

## Complex Systems Engineering

### Designing in sociotechnical systems for the energy transition

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## Complex Systems Engineering: designing in socio-technical systems for the energy transition

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### Abstract

The EU has set ambitious targets for an energy transition. While research often focuses on technology, institutions or actors, a transition requires complex coordination and comprehensive analysis and design. We propose a framework accounting for technology, institutions and actors' perspective to design in socio-technical systems. We present its application, firstly, to biodiesel production in Germany; secondly, to vehicle-to-grid contracts in a Car as a Power Plant microgrid. We show how using the framework as the core in modelling can contribute to the performance improvement of these systems. Future work will elaborate on the next generation of thermal energy systems, coordination control of microgrids and implementing flexibility through demand response aggregation. Overall, designing solutions to the problems described calls for comprehensive engineers who look beyond the technical design and deal with multi actor socio-political processes including institutional consideration.

**Keywords:** socio-technical systems, complex-adaptive systems, energy transition, framework, design, operation, performance

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### 1. Introduction

In 2011, the European Union (EU) set the long-term goal of reducing greenhouse gas emissions by 80 to 95% by 2050 [1]. Later in 2014, as part of the 2030 Framework for climate and energy, the EU set the targets of attaining at least 40% reduction in greenhouse gas emissions as compared to 1990 levels, and to increase the share of energy efficiency and renewable energies to 27% of gross energy consumption [2]. These policy changes have resulted in a significant transition in the EU from energy systems based on fossil fuels to those based on sustainable and renewable sources. These shifts have been supported by a wealth of research to replace fossil fuels by renewable bio-based fuels in the transportation sector [3], increase the penetration of renewable energy sources [4], design and deploy smart electricity [5] and thermal grids [6], provide flexibility as a response to variability of wind and solar generation [7],

increase the participation of consumers via demand response [8], as well as manage the emergence of new roles in the electricity markets such as aggregators [9].

Achieving the targets set by the EU has proven to be challenging due to many characteristics of energy systems as complex socio-technical systems [10]. An effective approach for solving many problems related to energy transition requires intelligent combinations of technological, economic, legal and social interventions. Challenges in the field of energy transition ask for new approaches for designing. Designing in socio-technical systems (STS) means not only designing technical solutions according to the latest technology, but also addressing new business opportunities and legal, ethical as well as social expectations and requirements.

A multi-actor network determines the development, operation and management of the technical systems, which in turn affects the behaviour of the actors. Moreover, the dynamic character of self-organizing

processes in which the system co-evolves often results in new emerging institutions, which influence the design process, too. Complex Systems Engineering (CSE) addresses not only the challenges and possibilities of technical artefacts but also multi-actor complexity of socio-technical systems. The proposed interventions form then a coherent combination of institutional arrangements and technical system design involving multiple actors on multiple levels.

Mostly, in mono-disciplinary approach research concentrates on the technology or institutions only and include broad assumptions on the remaining ones. While a systems perspective is adopted, then it often remains descriptive and does not necessarily reach formalization into quantitative tools for further analysis and design. Therefore, a question remains on how to provide analytical tools to aid the design process in socio-technical systems. Accordingly, this article aims at tackling the following question:

*“How to design in socio-technical systems for the energy transition?”*

To answer this question, we propose a conceptual framework that takes into account interactions among and within technical system, actors, and institutions; all of which affect the operation of the system. This framework is a general identification of main pillars, and the relations between them, that need to be considered when designing interventions in complex socio-technical systems for the energy transition. Through the framework, we address the research question in two ways. Firstly, by proposing its use for system analysis in order to focus on the interactions of a system, rather than on single components or perspectives. Secondly, by proposing its use for designing different arrangements within these systems.

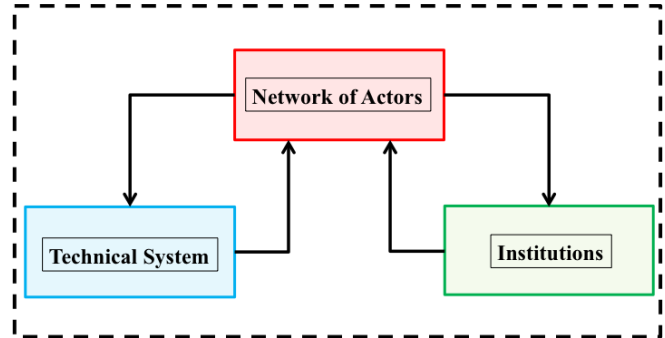
Overall, our framework applies the theory of complex adaptive systems to analyze socio-technical systems. Through the exploitation of the analytical power of agent-based modeling and simulations and the combination of advanced optimization algorithms under uncertainty, we address the compelling technical and institutional challenges that cloud the comprehensive understanding of sustainable energy systems.

The rest of the paper is organized as follows: in Section 2 we elaborate on the proposed framework. Then, in Section 3 we show the application of the framework with two case studies and introduce future work. Finally, in Section 4 we present our conclusions.

## 2. Conceptual framework definition

As shown in Figure 1, the conceptual framework for analysis and design builds on three pillars: institutions, network of actors, and the technical system. *“Institutions are the rules of the game in a society or, more formally, are the humanly devised constraints that shape human interaction”* and their *“major role in a society is to reduce uncertainty by establishing a stable (but not necessarily*

*efficient) structure to human interaction”*[11]. Actors (individuals, organizations, firms, etc.) are the entities that make decisions and participate in processes by performing different roles. The technical system refers to all technical elements in the system (infrastructure, technologies, artifacts, and resources) and physical flows and processes. When designing in socio-technical systems, these three elements and their interactions have to be considered at once.



**Figure 1.** Framework for the analysis of socio-technical systems

The interaction of institutions and actors might take place at different levels. At the lowest level, institutions refer to the rules, norms, and shared strategies that influence the behavior of individuals and shape the interaction between them within an organization. One level higher of analysis, institutions describe the different mechanisms of interaction between actors that are designed to coordinate specific transactions. At the highest level of analysis, institutions represent the rules of the game that influence the behavior of the actors.

The interaction between the technical system and the network of actors is less abstract. Actors design, build, operate, maintain and invest in different elements of the technical system. In turn, the technical system enables actors to create wealth, to coordinate transactions, and to track compliance with certain laws and regulations [12]. Institutions at all levels of analysis influence the interactions between the technical system and actors. They provide guidelines, constraints and rules for the actors to perform their roles in relation to the technical system.

The three pillars described above and the interactions among them can be identified when analyzing the transition towards future sustainable energy systems. For example, on the consumer side, the adoption of low-carbon microgeneration technologies such as solar photovoltaic (PV) systems can contribute to an increase of renewable electricity generated and used locally. A large scale diffusion of PV systems at the household level would eventually influence the operation of the traditional power plants, as less electricity is needed from the grid during the day. In the technical system, we consider the PV systems that are connected to the households and the distribution grids. Relevant actors influencing this transition are not only those involved in the development, manufacture and supply

of solar PV technologies, but also adopters, i.e. households and businesses that purchase PV systems. National and local governments and governmental bodies involved in relevant legislation and support schemes are also part of the network of actors interacting with each other. The question is how they should define new institutions to regulate e.g. the new role of households as prosumers. For instance, remuneration schemes like feed-in tariffs or net metering can be put in place to determine the price that a household receives for every kWh. These schemes, together with limits on the injected electricity that can be remunerated might affect the way consumers behave. As showed, for example, in [13] the potential value of look-ahead energy management strongly depends on the tariff structure. In particular, in systems where there is already a high penetration of renewable energy sources without a fixed feed-in tariff, there seems to be a larger value for demand response than with a fixed feed-in tariff.

As it was pointed out above, interactions among the technical system, network of actors, and the institutions influence the overall behavior of socio-technical systems. Therefore, when designing in socio-technical systems for the energy transition, the three main pillars and interactions among them have to be considered simultaneously and not only in isolation.

### 3. Conceptual framework in practice

#### 3.1. Biodiesel production in Germany

##### Case description

Production of biodiesel in Germany began in 1991, with the rapeseed as the main feedstock and transesterification as the technological process. Biodiesel production grew exponentially from 1997 onwards. Whereas in 1998 German production capacity was 65000 t/y, by 2006 it had grown to 3.5 million t/y [14], [15]. Governmental interventions, such as introduction of standard certifications and a single payment scheme, and rising oil prices have contributed to this growth in German biodiesel production [16].

This study focuses on the analysis of the effect of four formal institutions on the evolution of the German biodiesel supply chain, namely: the common agricultural policy (CAP), the liberalization of the EU agricultural market, the energy tax act and the biofuel quota act. The common agricultural policy (CAP), enacted in 1992, decommissioned a percentage (5–15%) of agricultural land to be earmarked, or set aside, for alternative uses. Farmers were allowed to cultivate non-food crops on those set-aside lands. However, it was forbidden to sell set-aside rapeseed in the food market. The liberalization of the EU agricultural market prompted (or initiated) the fundamental reform of the CAP in 2003. Production- and volume-focused policies were shifted to area related payments to stimulate a further liberalization of the EU agricultural market.

The energy tax act, enacted in 2006, defined an annual increase of the tax rate on biodiesel. Finally, the biofuel quota act, introduced in 2007, aimed to stimulate the biodiesel industry by pressuring biofuel producers and distributors, to meet a biodiesel quota.

##### Theories and methods

Three theories underpin the conceptual framework. Firstly, complex adaptive systems (CAS) theory is used to explain the creation of the macro behavior of the system (emergence) as a consequence of the interaction among the different system elements (complexity) and how, in turn, these elements adapt to the macro behavior they created (adaptation). Secondly, neo-institutional economic theory is used to specify the interaction between institutions and the network of actors and to describe the interaction between actors (spot market, bilateral contracts, vertical integration). Finally, the theory of the critical price linkages and economics of blend mandates states that biofuel policies cause a link between crop and biofuel prices. Unlike the crop-biofuel price link, the biofuel-fossil fuel link is policy-regime dependent. If a biofuel consumption subsidy is enacted, biofuel prices, and therefore crop prices, are locked onto fossil fuel prices. When the mandate is binding, biofuel prices are delinked from fossil fuel prices.

Supported by these theories, the conceptual framework is further formalized into an agent-based model to analyze the influence of institutions on biofuel supply chains, with German biodiesel production as a case study. Agent-based modelling was chosen owing to its bottom-up perspective, adaptability, and generative nature [17].

##### Development of agent-based model – ODD protocol

The description of the agent-based model is based on the ODD protocol proposed by [18]. The *overview* of the model is presented in this section, and the *design concepts* and *details* can be found in the Appendix A.

*Purpose:* The aim of the model is to shed light on what behavioral mechanisms of actors led to the emergence of the German biodiesel supply chain. The impact of bioenergy and agricultural policies on the different actors involved in the supply chain for biodiesel are to be modeled, replicating not only the currently observed pattern, but also exploring what conditions might lead to different outcomes.

##### Entities, state variables and scales

Farmers, biofuel producers, and distributors are the actors, called here agents, considered in the analysis of the biodiesel supply chain. Agents, unlike traditional economic analysis, behave based on their own local information. Agents have different roles; farmer agents perform the role of rapeseed suppliers; biofuel producers agents perform the role of biodiesel producers; distributors are responsible for dispensing biofuel. The state variables of agents are described in **Table 1**. Global environment consists of formal institutions (subsidies, tax rates, blend mandate and penalties). The model time step is one year, and simulation

run for 22 years (1992-2014). The model landscape is 16 x 16 patches in size and it is assumed to cover the entire surface area of Germany. A thorough description of the model is provided by [12].

**Table 1.** Main state variables of the agents and global variables

Parameter	Brief description	Units
Farmers		
farm-area	Surface area	ha
rape-prod-cost	Production cost of rapeseed	euro/t
wheat-prod-cost	Production cost of wheat	euro/t
Biofuel producers		
prod-capacity	Production capacity	Ml
biod-prod-cost	Production cost of biodiesel	euro/l
yield-biodiesel	Yield of biodiesel per kg oil	kg/kg
prof-margins	Profit margins	%
Distributors		
capacity	Capacity	Ml
prof-margins	Profit margins	%
Global variables		
tax-bio	Tax on biodiesel	euro/l
penalty-bio	Penalty on biodiesel	euro/l
ratio-quota-total-capacity	ratio between quota for biodiesel production and total production capacity	dmnl

**Process overview and scheduling**

The scheduling is formed by a set of events that take place sequentially in discrete periods (see Figure 2). The first year can be considered as a “warm up” period for the simulation. In this year, farmers make decisions about land use under endogenous expectations. Biofuel producers and distributors determine their bids for rapeseed, and biodiesel, respectively, by forecasting biodiesel prices for the next year. Biofuel producers also procure rapeseed. In the second year, biodiesel is produced and its price is determined in the biodiesel market. Biofuel producers decide whether to invest in production capacity based on market developments. The activities described in the first year for the rapeseed market are also carried out in parallel during the second year. The cycle is repeated until the simulation reaches the final year.

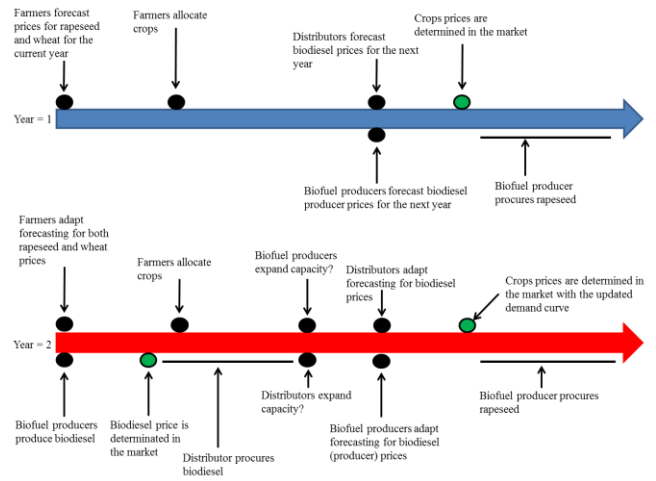


Figure 2. Model narrative (adapted from Moncada *et al.* [19])

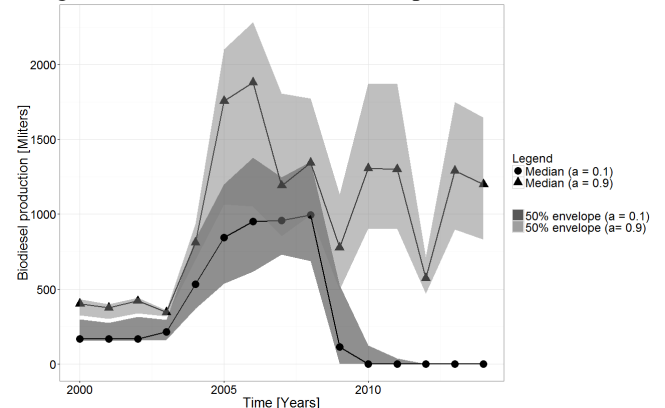
Agents improve their forecasting based on the following equation [20].

$$C_t^e = C_{t-1}^a (C_{t-1}^e)^{(1-a)} \quad (1)$$

$C_{t-1}^e$  is the estimate for the previous year,  $C_{t-1}$  is the actual value from the past year, and  $C_t^e$  is the updated estimate for the current year.  $a$  is a parameter that weighs the influence of the actual value of the previous year as compared to the estimate in the forecasting,  $0 \leq a \leq 1$ .

**Results**

Figure 3 shows biodiesel production patterns as a function of time at different values of the parameter  $a$  in Equation 1. Values of parameter  $a$  close to the unity implies that agents adapt their forecasting by taking into account the actual price endogenously calculated in the system. On the contrary, a value of the parameter  $a$  close to zero implies that agents ignore the market signals when prices are to be forecasted. For the cases ( $a=0.1$ ;  $a=0.9$ ), it was assumed that all agents had the same value for this parameter.





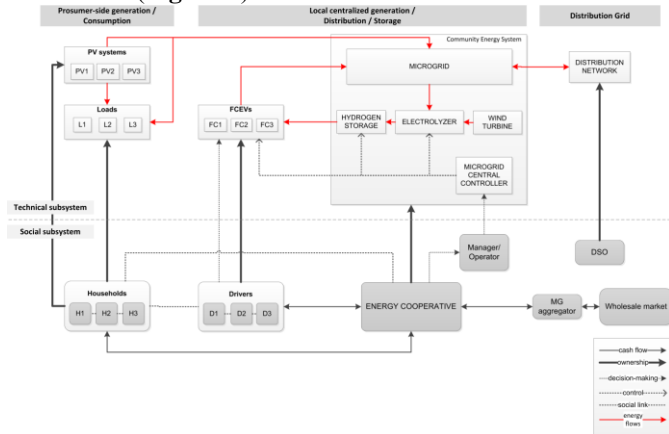
**Figure 3.** Biodiesel production as a function of time at different values of the parameter used in the forecasting of prices for rapeseed and biodiesel (see Equation 1). Adapted from [19].

Figure 3 shows that the impact of the parameter  $a$  is regime-dependent. Before the agricultural market was liberalized in 2003, the effect of the parameter on biodiesel production is negligible. However, when the agricultural market is liberalized in 2003, biodiesel production considerably increases at higher values of the parameter  $a$ . Biodiesel production is considerably affected at lower values of the parameter  $a$ ; specially, after the energy tax is enacted in 2006. This result suggests that the performance of the system depends on the ability of agents to adapt to it in the event that an external shock (the introduction of a new policy) is introduced in the system.

### 3.2. Vehicle-to-grid contracts in a Car as Power Plant microgrid

#### Case description

The Car as Power Plant (CaPP) concept proposes integrated transport and energy systems using fuel cell electric vehicles (FCEVs) as flexible power plants and hydrogen as storage [21]. A specific application of the CaPP concept is studied with the CaPP microgrid case. The technical system of the microgrid consists of a neighbourhood of 200 households, each with PV panels, 50 FCEVs, and a centralized electrolyzer and hydrogen storage system. Moreover, there are external wind turbines used to produce hydrogen. In the microgrid, surplus PV generation is used to produce hydrogen, and FCEVs are operated whenever it is insufficient (Figure 4).

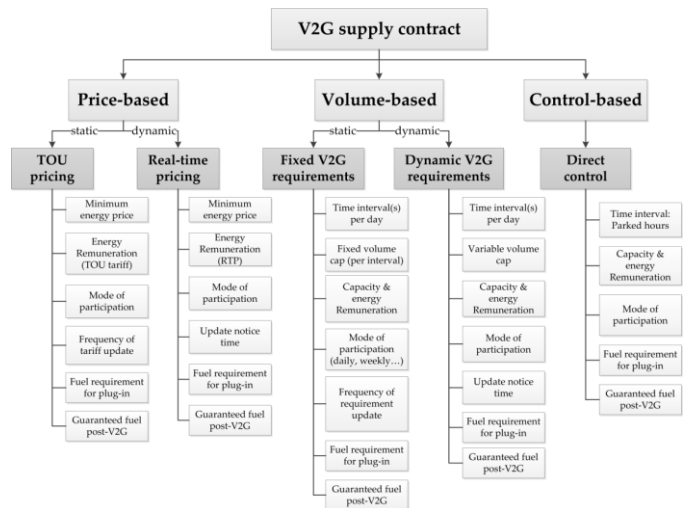


**Figure 4.** Diagram of the socio-technical system of a CaPP microgrid

The operation of the microgrid, including the use of vehicles is studied in our previous work with optimization models

[22], and with a fair FCEV scheduling mechanism proposed to distribute the operation of cars fairly among drivers [23]. In all models, we assumed cars were plugged in for V2G whenever they were parked in the neighborhood.

The main types of actors in this system are the fuel cell car drivers and the microgrid operator. While in previous works these actors were assumed to follow the system needs, in this paper we introduce the institutions used by actors at the operational level: the vehicle-to-grid (V2G) contracts between drivers and aggregator. These are mentioned in the V2G literature [24] as a coordination mechanism of EV drivers. However, the contractual arrangements and their effect at the operational level are not tested. Thus, for this case contract types and specifications for V2G power supply are developed (Figure 5), based on the demand response literature [25]. Two of the contract types are compared, namely the static volume-based and control based contracts, by looking into the effects on system performance and implications for drivers.



**Figure 5.** Contract types and specifications for V2G supply

#### Theories and methods

Complex adaptive systems (CAS) theory is used to view the microgrid's emergent system behaviour as a result of the interactions between the elements in the technical subsystem and the involved actors, influenced partly by rules. Characteristics of individual actors might influence differently the decisions they take on the technical elements (e.g. drivers on the use of FCEVs). These decisions, in turn, have an effect on the number of FCEVs available for operation and the amount of electricity that the central microgrid operator is allowed to generate with them. Adaptive behaviors of actors will be added in future research, and in this study we focus on the rules that can be used to coordinate drivers with heterogeneous characteristics.

Since we are looking at institutions on the operational level, the main theory used for the analysis of institutions in this case belongs to transaction cost economics (TCE) [26]. Within Williamson's framework of the four layers of

institutional analysis, the TCE operates at the third level and is concerned with second-order economizing and thus governance structures and contractual arrangements.

To study the CaPP microgrid system using the proposed framework and the theories mentioned above we use agent-based modeling and simulation. This method allows us to model heterogeneous agents with contracts with different characteristics and to simulate the operation and analyse the effect of institutions on the system performance.

**Development of agent-based model – ODD protocol**

The agent-based model of the Car as Power Plant microgrid is described in this section following the ODD protocol [18]. The *overview* of the model is presented in this section, and the *design concepts* and *details* can be found in the Appendix B.

*Purpose:* The purpose of the model is to understand the effect of institutions (V2G contracts) on the operation of each FCEV in the system, and in turn on the performance of the microgrid system.

**Entities, state variables and scales**

Agents represented in the model for the operation of the microgrid are the drivers and the microgrid operator. In this model the operator only makes decisions to operate the system. The main states and characteristics of driver agents are shown in

Table 2. Objects are elements in the technical subsystem: PV systems, wind turbine, electrolyzer, hydrogen storage, and households. Households are modelled as objects since they do not make decisions that affect their consumption or use of the cars. The vehicle (object) and driver (agent) are represented together in one *FCEV* agent.

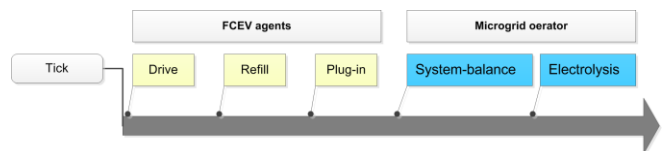
**Table 2.** FCEV agent states

State	Description	Type
Arr-wday   Arr-wend	Arrival time in weekdays and weekends	Integer
Dep-wday   Dep-wend	Departure time in weekdays and weekends	Integer
Dist-wday   Dist-wend	Total daily distance driven in weekdays and weekends	Float [km]
Driving_t	List of km driven in all time steps	List
H2-tank	Current amount of hydrogen	Float [kg]
H2-refill	List of amount of hydrogen refilled in all time steps	List
Here?	Indicates if car is in neighbourhood	Boolean
CaPP?	Indicates if car is in V2G mode	Boolean
Refilling?	Indicates if car is refilling	Boolean
SU	Total start-ups of the vehicle (for CaPP)	Integer
Owner	Household the driver belongs to	Who

Interval-wday   Interval-wend	Contract specification: time interval for plug-in [Volume-based contract]	List of integers
Vol-wday   Vol-wend	Contract specification: Volume cap that can be provided in each time interval [Volume-based contract]	Integer [kWh]
H2-v2g-wday   H2-v2g-wend	Contract specification: minimum hydrogen needed before plug-in [Volume-based contract / Direct control contract]	Float [kg]
H2-guarant	Guaranteed hydrogen in tank - minimum hydrogen for one round-trip + safety margin	Float [kg]

**Process overview and scheduling**

The scheduling is done in one-hour ticks throughout the simulation run. Every tick, the following procedures are executed (See Figure 6):



**Figure 6.** Procedures in simulation

- Drive: According to drivers’ arrival and departure time, FCEV agents leave or arrive. In doing so, the hydrogen level in the vehicle’s tank is updated.
- Refill: When cars arrive in the neighbourhood and they don’t have enough fuel for plug-in, they refill by topping up the tank.
- Plug-in: Following time interval specifications, the FCEV agents plug-in after arriving in the neighbourhood. They will stay connected every tick unless the time interval is up or the volume cap has been reached.
- System-balance: the microgrid operator performs the balance of the system. The residual load is calculated, and FCEVs are switched on and operated if necessary. A fair scheduling mechanism is used in this model, as in [23].
- Electrolysis: Two electrolyzers are operated; one for the surplus PV generation and the other one for the external wind power generated. Hydrogen is produced and stored in the central hydrogen tank.

**Results**

The results in Table 3 show that the volume-based contracts used have lower plug-in requirements for drivers but lead to higher shortage hours.

**Table 3.** Yearly results

Contract type	System performance		Implications for drivers		
	Residual load supply %	Shortage hours	Avg. plug-in hours (h/day)	Avg. total V2G supply per start-up (kWh)	Avg. total SU per week
VBC1	91.3%	953.0	7.5	32.8	4.5
VBC2	91.1%	995.7	7.1	42.4	3.5
DCC1	97.4%	394.5	14.5	47.3	3.3
DCC2	99.9%	18	14.5	52.7	3.1

contracts perform better at the system level. Therefore, a glimpse of the tensions seen between drivers (actors) and system needs (technical system) can be seen in this case; which was not derived explicitly from previous works [22], [23], [27].

This model was used to test the effect of contract specifications on the technical system. As an exploratory study, the same type of contract was assigned to all drivers, with slight differences in the specifications. To further develop the model we will incorporate the preferences of agents and their adaptive behavior, allowing agents to choose and change contract specifications based on their individual goals.

### 3.3. Introduction of future case studies

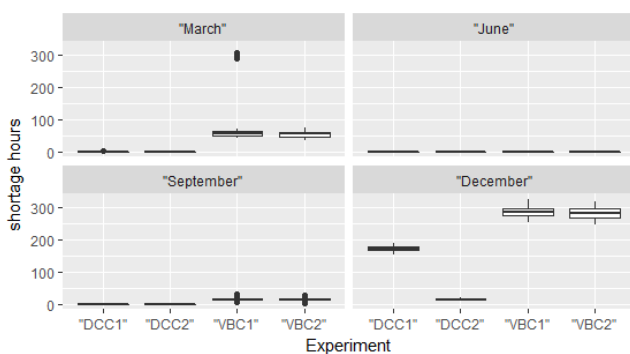
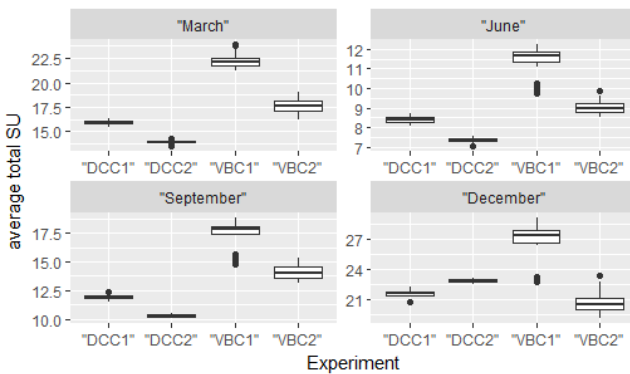
#### Next generation of thermal energy systems in the built environment

While heating and cooling accounts for 50% of the final energy consumed in the European Union [28], this sector also provides opportunities to enhance flexibility in the energy system. For instance, thermal energy storage units [29], [30] and generators [31] can operate both connected or disconnected from the grid, and the patterns of use of heating, ventilation and air conditioning of buildings can be controlled in order to minimize their operation costs [32]. In the future, as described in [6] heating and cooling systems in the built environment can become smart thermal grids, and together with institutions they will become the next generations of district heating.

Nonetheless, questions remain on how this future infrastructure can come into being. These questions involve not only technology but also institutions and actors [6]. Therefore, conceptual and computational tools for socio-technical design in the next generation of thermal energy systems in the built environment are needed. The framework proposed in this paper will serve as the basis to develop these tools. The use of Ostrom's Institutional Analysis and Development framework [33] and socio-psychological theories are envisioned, as well as multi-perspective agent-based models with optimization and game theory approaches. Aspects of the system such as type, size and seasonality of thermal energy loads, degree of market opening as well as institutions will be considered.

#### Coordination control of microgrids

To address the issues of uncertainty in the electric grid management, caused due to the high penetration of Renewable Energy Systems (RES), increasing flexibility is critical, and it should be considered using a bottom-up approach. For this purpose, micro-grids provide an ideal framework for integration of distributed energy resources (DERs) into the grid. They also provide a high degree of flexibility in terms of ownership and operational strategies for the DERs [43]. In this sense, micro-grids can leverage from the services that are offered by individual prosumers [44], or from the collective action of a society [45] to

**Figure 7.** Shortage hours in monthly runs**Figure 8.** Average number of total start-ups in monthly runs

Although the direct control contracts seem to perform better at the system level, they require drivers to be plugged in around 60% of the day. By cutting down this time in half, a 91% of the residual load can be supplied throughout a year. Moreover, the monthly results show that the system performance and V2G requirements change throughout the seasons (Figure 7, Figure 8). Therefore, there is potential to increase the system performance using volume-based contracts by adjusting specifications on a monthly or seasonal basis. This can be done by reducing plug-in times in summer months and increasing volume caps and time intervals in winter months.

While volume-based contracts seem to give more autonomy to drivers for using their vehicle freely, direct control



provide increased levels of flexibility in the distribution grid.

However, given the constrained amount of energy availability, arbitration is going to be a major challenge for energy transition. In market environments, commercial actors have the responsibility of contract fulfilment, which adds stress on the grid, while the technical actors involved are charged with ensuring its integrity [46]. In order to address, the conflicting objective of actors, control strategies that account for actor interactions need to be considered in the context of a socio-technical system.

Co-ordination control applied to multi-actor systems is a promising methodology for the treatment of the aforementioned issues. For achieving co-ordination among the disparate self-objective driven actors, we need a combination of: mathematical algorithms; for efficient distributed energy management, institutional design; for determining approaches to achieve effective demand response, and ICT networks for relaying information between the required actors in a real-time and robust manner. Thus through the investigation of different strategies that promote the seamless interaction between technical systems, actors and institutions we aim at satisfying power delivery contracts while acknowledging constraints of voltage quality, and grid stability and reliability.

### Flexibility through demand response aggregation

In the future energy systems, in order to tackle the variability caused by integration of intermittent renewable energy sources like wind and solar energy, flexibility provided by the customers which is called as demand response is essential. Demand response is obtained by changing the electricity usage of customers according to system needs and changes in the electricity price [34]. To enable small customers like residential and commercial customers to take part in demand response activities, they need to be aggregated. An aggregator is a mediator between electricity customers, who offer demand response or provide distributed energy resources, and electricity market actors like Distribution System Operators (DSOs) and Balance Responsible Parties (BRPs) that wish to exploit these services [35]. Namely, aggregators gather the demand response provided by the customers and then they offer this flexibility to the market players.

It is not clear how increasing the participation of aggregators would affect the electricity market and the distribution networks. The goal is to examine the institutional, social and technical impacts of aggregators in order to in order to integrate them to the electricity system using the framework discussed in this paper. From the actors' perspective, interactions of aggregators with the consumers and the conflict of interests with other market actors have to be analyzed. Concerning the technical side, it is necessary to consider the impacts of the aggregators on the distribution grid. Regarding the institutional side, the

regulations and rules needs to be modified so as to enable the aggregators to participate in the electricity markets.

## 3.4. Discussion

Our findings suggest that individual behaviors of actors, and their interactions with institutions, are necessary to understand patterns in socio-technical systems. In the analysis of the German biodiesel supply chain was found that poor adaptation mechanisms for forecasting prices on biodiesel production lead to lower biodiesel production, provided that an external shock (the introduction of a new policy) is introduced in the system. In the second case study, we found a tradeoff between plug-in requirements for drivers and system performance. The results show that using volume-based contracts, plug-in requirements for drivers can be halved at the expense of a reduced the system performance by 6-8% with respect to direct control contracts. This is a relatively small reduction and can be improved by adjusting requirements monthly and incentivizing drivers to be plugged in at different time intervals.

Traditional approaches involve analyzing the technical or institutional aspects independently. The study of the German biodiesel supply chain presented above extends the analysis done by [15] by shedding light on new mechanisms that drive the behavior of the system such as the co-evolution between individual behavior and system behavior. Moreover, in the previous studies on the Car as Power Plant case, the focus of analysis remains on the technical aspects as in [22], [23], [27], where the operation may be optimized by forcing drivers to follow system needs. However, in this paper we show that the balance between system needs and driver preferences and participation should be addressed to improve the performance of the system. This can be done by focusing on the institutional aspects, i.e. contracts. Moreover, while contracts are mentioned in the V2G literature [24], [36], they are not formalized into variables in simulation models. Therefore, it is not clear how contracts can be used and how they affect drivers and aggregators, and in turn the system.

The conceptual framework proposed offers an alternative for thinking about energy systems in general. One concrete advantage is exploited when the conceptual framework is formalized into a computational model. The model facilitates the systematic exploration of the consequences of the interaction among physical components, actors, and institutions on the energy system behavior. Once we understand the effect of these interplays on system performance (behavior space), we can improve its operation by specifying performance goals (design objectives) and the means available in the design space to meet those objectives (design variables). It is also shown that the conceptual framework can be used to design in the fields of thermal energy systems, microgrids and demand response aggregation.

The focus of this study was on socio-technical rather than socio-ecological systems, or the interactions between

technical and ecological components. Nonetheless, socio-technical systems could not function without the services provided by ecosystems (provision of food and water, control of climate, etc.). Thus, future research should explore the co-evolution of socio-technical systems and ecological systems.

## 4. Conclusions

This paper was set out to answer the following research question: “How to design in socio-technical systems for the energy transition?” As an answer to this question, we proposed the formalization of an analytical framework into computational models and simulations. The conceptual framework describes energy systems in terms of actors, institutions and technology, as well as their interactions. Formalizing these three elements requires the use of theories to explain how they interact, as well as assumptions to operationalize them into models. The resulting tools can be used to gain insights on what factors and interactions influence the performance of the system. These insights might assist the design process by making clear the mapping from design variables to design objectives.

The results of the first case study suggest that robustness in biodiesel production (design objective) depends on the actors’ adaptation mechanism, given that an external shock is introduced into the system. As, in turn, the adaptation mechanisms are a function of the information available to actors (design variables), this insight implies that it is needed to design mechanisms that improve the accessibility of pertinent information to the actors to ensure the robustness of the system.

In the second case study, the results show that direct control and static volume-based contracts have different effects on drivers’ requirements and the overall system operation and performance. Possibly conflicting goals and needs can be seen as the stricter contract types and specifications for drivers lead to better system performance in all cases. Given that a relatively small reduction in system performance is achieved with half of the plug-in time requirements, we can further explore the design variables to improve system operation without low requirements for drivers. By expanding the model with heterogeneous drivers, the effect of other institutional design variables on drivers and the system performance will be further tested.

With the two case studies and the outline for future research we have showed that our framework and its formalization in computer models can be used as a tool for designing in complex systems. While the case studies presented were limited to the domain of energy transition, our approach can also be potentially used for the analysis and design in other areas where the complexity of the socio-technical system has to be taken into account in the design process.

The research described in this paper, executed at the Faculty of Technology, Policy and management, is closely related to education. One of the MSc programmes on this faculty is COSEM: Complex Systems Engineering and

Management. CoSEM educates students as designers and managers of large-scale complex multi-actor systems within a technology domain. One of these domains is Energy. As shown in this paper to design solutions for complex contemporary socio-technical problems considering technical, economics and social knowledge is needed. This can be offered by comprehensive engineers approaching problems not simply as a technical challenge, but also including numerous actors’ preferences and institutional considerations.

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## Appendix A. Biodiesel production in Germany – ODD protocol

### A.1. Design concepts

*Basic principle:* Patterns in production capacity and biodiesel production result from investors basing their decisions on optimistic perceptions of the development of the market that increase with a favorable institutional framework.

*Emergence:* Emergent system dynamics includes rapeseed and biodiesel prices, and the structure of the biodiesel supply chain.

*Adaptation:* Farmers, biofuel producers, and distributors exhibit adaptive behavior in the model. Farmers adapt their land use patterns, biofuel producers and mills adapt their offers in the rapeseed and or biodiesel markets. This behavior is driven by a profit maximization strategy.

*Objectives:* All the entities are profit maximizing agents. They tend to maximize their profits by producing the commodity (rapeseed/wheat) with the highest price in the market and by sourcing rapeseed/biodiesel to the lowest price possible.

*Learning/prediction:* Agents do not use any learning mechanism. Agents improve their forecasting based on the following equation [58].

$$C_t^e = C_{t-1}^a \left( C_t^e \right)^{(1-a)} \quad \text{A.1}$$

where  $C_{t-1}^e$  is the estimate for the previous year,  $C_{t-1}$  is the actual value from the past year, and  $C_t^e$  is the updated estimate for the current year.  $a$  is a parameter that weighs the influence of the actual value of the previous year as compared to the estimate in the forecasting,  $0 \leq a \leq 1$ .

*Sensing:* Agents are simply assumed to know, without uncertainty, the global variables (i.e., policy instruments) and market prices used to optimize their profits and adjust their predictions.

*Interaction:* Farmers and biofuel producers directly interact through the negotiation of rapeseed. Biofuel producers interact indirectly between themselves by competing in the rapeseed and biodiesel market. The interaction between biofuel producers and distributors is mediated via the biodiesel market.

*Stochasticity:* The model is initialized stochastically. The allocation of some properties such as yields, production costs, production capacity, farm size and location of the agents are randomly assigned.

*Collectives:* The model neglects the formation of aggregations among individuals, as in the case of a conspiracy.

*Observation:* Prices of rapeseed and biodiesel, production of rapeseed and biodiesel, and evolution of production capacity are the main variables to observe the system-level behavior.

### A.2. Initialization

30 mill agents, 90 farmer agents, and 10 distributor agents are initialized. Agents are located in random patches.

Table A.1. presents the parameters that describe the state of the agents at the start of the simulation.

Table A.1. Parameters of the agents used in the initialization of the simulation

Parameter	Value	Units
<b>Farmers</b>		
farm-area	uniform distribution {1200-50000}	ha
rape-prod-cost	uniform distribution {240-278}	euro/t
wheat-prod-cost	uniform distribution {80-130}	euro/t
<b>Biofuel producers</b>		
prod-capacity	uniform distribution {1-15}	MI
biod-prod-cost	uniform distribution {0.08-0.11}	euro/l
yield-biodiesel	normal distribution 1.1 (0.05)	kg/kg
prof-margins	3	%
<b>Distributors</b>		
capacity	uniform distribution {10-50}	MI
prof-margins	3	%
<b>Global variables</b>		
tax-bio	0.3	euro/l
penalty-bio	0.5	euro/l
ratio-quota-total-capacity	0.65	dmnl

### A.3. Input data

Data that (exogenously) change over time during the simulation is presented in Table A.2.

Table A.2. Yields for rapeseed and wheat for the period 1991 – 2014 [37]

Year	Rapeseed Yield	Wheat Yield
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	[t/ha]	[t/ha]
1991	3.30	6.77
1992	2.61	5.98
1993	2.83	6.58
1994	2.74	6.76
1995	3.19	6.89
1996	2.31	7.29
1997	3.14	7.27
1998	3.36	7.20
1999	3.58	7.54
2000	3.33	7.28
2001	3.66	7.88
2002	2.97	6.91
2003	2.87	6.50
2004	4.11	8.17
2005	3.76	7.47
2006	3.73	7.20
2007	3.44	6.96
2008	3.76	8.09
2009	4.29	7.81
2010	3.90	7.31
2011	2.91	7.02
2012	3.69	7.33
2013	3.95	8.00
2014	4.48	8.63

## Appendix B. Car as Power Plant- ODD protocol

### B.1. Design concepts

*Basic principles:* Contract specifications are introduced as rules that can allow more autonomy to drivers and reduce uncertainty for the microgrid operator. In our model, contract specifications translate to certain plug-in times and volume committed per driver. In this model we assume that drivers comply with contract specifications. The use of contracts leads to different system performances than with the previously studied methods [22], [27], [23] and reduced plug-in times for drivers.

*Emergence:* In the current model, the important outputs for the system performance (% self sufficiency and shortage hours) are an effect of the contract specifications imposed on drivers.

*Adaptation:* Adaptive behaviour is not taken into account in this model, but will be introduced in further work.

*Objectives:* Since the current model is exploratory, objectives by the drivers are yet to be introduced. At this

moment, the only objective is that of the microgrid operator to use as much power generated locally as possible.

*Learning/prediction:* Agents do not use any learning mechanism.

*Sensing:* Drivers have information about the level of hydrogen in their tank and make the decisions to refill. The microgrid operator has all information regarding the devices in the system, including the FCEVs. The amount of hydrogen in each tank, number of start-ups, etc. are all known accurately by the operator.

*Interaction:* Interaction occurs between the operator and the drivers. There is no interaction among drivers at the moment.

*Stochasticity:* All data regarding renewable generation, load, and driving behaviour is deterministic at the moment. Some contract specifications are set up stochastically.

*Collectives:* There is no aggregation of agents represented in the model.

*Observation:* Outputs needed are the total hours in which the power from FCEVs is not sufficient to serve the load, and the total % of the residual load that has been provided by FCEVs during a certain period (day, week, month, year). Moreover, the total plug-in hours of drivers, number of start-ups, and the total volume provided are relevant to compare the implications for drivers with different contracts.

### B.2. Initialization

During the setup, 50 driver agents are created. Each one is given characteristics of their driving behaviour based on a probability distribution build from driving data [38].

For the contracts, the characteristics were initialized according to Table B.1:

Table B.1. Initialization of contract specifications in agents – experiments VCB1, VBC2, DCC1, DCC2

Contract specification	Static volume-based contracts (VBC)	Direct control contracts (DCC)
Time interval: activation	Gamma distribution ( $\alpha=2, \lambda=2$ )	First hour after arrival
Time interval: duration	Min=3h; med=6h; max=9h (max. possible based on driving schedule)	Until fuel depletion or departure
Volume cap:	Random value between: Min= 30kWh, max= 60kWh [VBC1] or max= 90 kWh [VBC2]	-
Min fuel before plug-in	Based on volume committed	0 kg [DC1]; 50% of full tank [DC2]
Guaranteed fuel post-V2G	Fuel for daily driving + 50% safety margin	Fuel for daily driving + 50% safety margin

### B.3. Input data



At initialization, the input data from driving behaviour in the Netherlands is used. Every time step, the generation and consumption data is updated.

Table B.2. Variables initialized or updates using input data

Variable	Units	Source
Driving distance	km	[38]
Arrival time	Hours	[38]
Departure time	Hours	[38]
PV generation	kW	[39]
Wind speed	m/s	[40]
Household load	kWh	[41]