) known as Dalsland, in western Sweden. Dalsland is mostly rural or peri-urban according to the classification of municipalities and has approximately 25,000 cars. Of these, approximately 95% were fossil fuel cars, that is, cars that run either on gasoline or diesel, in 2016. From 2016, the municipality actors have been trying to increase the receptibility of AFVs in Dalsland by having electric charging stations installed, along with the installation of biogas filling stations, among other activities such as increasing awareness of AFVs among the residents and car drivers in Dalsland. A more detailed account of this case can be found in Ref. [18].

Both these cases are municipality-lead co-created local energy transitions. In both the cases, the social innovation was due to the co-creation actions of the municipality actors (MAs) and the corresponding members of the society, whether normal residents or other specific group of actors. Social innovation in both these cases were the novel actions the MAs undertook to co-create the transition process, along with the corresponding residents, and also the new social practices they started during the running of the EU Interreg project “Co-creating local green transitions”. This is important to stress since the MAs did not see themselves as just being involved in municipality-lead interventions but rather that they created new social practices that contributed to the energy transitions and created new avenues for transitions processes to take root.

The MAs defined co-creation as “municipal and private actors’ joint efforts to solve common problems through constructive exchange and application of experience, resources, skills and ideas”. They also defined five underlying principles of co-creation as being: (1) Transparency; (2) Common learning; (3) Energetic and active commitment; (4) Open and flexible processes; and (5) Dialogue [14].

3. Methods and models

This section gives the details of the methods adopted in this study and the models formulated to quantitatively assess the impact of SI in the local energy transitions cases.

3.1. System Dynamics modelling (SDM)

Systems thinking, the ability to see the world as being beyond simple cause and effect; essentially to see it as a complex system, ‘in which we understand you just can’t do one thing’ and ‘everything is connected to everything’ [19], and the aligned quantitative method of System Dynamics modelling (SDM) have an established history in modelling and decision-making of societal processes [20]. The application of SDM has spanned the domains of modelling non-linear processes to complex systems [21]. As such, SDM has been used in socio-techno-natural systems modelling [22–24] [25,26,27], and specifically energy systems modelling [28] as well.

Socio-technical transition theories consider energy transitions as non-linear processes [29,7]. These non-linear processes are characterized by the feedbacks between different factors and actors who underpin the transitions process [30].

In both cases, the dynamics of the adoption of the new technologies (solar PV and AFVs) is non-linear, since the rate of adoption is dependent on a number of factors which are not constant over time. There is feedback between the number of households with solar PV systems and the rate of adoption of solar PV systems. This is the main feedback in the solar PV adoption case. Likewise, there is feedback between the adoption of AFVs and the number of AFVs in circulation.

The SDM is a reliable and robust modelling method to handle non-linear processes [21]; SDM accounts for feedbacks between the different factors and is also a modelling method to account for various actor interactions [31], which are the cornerstones of SI in local energy transitions. In both cases, the actor interactions lead to information exchange between the municipality actors (MAs) and the prospective adoptees of the new technologies, which feeds into the adoption rate. Actor interactions underpin social value and the establishment of social practices which are temporally carried into the future, which are a vital part of SI.

The SDM has an established modelling process, which consists of the following steps: 1) reference modes and background data collection related to the transition, 2) drawing up a mental model of the transition, 3) building the initial model, in our study entailing a causal loop diagram (CLD) and a stock and flow diagram (SFD), and 4) refining the model with validation [19]. However, for this project, we follow a methodological process with certain modifications, presented in Fig. 1, adopted from Ref. [17]. The reason for the deviation from the general modelling process is the ultimate aim of the study, which is the measurement of impact of SI in local energy transitions, and thus the need to include the main actors involved in the local energy transition process, in this case the MAs.

Step 1 in the SDM process is data collection. The data requirements for this study was fulfilled by primary and secondary qualitative and quantitative data. The needed primary qualitative data was collected through interviews with the MAs, and this is explained in detail in Section 3.2.

Secondary qualitative data was obtained from the reports which were submitted by the MAs as part of the documentation of the ‘Samskabende Grøn Omstilling’ project. This included bi-monthly status updates and the planning reports and other minutes of the project workshops, which were held twice every year. These documents were analyzed textually, and the details of the SI activities carried out by the MAs were extracted. These reports also gave a sense of the time and effort put in by the MAs into the SI activities and how many residents participated in these activities.

Secondary quantitative data were obtained regarding the installed solar PV in Skåne and the number of cars driven in Dalsland, separated by fuel type. These were obtained from the Swedish Statistical Agency [32,33]. Primary quantitative data of the number of biogas filling stations and number of charging stations were obtained from the MAs.

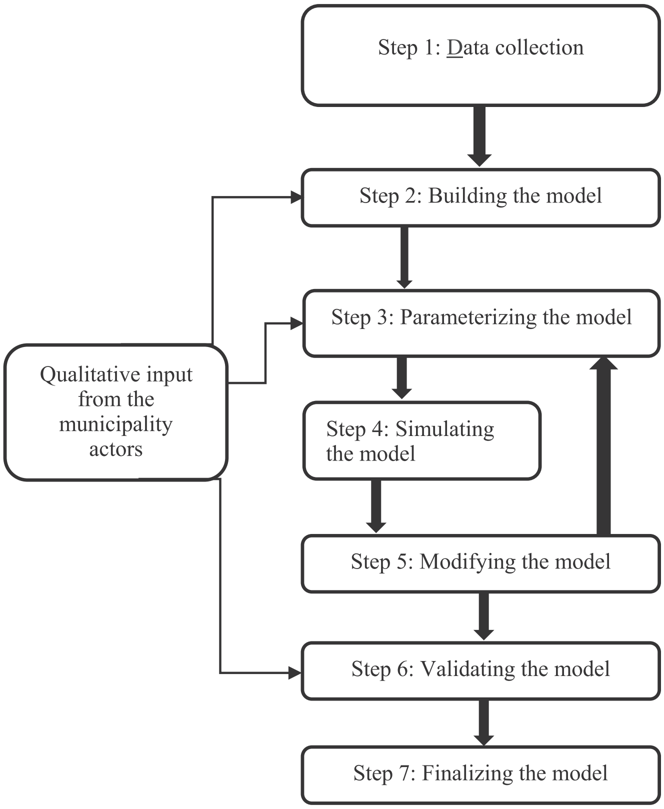


Fig. 1. The method flow used in this study, adapted from [17].

3.2. *Interviews with municipality actors (MAs)*

Our main qualitative data collection method involved multiple semi-structured in-depth interviews with the MAs. These interviews spanned several months, and mostly took place either in face-to-face oral form or face-to-face via voice over internet protocol (VOIP) methods.

We prepared for the interviews by submitting our understanding of the cases to the MAs and by providing a set of questions that we expected the MAs to answer. This also served as a script for the interviews. The questions asked of all the MAs in both the cases are given in Table 1.

We used the interviews to gauge both primary quantitative data central to the model and qualitative data, which we had to convert to quantitative factors (explained in Section 3.3 and Section 3.4).

In the solar PV case in Skåne, we interviewed two MAs simultaneously, who were both working on the project. In total, three interviews of approximately 70 min length were carried out over the course of two years, one through VOIP technology, and two in person face-to-face interviews.

Similarly, in the transition to AFVs in Dalsland, three interviews were carried out, all in person face-to-face interviews. The first interview was carried out with one MA, but the subsequent interviews were carried out with two MAs. The interviews were approximately 90 min in length. The second interview with the MAs was conducted with the CLDs in hand.

The interviews were not all similar. While the first interviews in both the cases included the questions we needed the MAs to answer, the subsequent interviews included the CLDs and SFDs that we had developed as a result of the interviews with them, and in the solar case, the third interview included some preliminary results.

The point to be emphasized here is that the method of eliciting data from the MAs was not linear but rather involved multiple iterative loops, and the input from the MAs were used in multiple steps of our modelling process; in data collection, formulating the model, parameterizing the model and then subsequently in validating the model.

3.3. *Developing SD models based on the information from the interviews*

The next step in the process, after the first interviews, was development of the SD models based on the information from the interviews. Here, we primarily use two modelling tools which belong to SDM. As introduced before, these are CLD and SFD.

The CLDs are conceptual modelling tools which are useful in mapping out the different variables pertinent to the modelling context and in mapping out the relationship between the variables. In the SFD, the relationships between the variables need to be defined in the form of equations. Simplistically, the SFD can be obtained by differentiating the variables in a CLD into stocks, flows and variables. Ultimately, we convert the CLD into SFD using the knowledge we have of the cases, and the modelling question in mind. A thorough explanation of CLDs and SFDs can be obtained from Ref. [19].

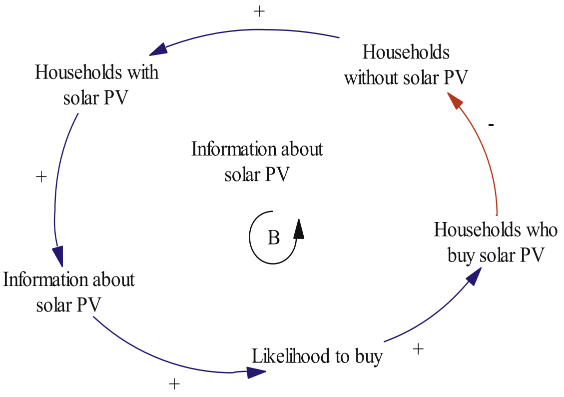


Fig. 2a. The initial CLD of the solar PV diffusion.

While the rate of adoption and its equation containing the potential households for solar PV adoption and households who have already adopted solar PV, along with the contact rate and adoption fraction are formulated according to Bass' work [34], the other variables defined, which are unique to the solar PV adoption in Skåne, need to be formulated by us. We do this mainly through our modeling experience, observed/learnt outcomes (both scientific and real-life) and the expected model behaviour. Similarly, the adoption of AFVs in Dalsland is also based on Bass' work, but with the local contextual factors added with the knowledge of the case. The explanation of the SD models built for both the cases is given in Section 3.4.

3.4. *The formulation of the SD models*

This section provides a detailed explanation of the formulation of the two models in this study.

3.4.1. *The solar PV diffusion SD model*

At its simplest, the diffusion of solar PV can be formulated as a balancing loop (as given in Fig. 2a, where the households who do not have solar PV increase their likelihood of buying solar PV with information about them which, in turn, reduces the households without solar PV. From herein in this study, solar PV refers to rooftop photovoltaic installations by grid connected households mostly for own consumption.

This is shown as an SFD in Fig. 2b. The stock of households which do not have solar PV are modelled as **Potential households for solar PV**, and with the adoption of solar PV, these households flow to **Households who have adopted solar PV** (see Fig. 3a and b).

Certain important facts were discovered by us during the discussion with the MAs. The role of MAs' can be defined as:

- Arranging information meetings and events
- Acting to establish study circles, which act as long-term channels of information
- Managing expectations of citizens who inquire about solar PV

Table 1
Questions asked of the MAs in the first interviews.

1.	How many hours in a year did you work on the social innovation activities in the project?
2.	What were the different activities you were engaged in?
3.	Can you give an approximate estimate of the proportion of time spent for each category of activity?
4.	What were the issues people spoke about, in connection to home solar PV systems?
5.	What were the biggest issues of people who were looking to buy an EV or a biogas car?

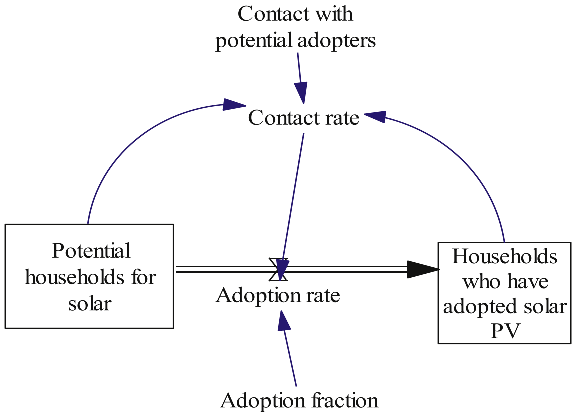


Fig. 2b. The initial SFD of the solar PV diffusion.

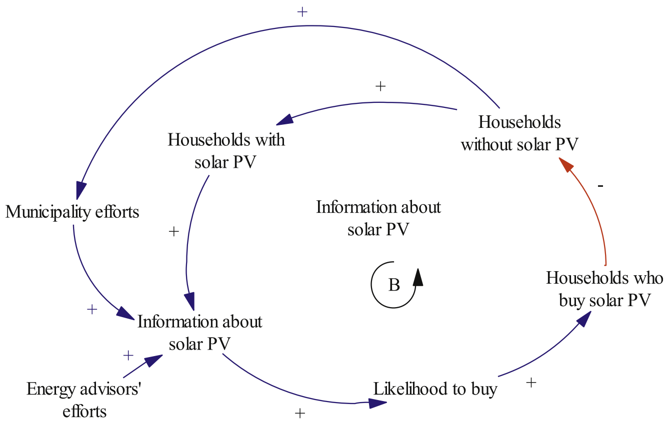


Fig. 3a. The CLD for solar PV diffusion with municipality actors' efforts.

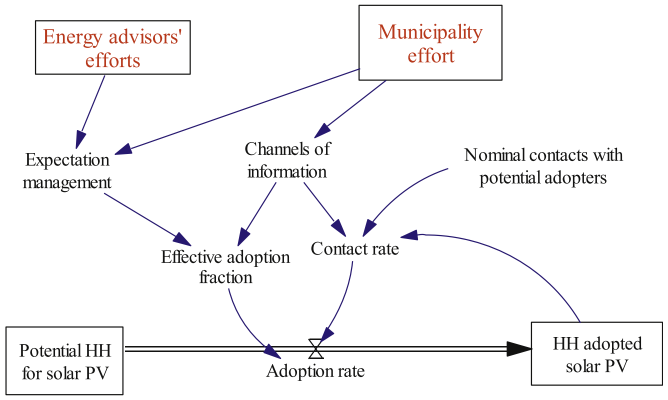


Fig. 3b. The SFD for solar PV diffusion with municipality actors' efforts.

With this information, we developed a refined CLD representing the co-creation activities which form the basis of the novel social practices, and a corresponding condensed SFD which is given in Fig. 4a and b. We surmise that the co-creation efforts work towards either increasing the contact rate or the effective adoption fraction of the flowrate in the SFD. A fraction of the municipality effort creates channels of information which increases the effective adoption fraction and the contact rate.

A complete and simulatable SFD was developed based on the discussions with the MAs and understanding the co-creation actions at the base of the diffusion of solar PV (see Fig. 4). The complete details of the model, along with its parameters can be obtained from Ref. [17] have documented the detailed process of model-building and provide the logical arguments for the model equations. But they do not present any numerical results of the model, and neither do they assess the impact of SI. Nevertheless, the study of [17] is a precursor to the solar PV diffusion case study here. Where [17] and this study differ significantly is in the presentation of the numerical results of the simulation model, and in the analysis of the impact of SI on the diffusion of solar PV in Skåne, Sweden.

In Fig. 4, the section which is highlighted in pink shows the different pathways in which **Channels of communication** are built. While **Information through peers** is the expected pathway of building **Channels of communication**, the model featured in Fig. 4 also shows how the MAs efforts also contribute to building **Channels of communication.**

The model variables which are necessary to understand the impact of SI in the case of solar PV diffusion in Skåne are **Channels of information**, **Effective adoption fraction** and the installed capacity of solar PV in Skåne.

The variable **Channels of information** is important, as this is modelled as the direct outcome of the new social practices undertaken as social innovation activities from 2016 to 2018, along with the information from peers who have solar PV, and the retailers of solar PV. Here, the **Channels of information** have the units of Hours/Year. Equation (1) (Eq. (1)) gives the formulation of Channels of information.

Channels of information $= (A * B) + (C * D) + (E * F) + G + H$ (1)

Where,

A = Energy advisors' efforts
B = Efficiency factor of energy advisors' efforts into channels of information
C = Events and info meetings
D = Efficiency factor of events turning into channels of information
E = Municipality effort
F = Efficiency factor of municipality effort into channels of information
G = Information through peers
H = Communication about solar PV by retailers

This equation has been formulated after the first discussion with the MAs, with regards to the different ways in which the potential households were given and received information about solar PV. This was also examined against information given in Ref. [35]. This formulation of **Channels of information** of course includes the MAs' efforts with the variable **Municipality effort** and the events and information meetings instigated by the MAs through the variable **Events and info meetings**.

Here, the variables **Efficiency factor of energy advisors' efforts into channels of information**, **Efficiency factor of events turning into channels of information** and **Efficiency factor of municipality effort into channels of information** are constant and given the value as estimated by the MAs and the modellers.

Similarly, the variable Effective adoption fraction is formulated as shown in Equation (2).

Effective adoption fraction = (Available effective information * Potential HH concentration) + Nominal adoption fraction + Likelihood to buy solar PV (2)

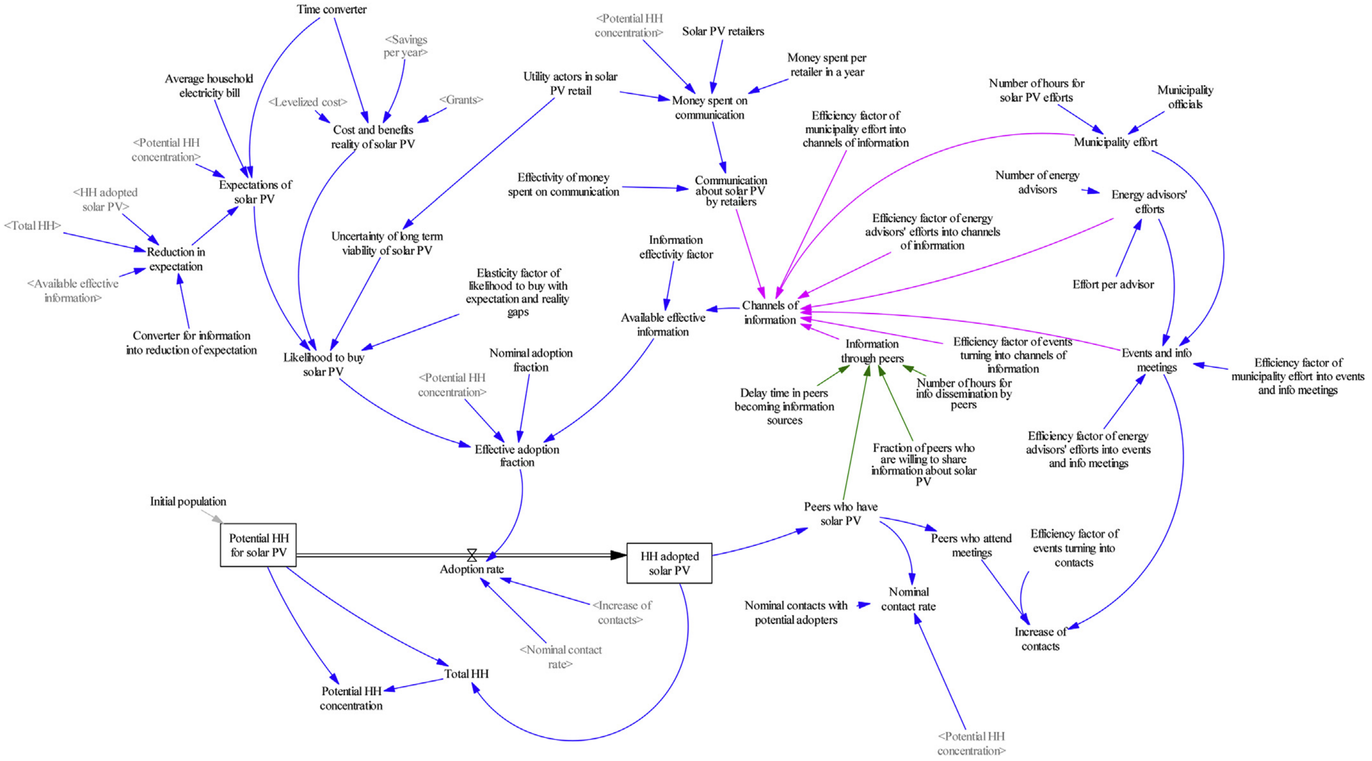


Fig. 4. The detailed SFD of the diffusion of solar PV in Skåne.

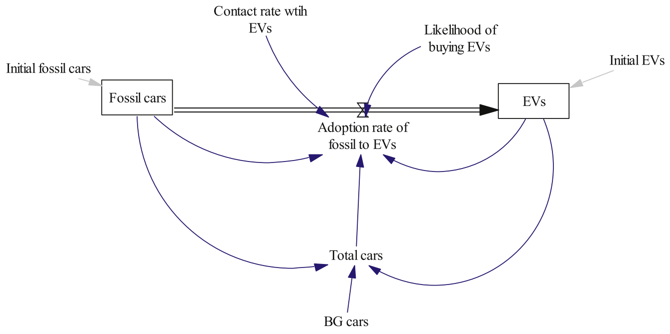


Fig. 5. The initial SFD for the diffusion of EVs.

The formulation of the variable **Effective adoption fraction** is done so that it reflects the positive feedback information that solar PV has on the real-life adoption process, which is why effective adoption fraction encompasses a **Nominal adoption fraction**, which is added to the effect of information given by the term **(Available effective information * Potential HH concentration)** and **Likelihood to buy solar PV.**

The actual installed capacity is obtained from the model by multiplying the number of Households who have adopted solar PV with the average size of the solar PV system in each household (which is assumed to be 6 kW, based on Svensk Solenergi, (2016)).

3.4.2. The AFVs diffusion SD model

The diffusion of AFVs (as an example only EV is shown here), similar to the diffusion of solar PV, can be thought of as flowing from fossil fuel cars (shortened to Fossil cars) to EVs, with the adoption of EVs to Fossil cars, as shown in Fig. 5. In this case study, **Fossil cars** is meant to imply any car that uses fossil fuels such as diesel, gasoline etc. Here, the adoption rate of fossil cars to EVs is increased by the **Likelihood of buying EVs** increasing and the with increasing rate of contact with EVs. This initial SFD is based on Bass' diffusion model [34].

Multiple interviews with the MAs in Dalsland gave us information on the different factors that affected the likelihood of residents from Dalsland buying EVs and biogas (BG) cars. We coupled this primary data with a comprehensive review of factors affecting the transitions to AFVs found in Ref. [36].

In the case of transition to EVs, the likelihood of buying EVs was formulated as being impacted by the information about EVs, the personal utility the EV presented to the buyer, the financial viability of having an EV as opposed to a Fossil car, and the range anxiety and the uncertainty associated with the EV (see Fig. 6). Similarly, the likelihood of buying a BG car and the factors that impact it are shown in Fig. 7.

The MAs' efforts are formulated as increasing multimedia communication about EVs and BG cars, efforts of communication via word of mouth (WOM), efforts towards establishing BG filling stations and installation of public electric charging facilities, which in turn reduce the uncertainty of EVs and BG cars, help reduce the range anxiety and increase the information availability. The details of these co-creation actions and how much time and effort were spent on it came to light through the interviews with the MAs.

The detailed SFD for the transition to EVs and transition to BG cars are given in Figs. 8 and 9.

As with the solar PV diffusion model for Skåne, the model variables which are necessary to understand the transition to EVs and BG cars in Dalsland are explained here. The necessary variables are stocks of **EV** and **BG cars**, **Likelihood of buying EVs**, **Likelihood of buying BG cars**, **Uncertainty of EVs**, and **Uncertainty of BG cars**.

The likelihood of buying EVs is formulated as being the addition of the factors shown in Fig. 6. It can be given in equation form as shown in Equation (3). The formulation is meant to reflect the additional effects of **Financial viability impact on EV**, **Personal**

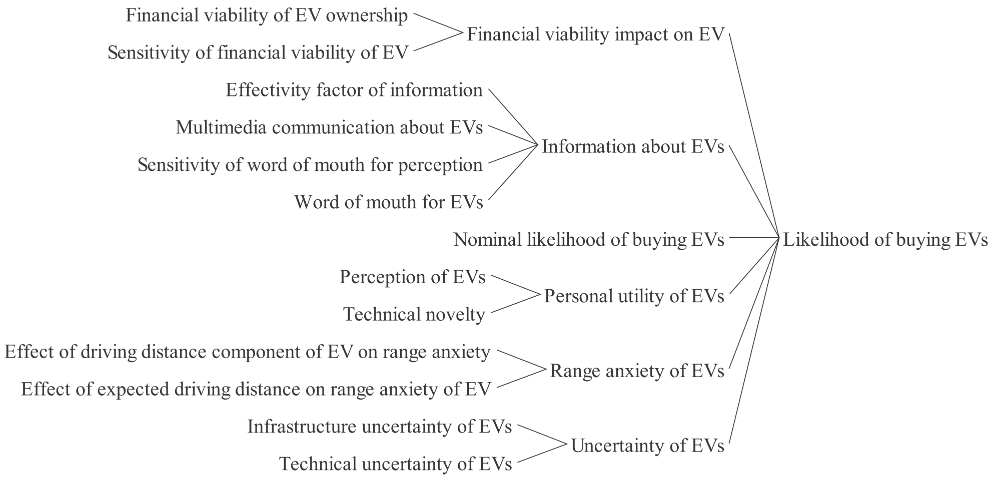


Fig. 6. The likelihood of buying EV as formulated in the SFD.

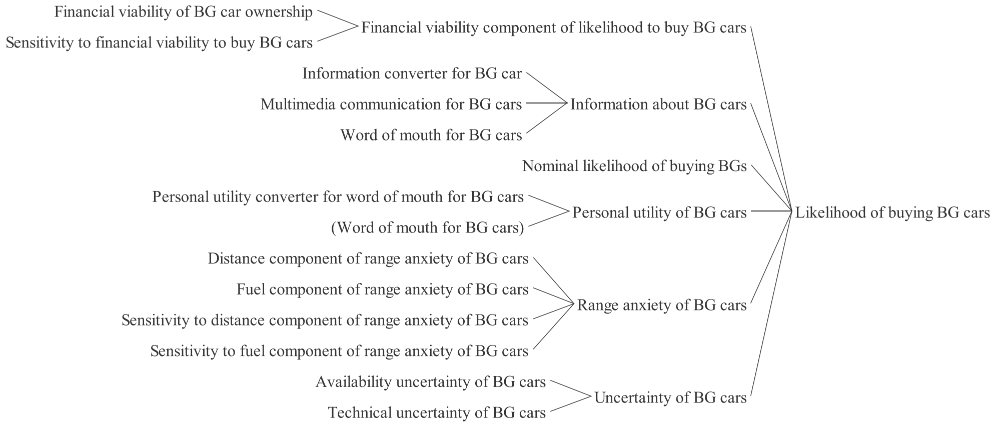


Fig. 7. The likelihood of buying BG car as formulated in the SFD.

utility of EVs, **Range anxiety of EVs**, **Uncertainty of EVs** and the **Information availability on the likelihood of buying EV**. This formulation resulted after the many discussions with the MAs.

Likelihood of buying EVs = A + B + C - D - E + F (3)

Where

A = Information about EVs
B = Financial viability impact on EV
C = Personal utility of EVs
D = Range anxiety of EVs
E = Uncertainty of EVs
F = Nominal likelihood of buying EVs

Similarly, the **Likelihood of buying BG cars** is given in Equation (4).

Likelihood of buying BG cars = A + B + C + D - E − F (4)

Where

A = Nominal likelihood of buying BG cars
B = Information about of BG cars
C = Financial viability impact on BG car ownership
D = Personal utility of BG cars
E = Range anxiety of BG cars
F = Uncertainty of BG cars

The MAs stated that their opinion is that the uncertainty associated with AFVs in general is one of the biggest barriers for the transition to AFVs in Dalsland. The uncertainty of EVs has two components to it: **Technical uncertainty** and **Infrastructural uncertainty**. Thus, it is formulated as shown in Equation (5).

Uncertainty of EVs = Infrastructure uncertainty of EVs + Technical uncertainty of EVs (5)

Here, **Technical uncertainty of EVs** is formulated as being inversely proportional to technical certainty, and the technical certainty is a cumulative of **Garages for EVs** and **Retailers selling EVs**. The importance of availability of garages for EVs and retailers was informed to us by the MAs, and the lack of these facilities was adversely affecting the transition process. Here, the term ‘garages’ is used to mean a place that gives services for mending and maintaining EVs and BG cars, such as service stations. The MAs had done a survey of existing service stations in Dalsland and found most of them did not have the competence to provide this service to EVs or BG cars.

Similarly, the uncertainty of BG cars is defined as shown in Equation (6).

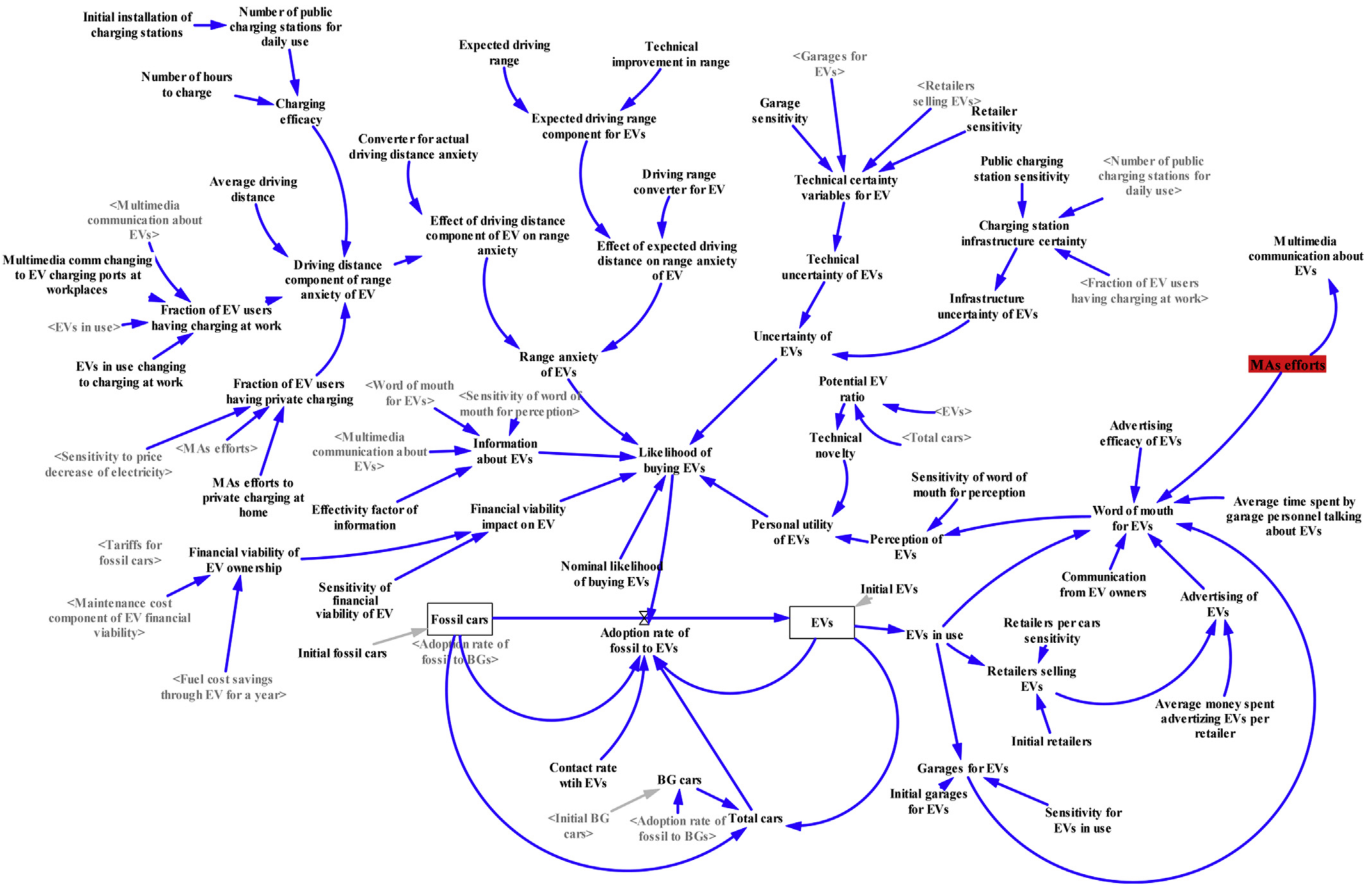


Fig. 8. The detailed SFD of diffusion of EVs in Dalsland.

$$\textbf{Uncertainty of BG cars} = \text{Availability uncertainty of BG} + \text{Technical uncertainty of BG} \tag{6}$$

The variables and the equations and/or values of the model variables are given in Appendix A (in Tables A1–A4).

These model variables are examples of how the impact of SI in these local energy transition cases may be understood and captured. The simulation is done for two separate runs, one with the SI actions in them, and the other with no SI.

3.5. *Model perspective of the quantification of impacts of social innovation*

The previous sections have described how the SD models for the two local energy transitions cases has been built (Section 3.3) and explained the transitions processes with equations, (Section 3.4). Nevertheless, the description and explanation of the overall principle behind the quantification of the SI impacts with the SD model is necessary.

As mentioned before, this study considers the novel social practices through the co-creation activities of the MAs as the SI in the local energy transitions processes. These SI actions took place from 2016 until the end of 2018. The models built and run only consider the SI actions between this specific time period.

The transitions processes in the local energy transition cases are modelled using fundamental SD principles of diffusion. The key variables and their equations are given in the previous sections (Equations (1)–(6)).

In the modelling process, the variables related to the social innovation are specifically considered, and these variables are parameterized and quantified to represent the context of the local energy transitions case studies. We have built the model so that the models represent the different SI and the transitions processes in the local energy transitions cases and their impacts as accurately possible. The communications and the involvement of MAs has aided this. This specificity has some drawbacks, such as reducing the generalizability of the results, and undermining the insights that can be drawn for other SI based energy transitions processes in other contexts. Nevertheless, this trade-off is considered necessary by the authors.

The actions of SI are parameterized quantitatively, according to the logic underpinning diffusion principles while also representing the actual local context. This process of diffusion of solar PV and AFVs has been discussed in Section 3.4. The MAs are involved in the formulation of the model. The real-life SI activities are modelled as variables and assigned quantitative values, which in turn are connected to other model variables which represent the transition. The basis for the assignation of values are also important. In the local context, the basis of the values is from the MAs' estimates or their knowledge regarding the case. In the case of variables generally applicable (without having any local specificity) the assumptions of value assignations are made by the authors. Some model assumptions are made from secondary quantitative data which already exist. Some model variable values are estimates made by the authors, with uncertainty attached to them. The authors use a trial-and-error method to estimate variables' values such that the simulated results remain robust. It is important to understand that this process of quantifying the impact of SI involves many value

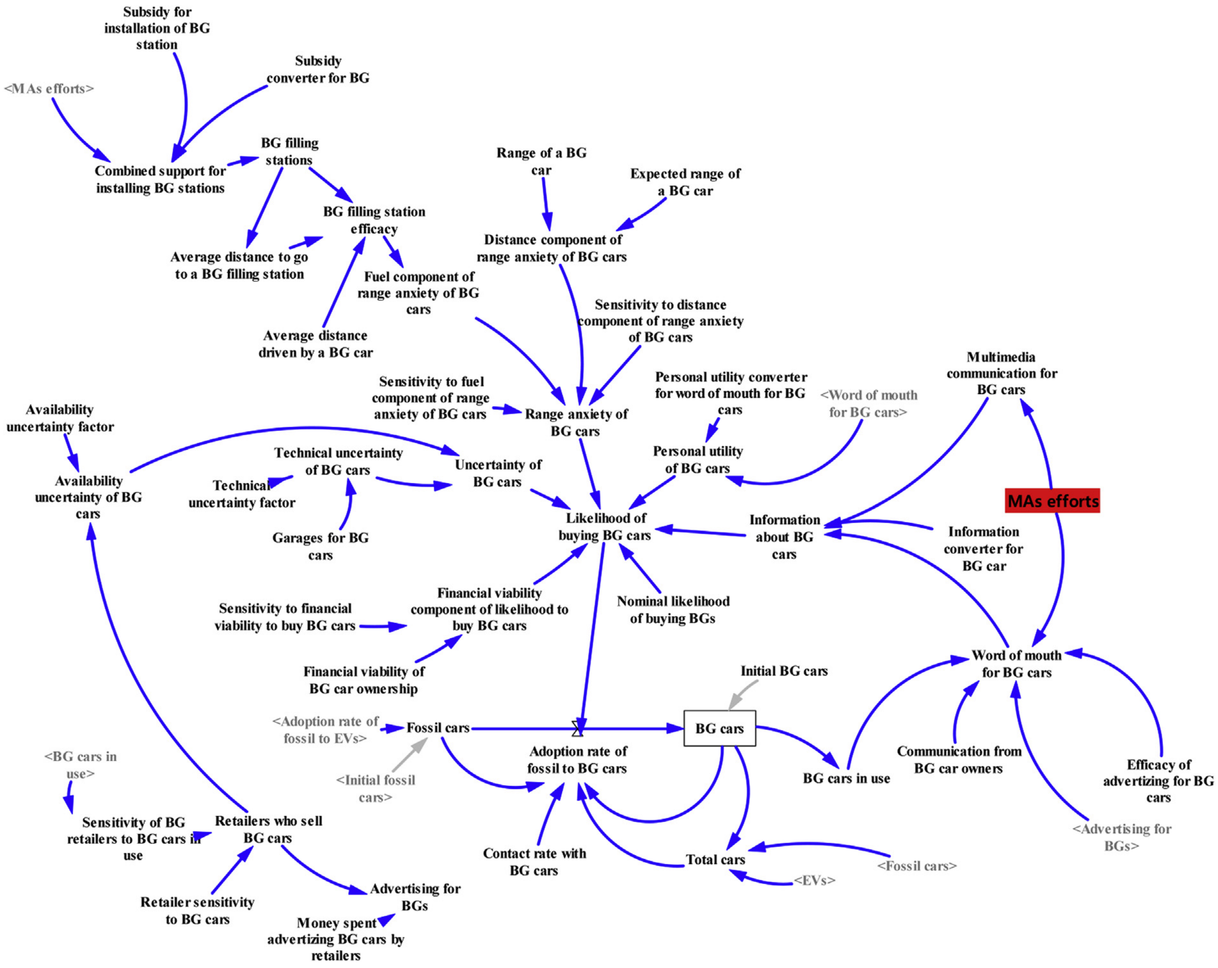


Fig. 9. The detailed SFD of the diffusion of BG cars in Dalsland.

estimations by the authors.

In the diffusion of solar PV case study, the model time horizon is from 2016 to 2041. This corresponds to the life-time of the solar PV system, which is assumed to be 25 years, as documented in Refs. [37]. For the years from 2012 to 2016 the actual data of solar PV diffusion in Skåne is obtained from Ref. [37], and the variables which are estimated by the authors and MAs are calibrated to fit the past data of solar PV diffusion of Skåne (from 2012 to 2016). It is important to note that this study does not consider the end-of-life treatment of solar PV, nor the decision to re-invest in solar PV, by the households.

In the diffusion of AFVs in Dalsland, the model time horizon is 2016–2028. This time horizon is chosen because in Dalsland the average life-time of a car or personal vehicle is estimated to be 12 years. This estimation was given by the MAs and is slightly higher than the life-time assumed in Ref. [38]. The MAs are of the opinion that the life-time of a personal vehicle in Dalsland is slightly higher than the average life-time for Sweden, since the socio-economic status of its residents is lower than the average of that in Sweden. The variables which are estimated by the authors and the MAs are calibrated using a trial-and-error method for the actual data of fossil fuel cars, EVs and BG cars in Dalsland for the years 2016–2018. The data from the above-mentioned period for the number of cars by type of fuel are obtained from Ref. [39].

The modelling is done for the SI activity undertaken from 2016 to 2018, and the impact of the of SI activity on the diffusion of the technologies is studied. The model variables and the values for the solar PV diffusion model are documented in Ref. [17]. The model variables and the values for the AFVs diffusion model are given in Appendix A (see Tables A1 to A4). The simulation models are implemented in a proprietary software called Vensim. The version used is DSS 32-Bit 7.1. More information about Vensim can be found at [40].

4. Results

The results from the simulation runs of the respective models built for both cases are presented in the following sections. Two simulation runs are performed for each of the cases, namely the Base run and No SI run. The Base run is the model run when SI activities were carried out by the municipality actors and residents, while the No SI run depicts the outcome if no such SI activities had taken place. The Base run includes the SI activity undertaken since in reality from 2016 to 2018 the MAs and the residents took part in the SI activities.

The model results for key variables which signify the outcome of the SI activities in both the cases will be presented individually. This means that in addition to the model results for installed capacity of the solar PV, and the uptake of the AFVs (in both the cases) for the two different runs, the variables which enable the difference between the different runs are also presented. These key variables are presented in Sections 3.4.1 and 3.4.2. These key variables are the direct result of the SI activities, and as such are proxies for the impact that SI has on the two local energy transitions cases.

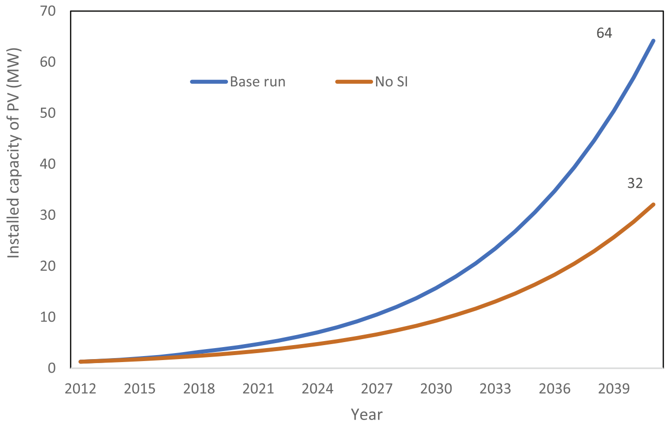


Fig. 10. The installed capacity of solar PV in Skåne, in the Base and No SI runs.

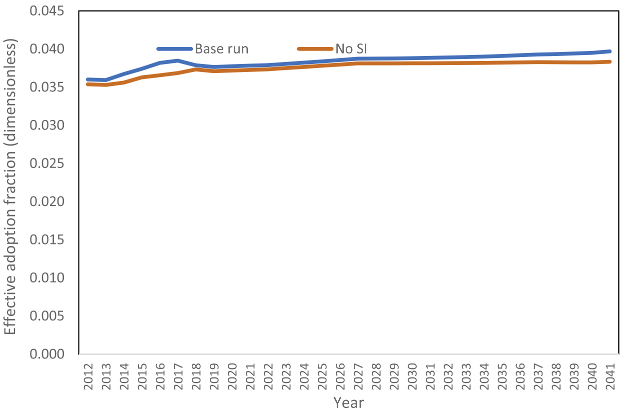


Fig. 11. The effective adoption fraction of solar PV for the Base and No SI runs.

4.1. Solar PV diffusion with social innovation

This section presents the results of the model of solar PV diffusion in Skåne, for the Base run and No SI run.

Fig. 10 shows the installed capacity of solar PV in Skåne, from 2012 to 2041, for the Base and No SI runs. In the end year of the simulation, there will be almost double the capacity of solar PV installed in the Base run, with SI, when compared to the No SI run.

Fig. 11 presents the effective adoption fraction of solar PV for the Base and No SI runs. The reason for the divergence for 2016 to 2018 can be clearly seen, which can be attributed to the MAs' SI actions, such as establishing study circles and conducting seminars and workshops. But, in the year 2018, the effective adoption fraction of the Base run drops back to the same level as found in the No SI run. But, in terms of installed capacity, the Base run installed capacity keeps increasing, when compared to the No SI run.

The reason for this can be better explained by exploring the trend of channels of information, as shown in Fig. 12. There is a discernible increase in the channels of information in the Skåne solar PV diffusion case in the years from 2016 to 2018, as a direct outcome of the MAs social innovation activities in the Base run, and then there is a marked drop in 2018. Nonetheless, because of the newly established channels of information through study circles and the interactions of peers with solar PV with potential buyers of solar PV, channels of information in the Base run never drops as low as that of the No SI run.

So, while the short term impact of the social innovation activities on the adoption fraction leads to some increase of the installed solar PV capacity in Skåne, in the long term, the impact is much higher, due to the established channels of information, which have a compounding effect.

The results here show that even a momentary increase in diffusion due to concerted SI efforts in a local setting can have larger impacts in the long term.

4.2. Transition to AFVs with social innovation

This section presents the results of the model of diffusion of EVs and BG cars in Dalsland, for Base and No SI runs.

Fig. 13 shows the diffusion of EVs and BG cars in Dalsland, from 2016 until 2028. In the case of EVs, the number of EVs increase from 10, to around 520 in the final year in the Base run. On the other hand, the BG cars increase from the level of 73 BG cars in 2016 to a maximum of 132 BG cars in 2019 and then reduce to approximately 40 cars in 2028. In the No SI run, there is no substantial increase in the EVs, and the number of BG cars also comes down, indicating that with no social innovation fossil fuel cars will not be phased-out with the diffusion of EVs and BG cars.

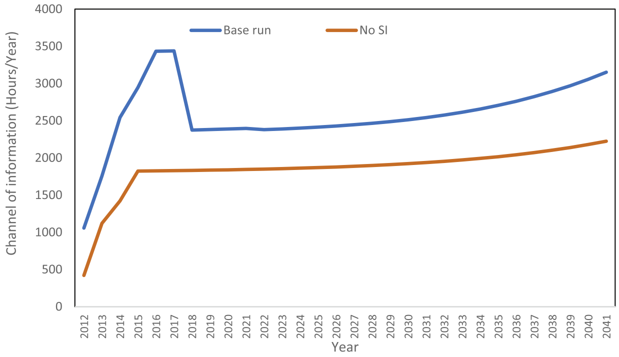


Fig. 12. The Channels of information trend for the Base and No SI runs in the Skåne case.

The trend observed in Fig. 13 can be explained by exploring the trend of the likelihood of buying the respective AFV (see Fig. 14). In the case of EVs, 2016 to 2018 sees a clear increase in the likelihood of buying EVs due to the MAs' SI activities, such as installation of electric charging stations and communication about EVs. Even though it comes to a value of 30 in 2019, the EVs adopted then bring about a slight increase in the likelihood of buying an EV in 2025 and in the later years, since the likelihood of buying an EV also depends on the number of existing EVs, since that reduces uncertainty about EVs.

To the contrary, in both runs, the likelihood of buying BG cars does not increase the number of BG cars in the long run. This is mainly because the price differential between a fossil fuel car and a BG car is not big enough to accrue savings to any potential adopter of a BG car. So, despite the SI activities of the MAs, while there is a momentary increase in the likelihood to buy BG cars in the Base run (which is also evident from the increase in the BG cars), after 2019, the number of BG cars decreases, with residents reverting to fossil fuel cars or EVs.

This trend is also reflected in the uncertainty around the AFVs, as well (see Fig. 15). The uncertainty of EVs decreases more in the Base run, when compared to the No SI run. The uncertainty comes to a constant level in the No SI run after the installation of the charging stations between the years 2016–2018, but the uncertainty keeps reducing in the Base run due to the higher number of EVs in Dalsland. Again, the long-term impact of a short-term activity is apparent in the EVs' case.

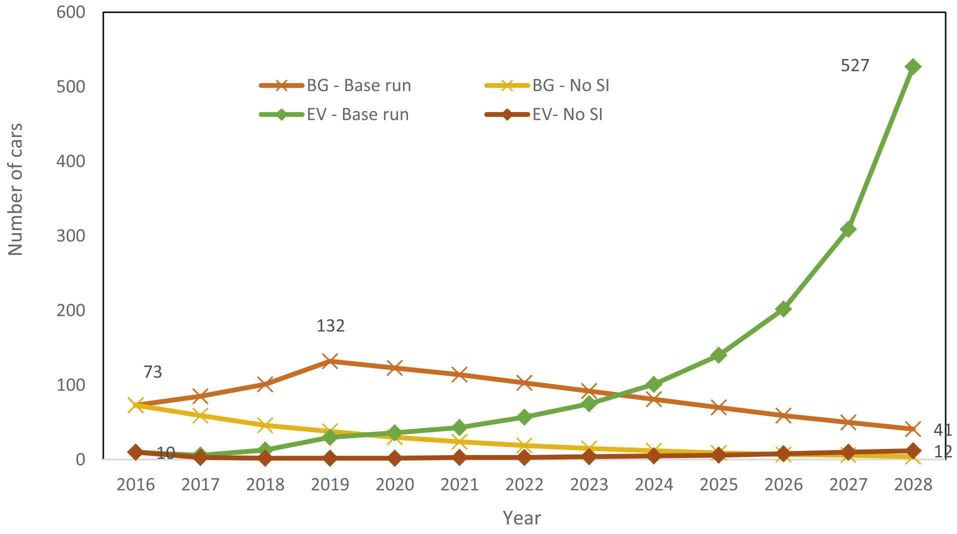


Fig. 13. The diffusion of EVs and BG cars in the Base and No SI runs.

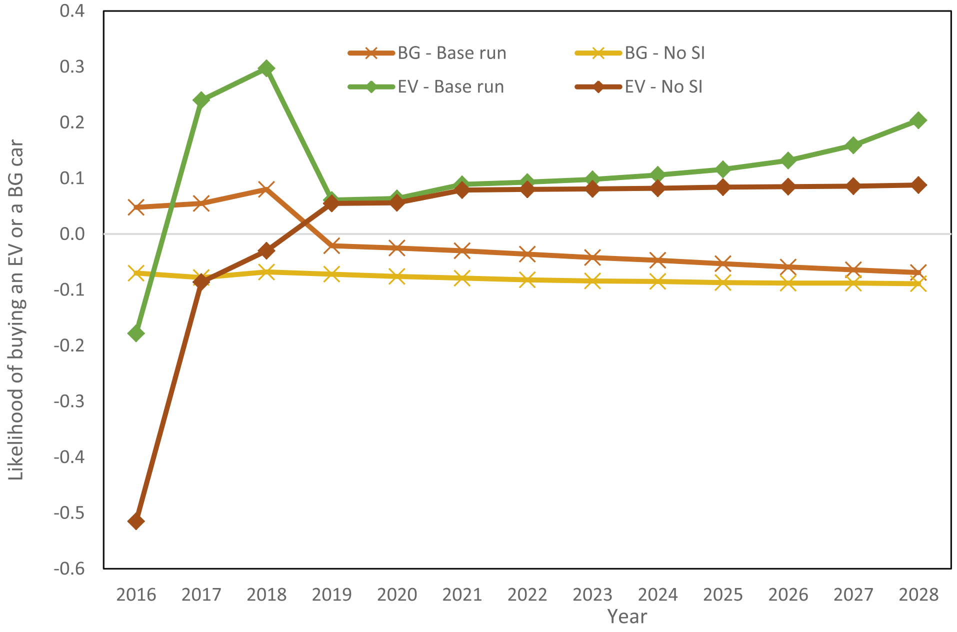


Fig. 14. The likelihood of buying an EV or BG car.

On the other hand, the uncertainty remains the same for BG cars in both the Base and No SI run. This implies that the uncertainty surrounding BG cars, which was modelled as a function of number of retailers selling BG cars and number of garages who give technical support to BG cars, did not increase since the uptake of BG cars was not high enough for that. The uptake of the BG cars was not high enough primarily because the impact of the information availability, which increased because of the SI activities, was still not at a sufficiently high level to increase the uptake to a level sufficient to overcome the uncertainty. Another exogenous reason could be the levels of subsidies for EVs and BG cars. From 2016 the EV qualified for a 50,000 SEK (the Swedish kronor) subsidy, and the BG car qualified for a 5000 SEK, irrespective of their actual investment cost. The decision to prolong or stop the subsidies has not been taken yet, and the model which produces the results assumes the subsidy will continue. The higher subsidy rate for the EVs, both as a ratio of the investment cost and in absolute numbers may be the reason for the increased uptake. Nevertheless, because of the structure of the model, that is more EVs increasing the levels of communication about EVs over the years and reducing the uncertainty of the EVs, the adoption of EVs increases over time.

5. Discussion and conclusions

5.1. Structure, behaviour and time frame

The dictum associated with SDM is that structure leads to behaviour [41]. In this study, the SI actions have been modelled to impact the adoption processes of solar PV and EVs and BG cars in Skåne and Dalsland, of Sweden, respectively. We have modelled SI as the novel social practices implemented by MAs in the two cases, and as such the novel social practices lead to more interactions,

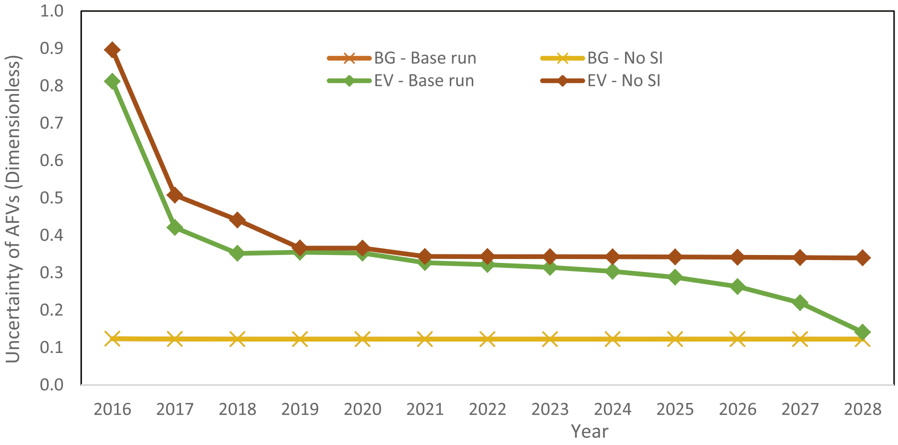


Fig. 15. The uncertainty of AFVs.

which in turn lead to the results showing expected behaviour. In terms of generalizing, both cases show an increase in the diffusion of solar PV and AFVs in the Base run, when compared to the No SI runs.

The solar PV diffusion in the Skåne model is modelled from 2012 and the modeling time frame is set to 25 years. This choice was a decision based on real-time data availability (the data of installed capacity for Skåne county is available from 2012) and the average lifetime of a solar PV (which is generally 25 years). On the other hand, in the model built for the AFVs transition for Dalsland, the modeling time-frame starts from 2016 and lasts until 2028, which corresponds to the average lifetime of a passenger car in Sweden.

In the case of solar PV diffusion in Skåne, the short-term impacts and the long-term dynamics due to the two-year social innovation activities by the MAs and the residents is shown through the model results. The results show that there are significant long-term transition impacts due to SI activities, but the short-term transitions impacts are not immediately visible. While it is difficult to reconcile the results of the model due to the long time-frame, it is possible to systematically think of the feedback, and its impacts, especially in the long term. In terms of policy, such an extended model with data for costs of the SI activities can help policy and decision makers look at the economic efficacy of SI activities, when compared to subsidies and other financial incentives. Such models could also shed light on the cumulative effects of SI over longer timeframes, and the enabling factors for such uptake, and provides a method to have discussions on possible policy pathways to achieve local energy transitions.

In the case of the AFVs, specifically EVs, the SI activities complement the transition sufficiently that the momentum of the diffusion of EVs is large enough to lead to wide-spread transition in the long-term. Conversely, during the period of SI activities the uptake of BG cars is not large enough to sustain the momentum. So, the reinforcing forces of transition dynamics are not present in the case of the BG cars in Dalsland. In a remarkable coincidence, the total number of biogas cars newly sold from January 2018 to November 2019 is 79 [33], which then leads to similar number of BG cars in real-life and as model results at the end of 2019. It is important to note here that this is merely a coincidence and does not imply that the model or its results should be treated as being perfect. Nevertheless, the model outcome is remarkably close to real-life numbers, which increases the trust placed in the model. Models such as those showcased here can yield better insight into internal dynamics, given proper and relevant information. In this case, proper and relevant information from local experts engaged in specific social innovation activities.

This study presents some key insights for real life transitions in places similar to Dalsland. Firstly, it shows the importance of social innovation and co-creation activities, and the potential short-term and long-term impacts it can have. Furthermore, it also shows the importance of the critical mass being reached for long-term transition to take root, and the dynamics underpinning that. The study also helps in increasing the understanding of why some local energy transitions do not take hold in some localities, while some others do. In the cases here, in the short-term, as with the solar PV diffusion in Skåne, the impacts are not visible. But, in the longer term, the impacts can be significant. Also, similar to the case of the BG cars in Dalsland, the efforts may not be sufficient to reach key momentum in the transition. Then, other interventions may be necessary.

5.2. General discussions

The purpose of this study was to propose a model to assess the impacts of SI in local energy transitions. In the above text, we have discussed the impacts of SI on the said transitions, as shown by the model, in the two cases. Furthermore, it needs to be stressed that the proposed model also shows a possible way to begin to quantify the impacts of SI within the confines of local energy transitions. It also puts forward a method to account for SI within a socio-technical transition and furthers the field of simulation of socio-technical dynamics.

There are many reasons for such modelling exercises [42]; such as results being taken as forecasts or predictions of future events, results being exploratory in nature, to indicate trends, or the models themselves clarifying certain dynamics and behaviour that may be observable in real life. Within those reasons, the models built in this study serve two purposes: they demonstrate the possible impacts of SI in the context of the two cases of local energy transitions, but they also paint a picture which help clarify the dynamics and behavior which is observable in real-life, and make it possible for practitioners to make sense of the real-world transitions.

Furthermore, models such as the ones showcased in this article are ideal for testing policy and action-oriented interventions in such local energy transitions contexts. The process of developing SD models as documented in this article are also ideal for communication with actors (in this case MAs) and in general in fostering trans-disciplinary cooperation. Multiple iterations of the models were built and input from the MAs were sought in testing the structure of the model. Such a way of model-building can be described as participatory model-building. Such model-building methods have many advantages, such as including a trans-disciplinary and multi-disciplinary view to building models, which also takes into account the multiple viewpoints that a model may need to consider, along with providing the actors the chance to actually be part of the meaning-making process as well [43].

But there are certain caveats that need to be mentioned and transparently discussed here. All models are simplistic representations of reality, and as such ‘are wrong’, but some are useful [44]. As discussed before, in a SD model, behaviour follows structure, and while the causalities and feedbacks are accounted for to the best of the modelers’ and MAs’ knowledge, other factors which are deemed beyond the boundary of the problem are not modelled. These factors and the ensuing interactions are ignored and assumed not to impact on the results, which may very well be a faulty assumption. This is an inherent disadvantage to almost all models and the same goes for models depicting energy transitions. Another important point to consider is that some variables in the models for both the cases contain values assigned to them which are the result of ‘educated guesses’ from the modelers’ and actors’ sides. These variables and their parameters are chosen such that the models’ results remain robust even when the values of these parameters are changed, but these variables increase the uncertainty attached to the model results. Finally, the model results for the future cannot be considered as an absolute certainty, since as mentioned before, there are variables whose parameters have uncertainty attached to them. As such, the results presented should be thought of as indicative values, and as depicting the order of magnitude of the impact of SI, rather than a fully accurate and near-certain value.

CRediT authorship contribution statement

Sujeetha Selvakkumaran: Writing - original draft, Visualization, Conceptualization, Methodology, Validation, Formal analysis. **Erik O. Ahlgren:** Writing - review & editing, Conceptualization, Methodology, Resources, Funding acquisition.

Acknowledgements

Authors would like to thank the municipality actors who participated in the research process in the paper. Authors would like to acknowledge funding from the EU Interreg project: 20200803 Samskabende Grøn Omstilling *(Co-creating green transitions)* and funding from the Swedish Energy Agency. Author SS is grateful to Elias Hartvigsson for the guidance in modelling, and discussions on modelling energy systems. Authors are also grateful to the reviewers for their insightful comments.

Appendix B. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.glt.2020.06.004.

Appendix A

Table A1
The variables and their values in the EVs diffusion case

Variable	Equations/Values	Units	Basis for value
Adoption rate of fossil to BG cars	Contact rate with BG*Likelihood of buying BG cars*Fossil cars*(BG cars/Total cars)	Cars/Year	
Adoption rate of fossil to EVs	Likelihood of buying EVs*Contact rate with EVs*Fossil cars*(EVs/Total cars)	Cars/Year	
Advertising efficacy of EVs	0.0001	Hours/(SEK*Year)	Assumption of authors
Advertising of EVs	Retailers selling EVs*Average money spent EVs per retailer	SEK	
Average driving distance	100	km	Estimate by MAs
Average money spent EVs per retailer	10,000	SEK	Estimate by MAs
Average time spent by garage personnel talking about EVs	1	Hours/(Year*Garages)	Estimate by MAs
BG cars	INTEG (Adoption rate of fossil to BGs, Initial BG cars)	Cars	
Charging efficacy	Number of public charging stations for daily use/Number of hours to charge	Stations*Cars/Hours	Formulation by authors
Charging station infrastructure certainty	(Number of public charging stations for daily use*Public charging station sensitivity)+Fraction of EV users having charging at work	Dimensionless	Estimate by MAs
Communication from EV owners	1	(Hours/Year)/Cars	Estimate by MAs
Contact rate with EVs	3	1/Year	Estimate by MAs
Converter for actual driving distance anxiety	0.0001	Stations*Cars/(km*Hours)	Assumption of authors
Decrease in price of electricity	Price of electricity-Average price of electricity through private means	SEK/kWh	
Driving distance component of range anxiety of EV	(1-Fraction of EV users having charging at work)*(1-Fraction of EV users having private charging)*Average driving distance/Charging efficacy	km*Hours/(Stations*Cars)	Formulation by MAs
Driving range converter for EV	0.001	1/km	Assumption of authors
Effect of driving distance component of EV on range anxiety	Driving distance component of range anxiety of EV*Converter for actual driving distance anxiety	Dimensionless	
Effect of expected driving distance on range anxiety of EV	WITH LOOKUP (Expected driving range component for EVs*Driving range converter for EV, ([(0,0)-(10,10)],(0.05,0.2),(5,5),(10,7.5)))	Dimensionless	Assumption of authors
Effectivity factor of information	0.0005	Year/Hours	Assumption of authors
EVs	INTEG (Adoption rate of fossil to EVs, Initial EVs)	Cars	

Table A1 (*continued*)

Variable	Equations/Values	Units	Basis for value
EVs in use	Cars	Cars	
EVs in use changing to charging at work	0.001	1/Cars	Assumption of authors
Expected driving range	300	km	Estimate by MAs
Expected driving range component for EVs	Expected driving range-Technical improvement in range	km	
Fossil cars	INTEG (-Adoption rate of fossil to BGs-Adoption rate of fossil to EVs, Initial fossil cars)	Cars	
Fraction of EV users having charging at work	(Multimedia communication about EVs*Multimedia comm changing to EV charging ports at workplaces)+(EVs in use*EVs in use changing to charging at work)	Dimensionless	
Fraction of EV users having private charging	(Decrease in price of electricity*Sensitivity to price decrease of electricity)+(0.001*MAs efforts to private charging at home*MAs efforts)	Dimensionless	
Fuel cost savings through EV for a year	(Fossil fuel cost-EV fuel cost)	SEK	
Garage sensitivity	0.1	1/Garages	
Garages for EVs	Initial garages for EVs+(EVs in use*Sensitivity for EVs in use)	Garages	Communication by MAs
Information about EVs	Effectivity factor of information*Multimedia communication about EVs+(Sensitivity of WOM for perception*Word of mouth for EVs)	Dimensionless	Formulation by authors
Infrastructure uncertainty of EVs	WITH LOOKUP (Charging station infrastructure certainty, ([(0,0)-(10,1)],(0,0.9),(0.05,0.75),(0.1,0.4),(0.5,0.25),(1,0.05),(2,0.01),(10,0.005)))	Dimensionless	Assumption by authors
Initial BG cars	73	Cars	[38]
Initial EVs	10	Cars	[38]
Initial fossil cars	24,037	Cars	[38]
Initial garages for EVs	STEP(1, 1)+STEP(2, 2)+STEP(2, 1)	Garages	
Initial installation of charging stations	1	Stations	Personal communication with MAs
Initial retailers	STEP(1, 1)+STEP(1, 2)+STEP(1, 5)	Retailers	Personal communication with MAs
Investment cost savings for an EV	(-Price of an EV + Price of fossil car + Subsidy grant for EV)/(1 + Average cost of capital)^Average lifetime of car	SEK	
Likelihood of buying EVs	Information about Evs + Financial viability impact on EV + Personal utility of EVs-Range anxiety of EVs	Dimensionless	Formulation by authors
Maintenance cost component of EV financial viability	(Maintenance cost of fossil car-Maintenance cost of EV)	SEK	
Maintenance cost of EV	Vehicle tax on EV	SEK	[45]
Maintenance cost of fossil car	6000+Tariffs for fossil fuel vehicle	SEK	[45]
MAs efforts	1800 − STEP(1800, 3)	Hours/Year	Estimate by MAs
MAs efforts to private charging at home	0.1	Year/Hours	Estimate by MAs
Multimedia comm changing to EV charging ports at workplaces	0.0005	Year/Hours	Assumption by authors
Multimedia communication about EVs	MAs efforts*0.25	Hours/Year	Estimate by MAs
Nominal likelihood of buying EVs	0.05	Dimensionless	Assumption by authors
Number of hours to charge	6	Hours/Cars	Assumption by authors
Number of public charging stations for daily use	(Initial installation of charging stations + STEP(2, 1)+STEP(2, 3))	Stations	Communication by MAs
Perception of EVs	WITH LOOKUP (Word of mouth for EVs*Sensitivity of word of mouth for perception, ([(0,0)-(1,1)], (0,0), (0.1,0.25), (0.5,0.6), (1,0.95)))	Dimensionless	Formulation by authors
Personal utility of EVs	Perception of EVs + Technical novelty	Dimensionless	Formulation by authors
Potential EV ratio	EVs/Total cars	Dimensionless	
Financial viability impact on EV	Financial viability of EV ownership*Sensitivity of financial viability of EV	Dimensionless	
Financial viability of EV ownership	Investment cost savings for an EV + Maintenance cost component of EV financial viability	SEK	
Public charging station sensitivity	0.1	1/Stations	Assumption by authors
Range anxiety of EVs	Effect of driving distance component of EV on range anxiety + Effect of expected driving distance on range anxiety of EV	Dimensionless	Formulation by MAs
Retailer sensitivity	0.1	1/Retailers	Assumption of authors
Retailers per cars sensitivity	0.0001	Retailers/Cars	Assumption of authors
Retailers selling EVs	EVs in use*Retailers per cars sensitivity + Initial retailers	Retailers	
Sensitivity for EVs in use	0.0001	Garages/Cars	Assumption of authors
Sensitivity of financial viability of EV	0.000002	1/SEK	Assumption of authors
Sensitivity of WOM for perception	0.00001	Year/Hours	Estimate by MAs
Sensitivity to price decrease of electricity	0.00001	kWh/SEK	Assumption of authors

(*continued on next page*)

Table A1 (*continued*)

Variable	Equations/Values	Units	Basis for value
Tariffs for fossil fuel vehicle	(Average emission of a fossil car-Emission standard for fossil fuel car)*CO2 tax on fossil fuel car +360	SEK	[46]
Technical certainty variables for EV	(Garage sensitivity*Garages for EVs)+(Retailers selling EVs*Retailer sensitivity)	Dimensionless	
Technical improvement in range	100+RAMP(1, 2, 12)	km	
Technical novelty	WITH LOOKUP (Potential EV ratio, ([(0,0)- (1,1)], (0,1), (0.01,0.95), (0.05,0.75), (0.1,0.35), (0.5,0.1), (1,0.005)))	Dimensionless	Assumption of authors
Technical uncertainty of EVs	WITH LOOKUP (Technical certainty variables for EV, ([(0,0)-(1,1)], (0,0.5), (0.01,0.5), (0.05,0.4), (0.1,0.25), (1,0.05)))	Dimensionless	Assumption by authors
Total cars	(Fossil cars + EVs + BG cars)	Cars	
Uncertainty of EVs	Infrastructure uncertainty of EVs + Technical uncertainty of EVs	Dimensionless	Formulation by authors
Word of mouth for EVs	Average time spent by garage personnel talking about EVs*Garages for EVs) +MAs efforts*0.1+(Advertising efficacy of EVs*Advertising of EVs)+(Communication from EV owners*EVs in use)	Hours/Year	Estimate by MAs

Table A2
The model variables and their values for the techno-economic model of diffusion to EVs

Variable	Equations/Values	Units	Basis for value
Average cost of capital	0.019	Dimensionless	
Average emission of a fossil car	128-RAMP(0.5, 1, 10)	Dimensionless	[45]
Average lifetime of car	12	Dimensionless	Assumption of authors
Average price of electricity through private means	(NPV of investment cost/Yearly electricity taken from the private charging station) + 1.01	SEK/kWh	
CO2 tax on fossil fuel car	22+STEP(60, 2)	SEK	[45]
Decrease in price of electricity	Price of electricity-Average price of electricity through private means	SEK/kWh	
Emission standard for fossil fuel car	111-STEP(16, 2)	Dimensionless	[45]
EV fuel cost	Price of electricity*Yearly driving distance/Fuel efficiency of EV	SEK	
Fossil fuel cost	Price of fossil fuel*Yearly driving distance/Fuel efficiency of fossil fuel	SEK	
Fraction of EV users having private charging	(Decrease in price of electricity*Sensitivity to price decrease of electricity)+(0.001*MAs efforts to private charging at home*MAs efforts)	Dimensionless	
Fuel cost savings through EV for a year	(Fossil fuel cost-EV fuel cost)	SEK	
Fuel efficiency of EV	19+RAMP(0.5, 2, 12)	km/kWh	See Supplementary information
Fuel efficiency of fossil fuel	14	km/Liter	See Supplementary information
Investment cost of private charging infrastructure	10,000	SEK	[12]
Investment cost savings for an EV	(-Price of an EV + Price of fossil car + Subsidy grant for EV)/(1 + Average cost of capital) ^Average lifetime of car	SEK	
Maintenance cost component of EV financial viability	(Maintenance cost of fossil car-Maintenance cost of EV)	SEK	
Maintenance cost of EV	Vehicle tax on EV	SEK	
Maintenance cost of fossil car	6000+Tariffs for fossil fuel vehicle	SEK	[47]
Net investment cost of private charging infrastructure	Investment cost of private charging infrastructure-Subsidy for private charging infrastructure	SEK	
NPV of investment cost	(Net investment cost of private charging infrastructure)/(1.019^20)	SEK	
Price of an EV	600,000	SEK	See Supplementary information
Price of electricity	1.8	SEK/kWh	
Price of fossil car	350,000	SEK	See Supplementary information
	14.6	SEK/Liter	
Financial viability of EV ownership	Investment cost savings for an EV + Maintenance cost component of EV financial viability+Fuel cost savings through EV for a year	SEK	
Subsidy for private charging infrastructure	Investment cost of private charging infrastructure*0.5	SEK	
Subsidy grant for EV	60000-STEP(10000, 2)	SEK	[46]
Tariffs for fossil fuel vehicle	(Average emission of a fossil car-Emission standard for fossil fuel car)*CO2 tax on fossil fuel car +360	SEK	
Vehicle tax on EV	360	SEK	[47]
Yearly driving distance	15,000	km	[39]
Yearly electricity taken from the private charging station	2300	kWh	

Table A3
The model variables and their values to the diffusion to BG cars

Variable	Equations/Values	Units	Basis for value
Adoption rate of fossil to BG cars	Contact rate with BG cars*Likelihood of buying BG cars*Fossil cars*(BG cars/Total cars)	Cars/Year	
Adoption rate of fossil to EVs	Likelihood of buying EVs*Contact rate with EVs*Fossil cars*(EVs/Total cars)	Cars/Year	
Advertising for BG cars	Money spent on BG cars by retailers*Retailers who sell BG cars	SEK	
Availability uncertainty factor	0.0001	1/Retailers	Assumption of authors
Availability uncertainty of BG	WITH LOOKUP (Retailers who sell BG cars*Availability uncertainty factor, ([(0,0)-(0.1,0.3)], (0,0.025), (0.001,0.02), (0.005,0.01), (0.01,0.005), (0.05,0.004), (0.1,0.003)))	Dimensionless	
Average distance driven by a BG car	50	km	Estimate by MAs
Average distance to go to a BG filling station	IF THEN ELSE(BG filling stations>0, 35, 100)	km	
BG cars	INTEG (Adoption rate of fossil to BG cars, Initial BG cars)	Cars	
BG filling station efficacy	((Average distance driven by a BG car/Average distance to go to a BG filling station)^0.5)*(1+BG filling stations)	Stations	
BG filling stations	IF THEN ELSE(Combined support for installing BG stations>0, STEP(3, 2), 0)	Stations	Assumption of authors
BGs in use	BG cars	Cars	
Combined support for installing BG stations	MAs efforts*0.1+(Subsidy converter for BG*Subsidy for installation of BG station)	Hours/Year	
Communication from BG owners	2	(Hours/Year)/Cars	Estimate by MAs
Contact rate with BG	3	1/Year	Estimate by MAs
Distance component of range anxiety of BG cars	Expected range of a BG car-Range of a BG car	km	
Efficacy of for BG cars	0.0001	Hours/(Year*SEK)	Assumption of authors
Expected range of a BG car	400	km	Estimate by MAs
Fuel component of range anxiety of BG cars	1/BG filling station efficacy	1/Stations	
Fuel cost savings of BG	Fossil fuel cost-Biogas fuel cost	SEK	
Garages for BG cars	STEP(1, 1)+STEP(1, 2)	Garages	Information from MAs
Information about of BG cars	(Multimedia communication for BGs + Word of mouth for BGs)*Information converter for BG	Dimensionless	Formulation by authors
Information converter for BG cars	0.00015	Year/Hours	Assumption of authors
Investment cost savings for a BG	(Price of fossil car-Price of a BG car + Subsidy for a BG car)/(1 + Average cost of capital)^Average lifetime of car	SEK	
Likelihood of buying BG cars	Nominal likelihood of buying BG cars + Information about of BG cars + Financial viability component of likelihood to buy BG cars + Personal utility of BG cars-Range anxiety of BG cars-Uncertainty of BG cars	Dmnl	Formulation by authors
Maintenance cost component of financial viability of BG cars	(Maintenance cost of fossil car-Maintenance cost of BG car)	SEK	
Maintenance cost of BG car	3000+(Average emission of BG car-Emission standard for BG car)*CO2 tax of BG car	SEK	
Money spent BG cars by retailers	10,000	SEK/Retailers	Estimates by MAs
Multimedia communication for BG cars	MAs efforts*0.25	Hours/Year	Estimates by MAs
Nominal likelihood of buying BG cars	0.05	Dimensionless	
Personal utility converter for word of mouth for BG cars	0.000125	Year/Hours	Assumption of authors
Personal utility of BGs	Word of mouth for BG cars*Personal utility converter for word of mouth for BG cars	Dimensionless	Assumption of authors
Financial viability component of likelihood to buy BGs	Financial viability of BG car ownership*Sensitivity to financial viability to buy BG cars	Dimensionless	
Financial viability of BG ownership	Fuel cost savings of BG cars + Investment cost savings for a BG car + Maintenance cost component of financial viability of BG car	SEK	
Range anxiety of BG cars	(Distance component of range anxiety of BG cars*Sensitivity to distance component of range anxiety of BG cars)+(Fuel component of range anxiety of BG cars*Sensitivity to fuel component of range anxiety of BG cars)	Dimensionless	Formulation by MAs
Range of a biogas car	300+RAMP(1, 2, 15)	km	See Supplementary information
Retailer sensitivity to BG cars	10	Retailers/Cars	Assumption of authors
Retailers who sell BG cars	STEP(3, 0)+(Sensitivity of BG retailers to BG in use*Retailer sensitivity to BG cars)	Retailers	Communication by MAs
Sensitivity of BG retailers to BG in use	IF THEN ELSE(BGs in use ≥ 1, 0.01, 0)	Cars	Assumption of authors
Sensitivity to distance component of range anxiety of BG cars	0.0001	1/km	Assumption of authors
Sensitivity to fuel component of range anxiety of BG cars	0.01	Stations	Assumption of authors
	0.000001	1/SEK	

(*continued on next page*)

Table A3 (*continued*)

Variable	Equations/Values	Units	Basis for value
Sensitivity to financial viability to buy BG cars			Assumption of authors
Subsidy converter for BG	0.0001	Hours/(Year*SEK)	
Subsidy for installation of BG station	400,000	SEK	Communication by MAs
Tariffs for fossil vehicle	(Average emission of a fossil car-Emission standard for fossil fuel car)*CO2 tax on fossil fuel car +360	SEK	[48]
Technical uncertainty factor	0.01	1/Garages	
Technical uncertainty of BG cars	WITH LOOKUP (Garages for BG cars*Technical uncertainty factor, ([(0,0)-(10,0.1)], (0,0.1), (1,0.05), (2,0.025), (3,0.0015), (10,0.0005)))	Dimensionless	Assumption of authors
Uncertainty of BG cars	Availability uncertainty of BG + Technical uncertainty of BG	Dimensionless	Assumption of authors
Word of mouth for BG cars	MAs efforts*0.1+(Advertising for BG cars*Efficacy of for BG cars)+(BG cars in use*Communication from BG car owners)	Hours/Year	Assumption of authors

Table A4
The model variables and their values in the techno-economic model variables in the diffusion to BG cars

Variable	Equations/Values	Units	Basis for value
Average emission of BG car	128	Dimensionless	[45]
Biogas fuel cost	Fuel cost of BG*Yearly driving distance/Fuel efficiency of BG cars	SEK	
CO2 tax of BG car	11	SEK	[46]
Emission standard for BG car	111	Dimensionless	[48]
Fuel cost of BG	18.26	SEK/kg	See Supplementary information
Fuel cost savings of BG car	Fossil fuel cost-Biogas fuel cost	SEK	
Fuel efficiency of BG cars	25+RAMP(0.5, 2, 12)	km/kg	See Supplementary information
Investment cost savings for a BG car	(Price of fossil car-Price of a BG car + Subsidy for a BG car)/(1 + Average cost of capital) ^Average lifetime of car	SEK	
Maintenance cost component of financial viability of BG car	(Maintenance cost of fossil car-Maintenance cost of BG car)	SEK	
Maintenance cost of BG car	3000+(Average emission of BG car-Emission standard for BG car)*CO2 tax of BG car	SEK	
Maintenance cost of fossil car	6000+Tariffs for fossil fuel vehicle	SEK	
Price of a BG car	385, 000	SEK	See Supplementary information
Financial viability of BG car ownership	Fuel cost savings of BG + Investment cost savings for a BG car + Maintenance cost component of financial viability of BG car	SEK	
Subsidy for a BG car	8000+STEP(2500, 2)	SEK	[46]

Some of the values given in Tables A1–A4 are functions which are built into the computer program application, Vensim, used to build the simulation models. Descriptions of the functions; STEP; RAMP; LOOKUP and IF THEN ELSE can be found at [40].

References

[1] J. Ackva, J. Hoppe, The carbon tax in Sweden, fact sheet for federal ministry for the environment, Nat. Conserv. Nucl. Saf. (BMU) (2018).

[2] H.K. Anheier, G. Krlev, G. Mildenberger, Social innovation - comparative perspectives, in: H.K. Anheier, G. Krlev, G. Mildenberger (Eds.), Routledge Studies in Social Enterprise & Social Innovation, 2019.

[3] F. Avelino, et al., Transformative Social Innovation and (Dis)empowerment, Technol. Forecast. Soc. Change 145 (2019) 195–206. Elsevier.

[4] F.M. Bass, The relationship diffusion rates, experience curves, and demand elasticities for consumer durable technological innovations, J. Bus. 53 (3) (1980).

[5] S. Bolwig, et al., Modelling energy transitions pathways, Int. Sustain. Transit. 2018 (June) (2018) 2–12. Available at: https://www.researchgate.net/publication/327755499_Modelling_energy_transitions_pathways.

[6] A. van Bruggen, I. Nikolic, J. Kwakkel, Modeling with stakeholders for transformative change, Sustainability 11 (3) (2019) 825, https://doi.org/10.3390/su11030825.

[7] M. Rabadjieva, A. Butzin, Emergence and diffusion of social innovation through practice fields, Eur. Plan. Stud. Taylor Francis (2019) 1–16, https://doi.org/10.1080/09654313.2019.1577362, 0(0).

[8] G. Cajaiba-Santana, Social innovation: moving the field forward. A conceptual framework, Technol. Forecast. Soc. Change 82 (1) (2014) 42–51, https://doi.org/10.1016/j.techfore.2013.05.008. Elsevier B.V.

[9] E.U. Carfax, Vehicle tax - calculation and payment in Sweden, Available at: https://www.carfax.eu/article/vehicle-tax-sweden, 2019.

[10] Dalsland Kommunalforbund, Available at: http://www.dalsland.se/energi-klimat/, 2017.

[11] B. Ecker, et al., Social Innovation in the Energy Field in Structurally Weak Regions . Insights into European Trends and Tendencies, 2018 (March).

[12] W.H. Voorberg, V.J.J.M. Bekkers, L.G. Tummers, A Systematic Review of Co-Creation and Co-Production: embarking on the social innovation journey, Publ. Manag. Rev. (2014) 1–25, https://doi.org/10.1080/14719037.2014.930505. July 2014.

[13] B. Edmonds, et al., Different modelling purposes, J. Artif. Soc. Soc. Simul. 22 (6) (2019), https://doi.org/10.18564/jasss.3993.

[14] Skåne Energikontoret, Solar Regionen Skåne, 2016.

[15] T.S. Fiddaman, Exploring policy options with a behavioral climate-economy model, Syst. Dynam. Rev. 18 (2) (2002) 243–267, https://doi.org/10.1002/sdr.241.

[16] A. Genus, A.M. Coles, Rethinking the multi-level perspective of technological transitions, Res. Pol. 37 (9) (2008) 1436–1445, https://doi.org/10.1016/j.respol.2008.05.006.

[17] Government Offices of Sweden, Bonus-malus System for New Vehicles, 2018.

[18] K. Hasselmann, et al., 'Free-riders to forerunners', *nature Geoscience* 8, Nature Publishing Group, 2015, pp. 895–898, https://doi.org/10.1038/ngeo2593, 12.

[19] R.J. Hewitt, et al., Social innovation in community energy in Europe: a review of the evidence, Front. Energy Res. 7 (2019) 31, https://doi.org/10.3389/fenrg.2019.00031.

[20] R. Hölsgens, S. Lübke, M. Hasselkuß, Social innovations in the German energy transition : an attempt to use the heuristics of the multi-level perspective of transitions to analyze the diffusion process of social innovations, Energy Sustain. Soc. 8 (8) (2018).

[21] A. Horsbøl, 'Co-Creating green transition: how municipality employees negotiate their professional identities as agents of citizen involvement in a cross-local setting', *environmental communication*, Taylor Francis (2018) 1–14, https://doi.org/10.1080/17524032.2018.1436580, 0(0).

[22] J. Howaldt, et al., TOWARDS A GENERAL THEORY AND TYPOLOGY OF SOCIAL INNOVATION, 2017.

[23] J. Köhler, B. Turnheim, M. Hodson, 'Low Carbon Transitions Pathways in Mobility: Applying the MLP in a Combined Case Study and Simulation

Bridging Analysis of Passenger Transport in the Netherlands', *Technological Forecasting and Social Change*, Elsevier, 2018, pp. 1–17, https://doi.org/10.1016/j.techfore.2018.06.003. August 2017.

[24] D.C. Lane, 'Should system dynamics be described as a "hard" or "deterministic" systems approach?', Syst. Res. Behav. Sci. 17 (1) (2000) 3–22, https://doi.org/10.1002/(sici)1099-1743(200001/02)17:1<3::aid-sres344>3.3.co;2-z.

[25] A. Leopold, Energy related system dynamic models: a literature review, Cent. Eur. J. Oper. Res. 24 (1) (2016) 231–261, https://doi.org/10.1007/s10100-015-0417-4. Springer Berlin Heidelberg.

[26] J. Lindahl, C. Stoltz, National Survey Report of PV Power Applications in Sweden 2017, IEA PVPS, 2018.

[27] Naturvardsverket, Support for Charging Stations - Klimatklivert, no date, 2017.

[28] M. Nilsson, Green Overhaul of Swedish Fuel and Vehicle Taxation, Green Budget Europe, 2018, pp. 3–4.

[29] J. Palm, Household installation of solar panels – motives and barriers in a 10-year perspective, Energy Pol. 113 (June 2017) (2018) 1–8, https://doi.org/10.1016/j.enpol.2017.10.047. Elsevier Ltd.

[30] Gron Omstilling Samskabende, E.U. Interreg, sagrom.com, Available at: http://sagrom.com/, 2016. (Accessed 21 May 2018).

[31] S. Selvakkumaran, E.O. Ahlgren, Understanding the local energy transitions process: a systematic review, Int. J. Sustain. Energy Plann. Manag. 14 (2017), https://doi.org/10.5278/ijsepm.2017.14.5.

[32] S. Selvakkumaran, E.O. Ahlgren, Determining the factors of household energy transitions: a multi-domain study, Elsevier Ltd, Technol. Soc. (December) (2018a), https://doi.org/10.1016/j.techsoc.2018.12.003, 0–1.

[33] S. Selvakkumaran, E.O. Ahlgren, Model-based exploration of co-creation efforts: the case of Solar Photovoltaics (PV) in Skåne, Sweden, Sustainability (Switzerland) 10 (11) (2018b), https://doi.org/10.3390/su10113905.

[34] Centralbyrån Statiska, New registratered passenger cars by region, Fuel Month (2019).

[35] J. Sterman, System dynamics at sixty: the path forward, Syst. Dynam. Rev. 34 (1–2) (2018) 5–47, https://doi.org/10.1002/sdr.1601.

[36] J.D. Sterman, Business Dynamics - Systems Thinking and Modeling for a Complex World, 2000.

[37] J.D. Sterman, All models are wrong: reflections on becoming a systems scientist, Syst. Dynam. Rev. 18 (4) (2002) 501–531, https://doi.org/10.1002/sdr.261.

[38] J.J.R. Struben, J.D. Sterman, 'Transition challenges for alternative fuel vehicle and transportation systems, Environ. Plann. B Plann. Des. Boston 35 (6) (2008) 1070–1097, https://doi.org/10.1068/b33022t.

[39] Svensk Solenergi, 'Förslag till Strategi för Ökad Användning Av Solel [Proposal for Strategy of Increased Use of Solar Electricity]', *Et 2016:16*, vol. 44, Svensk Solenergi, Stockholm, 2016, pp. 1404–3343.

[40] I. System, D. Review, System dynamics review, Syst. Dynam. Rev. 22 (22) (2006) 2006, https://doi.org/10.1002/sdr.

[41] Trafikanalys, Transport Statistics, Trafikanalys, 2019a.

[42] Trafikanalys, Vehicle Statistics, Trafikanalys, 2019b.

[43] Trafikanalysis, Statiska Centralbyrån, Vehicles in Counties and Municipalities 2016, Statiska Centralbyrån, 2017.

[44] B. Turnheim, F.W. Geels, 'Incumbent actors, guided search paths, and landmark projects in infra-system transitions: Re-thinking Strategic Niche Management with a case study of French tramway diffusion (1971–2016)', Res. Pol. 48 (6) (2019) 1412–1428, https://doi.org/10.1016/j.respol.2019.02.002. Elsevier.

[45] S. Ulli-Beer, et al., Participative modelling of socio-technical transitions: why and how should we look beyond the case-specific energy transition challenge? Syst. Res. Behav. Sci. 34 (4) (2017) 469–488, https://doi.org/10.1002/sres.2470.

[46] Vensim, Vensim help - user's guide models, user guide, Available at: https://www.vensim.com/documentation/index.html, 2019.

[47] E. Wolstenholme, Using Generic System Archetypes to Support Thinking and Modelling, vol. 20, 2004, pp. 341–356, https://doi.org/10.1002/sdr.302, 4.

[48] X. Zhao, et al., The sustainable development of the economic-energy-environment (3E) system under the carbon trading (CT) mechanism: a Chinese case, Sustainability (Switzerland) 10 (1) (2018), https://doi.org/10.3390/su10010098.