

Technical report 19-002

# **A hydrogen-based integrated energy and transport system: The design and analysis of the car as power plant concept\***

S.S. Farahani, R. van der Veen, V. Oldenbroek, F. Alavi,  
E.H. Park Lee, N. van de Wouw, A. van Wijk, B. De Schutter, and  
Z. Lukszo

*If you want to cite this report, please use the following reference instead:*

S.S. Farahani, R. van der Veen, V. Oldenbroek, F. Alavi, E.H. Park Lee, N. van de Wouw, A. van Wijk, B. De Schutter, and Z. Lukszo, "A hydrogen-based integrated energy and transport system: The design and analysis of the car as power plant concept," *IEEE Systems, Man, and Cybernetics Magazine*, vol. 5, no. 1, pp. 37–50, Jan. 2019. doi:[10.1109/MSMC.2018.2873408](https://doi.org/10.1109/MSMC.2018.2873408)

Delft Center for Systems and Control  
Delft University of Technology  
Mekelweg 2, 2628 CD Delft  
The Netherlands  
phone: +31-15-278.24.73 (secretary)  
URL: <https://www.dcsc.tudelft.nl>

---

\* This report can also be downloaded via [https://pub.bartdeschutter.org/abs/19\\_002.html](https://pub.bartdeschutter.org/abs/19_002.html)

# A Hydrogen-Based Integrated Energy and Transport System: The Design and Analysis of the Car as Power Plant Concept

Samira S. Farahani<sup>1</sup>, Reinier van der Veen<sup>1</sup>, Vincent Oldenbroek<sup>2</sup>, Farid Alavi<sup>3</sup>, Esther H. Park Lee<sup>1</sup>, Nathan van de Wouw<sup>4</sup>, Ad van Wijk<sup>2</sup>, Bart De Schutter<sup>3</sup>, Zofia Lukszo<sup>5</sup>

**Abstract**—In recent years, the European Union has set ambitious targets towards a carbon-free energy transition. Many studies show that a drastic reduction in greenhouse gas emissions - at least 90% by 2050 - is required. In the transition towards a sustainable energy system, solar (or green) hydrogen plays many important roles, as it is a clean and safe energy carrier that can be also used as a fuel in transportation and in electricity production. To understand and steer the transition from the current energy system towards an integrated hydrogen-based energy and transport system, we propose a framework that integrates a technical and economic feasibility study, controllability study and institutional analysis. This framework is applied to the Car as Power Plant (CaPP) concept, which is an integrated energy and transport system. Such a system consists of a power system based on wind and solar power, conversion of renewable energy surpluses to hydrogen using electrolysis, hydrogen storage and distribution, and hydrogen fuel cell vehicles that provide mobility, electricity, heat, and water. Controlling these vehicles in their different roles and designing an appropriate organizational system structure are necessary steps in the feasibility study. Our proposed framework for a future 100% renewable energy system is presented through a case study.

## I. INTRODUCTION

The urgency to significantly reduce the impacts of climate change is felt around the globe. By signing the Paris agreement, 195 governments have agreed on a long-term goal of keeping the increase in global average temperature below 2 °C above preindustrial levels and on aiming to further limit the increase to 1.5 °C [1]. To reach these goals major technological, organizational, and social changes in both the energy and the transport system and services are needed.

As zero-emission systems are the final goal, the main technological transition in the transport field will be from combustion engines to electric engines. The electricity will be provided by batteries or fuel cells that can produce electricity with high efficiencies from hydrogen. In addition, an electricity charging infrastructure and/or hydrogen fueling infrastructure

is needed to accommodate the introduction of electric vehicles [2]. Due to the intermittent nature of the renewable energy sources such as solar and wind, there is a need for more flexibility in the electricity system. This may be provided by flexibility in demand response, electricity storage, electricity conversion into fuels, chemicals or heat, and (distributed) smart grids [3]. Recent years have shown that the integration of energy and transport systems may solve major problems related to the separate transitions described above, and create synergies [4]–[7].

To integrate electricity and transport systems, we have developed a concept known as *Car as Power Plant* (CaPP) [8] to utilize automotive fuel cells as stationary power production units during non-driving hours (typically at home, or in parking lots during office hours). When the car is parked, the fuel cell unit can deliver power back to the grid to balance the electricity grid, decrease peak demands, or serve as a base load power generator. Hydrogen is used as a storage means for decoupling renewable power supply and demand in terms of time and distance. CaPP has the potential to replace electricity production power plants worldwide, creating an integrated, efficient, reliable, flexible, clean and smart energy and transport system.

The development and implementation of the CaPP concept is not something that is done overnight. It requires combining different disciplines to provide comprehensive models and tools supported by real-life pilot projects. To this end, the research presented in this paper goes beyond technical design and includes analysis of operation and control, policies and regulations, and economic feasibility. In our previous works, we have shown that reaching a fully renewable energy system is achievable and viable [2], [9]–[11]. We used solar and wind energy as well as hydrogen, and used Fuel Cell Electric Vehicles (FCEVs) to provide backup and balancing power. We also demonstrated that with optimal scheduling it is possible to minimize the electricity import from an external network in a microgrid [12]–[17], and showed that investing in such energy systems can be profitable for all parties involved [18].

Emphasizing the need for more in-depth interdisciplinary research into a future energy system, this paper aims to provide a single comprehensive framework for designing a complex socio-technical system from different perspectives. In this paper we show that technical, economic, operational and social aspects are necessary ingredients to obtain a complete understanding of such a system [19] and that system design and operation are deeply intertwined. Stand-alone technical analysis is not complete without economic and social analysis. To this end, we introduce a fully renewable energy system

<sup>1</sup>The authors are with the Department of Engineering, Systems and Services, Delft University of Technology, 2628 BX Delft, the Netherlands. Corresponding author: s.farahani@tudelft.nl

<sup>2</sup>The authors are with the Department of Process and Energy, Delft University of Technology, 2628 CB Delft, the Netherlands.

<sup>3</sup>The authors are with the Delft Center for Systems and Control, Delft University of Technology, 2628 CD Delft, the Netherlands.

<sup>4</sup>The author is with the Department of Mechanical Engineering, Eindhoven University of Technology, 5600 Eindhoven, Netherlands, with the Delft Center for Systems and Control, Delft University of Technology, 2628 CD Delft, Netherlands, and with the Department of Civil, Environmental and Geo-Engineering, University of Minnesota, Minneapolis, MN 55455-0116 USA.

<sup>5</sup>The author is with the Department of Engineering, Systems and Services, Delft University of Technology, 2628 BX Delft, the Netherlands, and with the Department of Energy, Politecnico di Torino, 10129 Torino, Italy.

for a smart city in 2050, inspired by the city of Hamburg in Germany, and perform a comprehensive analysis based on technical, economic, operational and social properties. The year 2050 has been deliberately chosen to indicate that the EU's goal to ensure a carbon-free power sector by 2050 is indeed achievable.

The remainder of this paper is organized as follows. Section II describes the energy system in the city of Hamburg. Section III is dedicated to the techno-economic analysis of the described system to achieve a 100% renewable and self-sufficient energy system. Section IV summarizes the control strategies that are applied to minimize fuel consumption in the FCEVs while guaranteeing the supply-demand balance. Section V focuses on the optimal scheduling from a socio-technical point of view, taking into account the contracts in force between agents in the system. Section VI is the conclusion.

## II. SYSTEM DESCRIPTION

The smart city used as an illustrative example for 2050 is designed in such a way that it fulfills the following design requirements: 1) the city's energy and transport systems use only electricity and hydrogen as energy carriers. End use is electric only; 2) the city uses only hydrogen as seasonal energy storage and fuel to power all road transport vehicles; 3) it can be operated in a network of multiple smart city areas and renewable hydrogen and electric energy hubs or centers [20], [21]; 4) it can be integrated into existing infrastructure and buildings; 5) it is not dependent on an in-urban area underground hydrogen pipeline transport network; 6) it uses abundant renewable energy sources in Europe: local solar and large scale wind only; 7) it is independent of natural gas and district heating grids or an expansion of these.

The size of the hydrogen-based integrated energy and transport system in the smart city area for this study is determined based on the dispersion of supermarkets and gas stations in Europe and Germany. Accordingly, 2000 households were selected (since for every 2000 households there is a medium-sized supermarket and one gas station) [22]. According to German statistics, 2000 German households correspond to an average of 4210 people, with a total of 2330 passenger cars and 140 other vehicles [22], [23]. Note that these numbers are subject to change over time based on the societal profile and social behaviors. The floor area of residential and services buildings was derived from national statistical data and scaled to 2000 households. An average dwelling has a floor area of 92m<sup>2</sup>. Residential and service sector roofs are used for solar electricity systems and for rainwater collection. Solar electricity systems are installed on roof areas: 9m<sup>2</sup> per person on residential buildings and 4m<sup>2</sup> per person on service sector buildings area. Roof area available for rainwater collection is 22.5m<sup>2</sup> and 10m<sup>2</sup> per person for residential and service buildings, respectively. For more details on the system components and dimensions, see [2].

Figure 1 illustrates the energy system in the smart city and its key components. Based on [2], hydrogen is produced within the urban areas from local surplus solar energy and from shared large-scale wind energy. Hydrogen is transported via

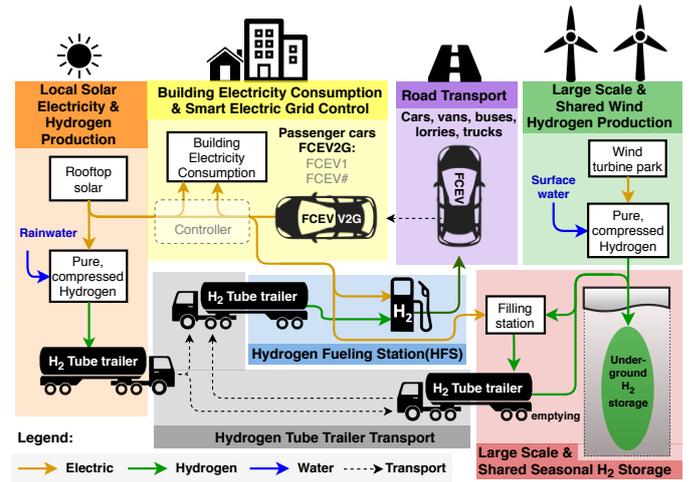


Fig. 1. Hydrogen-based integrated energy and transport system and its key elements.

tube trailers from the urban areas to hydrogen fueling stations, to other hydrogen hubs/consumers, or to the large-scale and shared underground seasonal hydrogen storage reservoirs [24]. The whole system consists of these seven major elements: 1) Local Solar Electricity & Hydrogen Production: local rooftop solar electricity and rainwater collection, purification and storage systems produce solar electricity and pure water for both the building's consumption and hydrogen production; 2) Building Electricity Consumption & Smart Electric Grid Control: the smart electric grid is managed by a controller, which connects all buildings, grid connected fuel cell electric vehicles (FCEVs), Hydrogen Fueling Station, solar electricity and hydrogen production, and the tube trailer filling station at the Seasonal Hydrogen Storage. Any shortage of electricity is met by the electricity produced from hydrogen (FCEV2G) through parked and 'Vehicle-to-Grid' (V2G) connected fuel cell electric vehicles; 3) Hydrogen Tube Trailer Transport: tube trailers towed by tube trailer tractors transport hydrogen from either the Local Solar Hydrogen Production Site or the Seasonal Hydrogen Storage to the Hydrogen Fueling Station or from the Local Solar Hydrogen Production Site to the Seasonal Hydrogen Storage; 4) Hydrogen Fueling Stations; 5) Road Transport: a fleet of road transport FCEVs being passenger cars, vans, buses or trucks; 6) Large-Scale & Shared Wind Hydrogen Production: an off-site large-scale wind turbine park is shared with other smart city areas and renewable hydrogen hubs or centers. All wind electricity is used with purified water for hydrogen production, which will be stored in a large-scale Seasonal Hydrogen Storage; 7) Large-Scale & Shared Seasonal Hydrogen Storage. For technical and economic details on the system components, see [2].

To design such a system, we propose an analysis framework (cf. Figure 2) based on four perspectives: a technical, an economic, an operational and control, and an institutional perspective. In the following sections, we explain how these perspectives will be combined to obtain a complete system design and analysis.

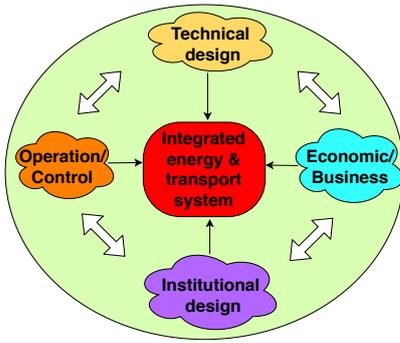


Fig. 2. Analysis framework for the design of the future smart city area.

### III. TECHNO-ECONOMIC ANALYSIS

In this section, the techno-economic analysis of the mid-century energy system for our smart city is presented. Our approach is based on: 1) Technological and economical characterization for the system components; 2) Hourly simulation of all energy flows and technical sizing of the system components; 3) Cost of energy calculation based on the sizing and economic characterization of the system components.

#### A. Modeling the hydrogen-based integrated energy & transport system

Figure 3 displays the simplified simulation scheme of the system and consists of an hourly and annual energy balance.

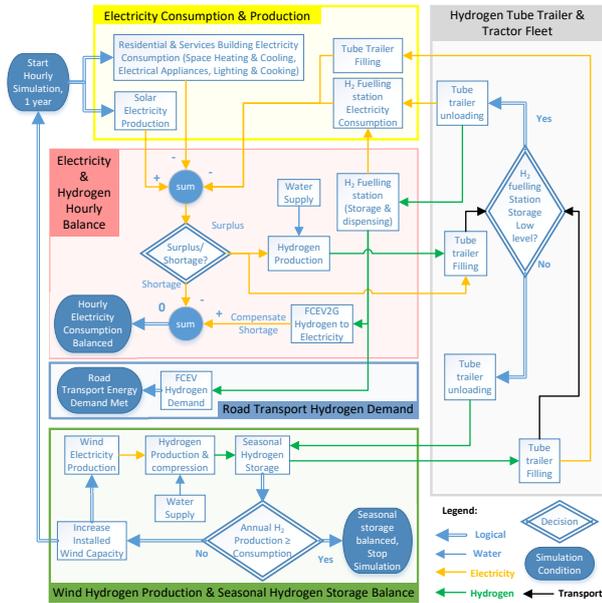


Fig. 3. Simplified hourly simulation scheme for a hydrogen-based integrated energy and transport system

First, the hourly electricity and hydrogen balance has to be met, either by converting surplus electricity into hydrogen or converting stored hydrogen into electricity. The net consumed hydrogen from the seasonal hydrogen storage in underground salt caverns needs to be zero on a yearly basis. The hourly simulation is done for the entire year 2014 to size the system components in such a way that there is no curtailment of electricity.

Figure 3 shows the hourly simulation scheme to investigate the system state in 2050. The yellow square includes the services and residential building, Hydrogen Fueling Station, Seasonal Hydrogen Storage electricity consumption, and solar electricity production. The hourly electricity consumption profile of the all-electric residential and services sector buildings includes space heating & cooling, hot water, lighting, cooking, and electrical appliances, and is based on the following inputs:

- National annual energy consumption data for hot water, lighting, cooking, and electrical appliances [22];
- Hourly normalized electricity and heating consumption profiles [25];
- Estimations on efficiency improvements in the year 2050, technology change (heat pumps) and energy reduction [2];
- Relations for determining space heating and cooling demand in buildings based on the Heating and Cooling Degree Days [26]–[28] derived from local air temperature data [29], [30] and the European Heating and Cooling Index [31]–[34].

Hourly hydrogen consumption for transport (blue in Figure 3) of the passenger cars, vans, buses and trucks is based on the German national annual driving data [35], [36], the estimated fuel economy in 2050 [2], and a recurring weekly fueling profile.

#### B. Cost of energy

We applied the cost calculation methods described in [2], which consider the different economic lifetimes, operation, and maintenance costs of the various components and a weighted average cost of capital of 3% [37]. The Total Cost (TC) of the hydrogen-based integrated energy and transport system in this smart city in k€/year is the sum of the total annual Capital Costs (CC) and the Operation and Maintenance Costs (OMC) of the individual subsystems. The Levelized Cost of Energy of electricity (LCoE<sub>e</sub>) from wind and solar does not include energy storage. Therefore, the system levelized cost of energy (SLCoE) is introduced [2]. The system levelized costs of energy built up from cost of energy for electricity consumption in buildings SLCoE<sub>e</sub> (€/kWh) and hydrogen consumption for driving SLCoE<sub>H</sub> (€/kg H<sub>2</sub>) are calculated by allocating a share of the Total Cost of the smart city area energy system [2].

#### C. Simulation results

1) *Energy balance*: Based on the hourly simulation, the annual energy balance is defined and presented in Figure 5.

We investigated the production and transport of hydrogen and the seasonal and tube trailer hydrogen storage in analyzing the annual system behavior (see Figure 5(a)). In the October–March period, hydrogen consumption is higher than hydrogen production, and the majority of the hydrogen production comes from wind power. From April to September, hydrogen consumption is lower than hydrogen production due to increasing solar energy and reduced building electricity consumption, resulting in more stored hydrogen. For the entire year, all hydrogen from solar surplus electricity goes to the Hydrogen Fueling Station, with the exception of May and June when

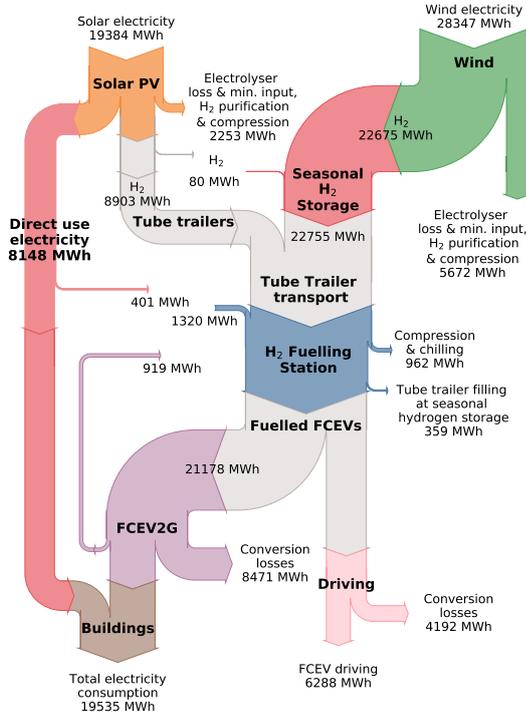
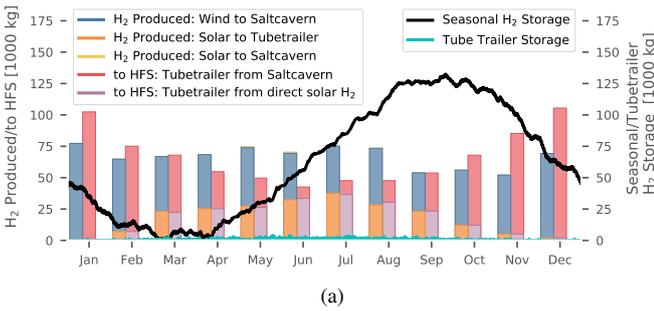
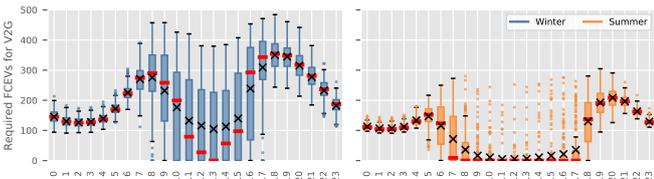


Fig. 4. Annual energy balance for a 2050 fully renewable electricity, heating and road transport system for the city of Hamburg.



(a)



(b)

Fig. 5. (a) Hydrogen production and transport (left axis) and seasonal and tube trailer hydrogen storage (right axis), (b) FCEV2G operation during winter (left) and summer (right, days ) period per hour of the day.

approximately 2000 kg is stored in the underground storage (see also Figure 4, H<sub>2</sub> 80 MWh).

In Figure 5(b), the FCEV2G power demand over the winter period (left) and summer period (right, days 91-274 of the year) is displayed for every hour of the day in box plots (based on a normal distribution). Dots indicate outliers. Daily averages and medians are respectively displayed as black 'x' marks and red horizontal lines in the bars. The annual peak of 485 cars (21%) occurs during winter at 18h. During the

night hours (23h-4h), summer and winter, on average between 100-200 cars are required (4-9%). Around 4h FCEV demand starts rising to an average of 280 (12%) at 8h in winter and 150 (6%) at 5h in summer. At these morning peak hours, solar electricity starts to cover the daytime electricity demand. In winter, the average minimum is 105 cars (5%) at 13h and in summer, it is less than 25 cars (1%) from 9h-16h. The average evening peak is 350 cars (15%) at 18h in winter and 210 cars (9%) at 20h in summer. Relatively more cars are needed during morning and evening hours. Also, some cars are likely to be used for driving and will therefore not be available for power production. However, on average this is still less than 15% of the cars. In the calculation of the V2G power production we used 10 kW output per car, i.e. only 10% of the rated fuel cell power. Any increase in the output, or including other vehicles such as vans and trucks, will result in fewer cars required. Demand response of the building load could possibly even further reduce the peaks. Accurate forecasting of electricity production from renewable electricity sources and building demand, monitoring availability of cars, and controlling their schedule is required to make this system operational and reliable.

2) *Cost analysis:* Before analyzing the operation of the CaPP system, we will present an economic feasibility analysis. Table I shows the aggregated results of the cost of the subsystems and components as presented in Figure 1.

| Subsystems                             | CC [k€/yr] | OMC [k€/yr] | TC [k€/yr] |
|--|------------|-------------|------------|
| Solar Electricity                      | 406        | 199         | 605        |
| Solar H <sub>2</sub> Production        | 273        | 70          | 343        |
| Wind Electricity                       | 360        | 226         | 586        |
| Wind H <sub>2</sub> Production         | 142        | 89          | 231        |
| Hydrogen Fueling Station               | 352        | 63          | 416        |
| Seasonal H <sub>2</sub> Storage        | 259        | 11          | 270        |
| H <sub>2</sub> Tube trailers transport | 143        | 151         | 293        |
| FCEV2G, Smart Grid & Control           | 268        | 72          | 341        |
| Total System Cost of Energy            | 2,204      | 881         | 3,085      |

TABLE I

CALCULATED CAPITAL (CC), OPERATION & MAINTENANCE (OMC), AND TOTAL COSTS (TC) FOR THE SUBSYSTEMS IN THE SMART CITY AREA.

The Total Cost (TC) of the smart city area energy system is 3085 k€/year and is the sum of the total annual Capital Costs (CC) of 2204 k€/year and the Operation and Maintenance Costs (OMC) of 881 k€/year of the individual subsystems. The LCoE<sub>e</sub> from wind and solar is respectively 0.03 €/kWh and 0.02 €/kWh. The SLCoE<sub>e</sub> is 0.11 €/kWh and the SLCoE<sub>H</sub> is 3.3 €/kg H<sub>2</sub>. These values are comparable with those for other future fully renewable integrated energy systems [37].

#### IV. OPTIMAL SCHEDULING

Promising conclusions from the techno-economic feasibility assessment lead to the question of how the fuel cell cars can be used efficiently for power balancing of the smart city area. To this end, we will further adjust the hydrogen-based integrated energy and transport system's model so that it can be controlled by a model predictive controller.

We assume that the energy management system is responsible for maintaining the power balance of the integrated energy

and transport system in a smart city area. The residual load of the smart city area at time step  $k$ ,  $P_{\text{res}}(k)$ , i.e. the actual load subtracted by the power generation of the solar photo voltaic (PV) cells, is assumed to be a predetermined power profile. If the residual load is negative, this indicates that the total power generation of the PV system is more than the load. In this case, excess power is used in an electrolyzer to maintain the power balance. If the load is more than the power generation of PV systems, the total power generation of fuel cell cars should be equal to the residual load of the smart city area to maintain the power balance constraint. The task of the control system is to determine the power generation profile of each fuel cell car to ensure the power balance of the smart city area is always maintained, while minimizing the operational cost of the system. The control system is designed to minimize FCEV2G, Smart Grid & Control cost from Table I.

#### A. Discrete-time model of the hydrogen-based integrated energy & transport system

In this section, we present a discrete-time model for the system, where the sampling time is indicated by  $T_s$ . The fuel levels of the fuel cell cars,  $x_{f,i}$ , for  $i \in \mathcal{I}$ , are considered as the system states, where  $\mathcal{I} = \{1, \dots, N_v\}$  indicates the index set of all cars. Here,  $N_v$  is the number of fuel cell cars. In the following modes, the fuel level of a car changes:

- Power generation mode: if the generated power at time step  $k$  is  $u_{f,i}(k)$ , the fuel level is decreased by  $\alpha_i u_{f,i}(k) + \beta_i$ , where  $\alpha_i$  and  $\beta_i$  are two constant parameters that can be determined from the specifications of the fuel cell stack.
- Refueling mode: fuel cell car  $i$  is refilled at step  $k$  if the binary refueling signal,  $s_{r,i}(k)$ , is equal to 1. In this case, the fuel level of that car will be at its maximum level,  $\bar{x}_{f,i}$ , at the next time step. Note that this criterion requires a large enough (greater than 15min) time step.
- Transportation mode: if car  $i$  is used for transportation at time step  $k$ , then the fuel level of that car is reduced by a predetermined value  $\gamma_i(k)$ . The value of  $\gamma_i(k)$  can be predicted by using the historical data of the driving patterns of car  $i$ . If the car is not in transportation mode at time step  $k$ , then  $\gamma_i(k) = 0$ .

Given the above operational modes for a fuel cell car, the evolution of the system states can be written as

$$x_{f,i}(k+1) = x_{f,i}(k) - s_{f,i}(k) (\alpha_i u_{f,i}(k) + \beta_i) T_s + s_{r,i}(k) (\bar{x}_{f,i} - x_{f,i}(k)) - \gamma_i(k). \quad (1)$$

In (1),  $s_{f,i}(k)$  is a binary variable that indicates the on/off operational mode of fuel cell  $i$  at time step  $k$ . The vector of control inputs related to fuel cell car  $i$ , is represented by  $u_i$  and it is defined as  $u_i(k) = [u_{f,i}(k) s_{f,i}(k) s_{r,i}(k)]^T$ .

Another state of the system is  $x_s(k)$ , the total amount of hydrogen that is present inside the smart city at time step  $k$ . The process of producing hydrogen is related to the power generation of renewable energy sources. Therefore, it is possible to predict the amount of hydrogen,  $h_s(k)$ , that is added to the smart city area at time step  $k$  inside the prediction window. Therefore, we can write the following equation for

the stored hydrogen at each time step  $k$ :

$$x_s(k+1) = x_s(k) + h_s(k) - \sum_{i \in \mathcal{I}} s_{r,i}(k) (\bar{x}_{f,i} - x_{f,i}(k)). \quad (2)$$

The last part of (2) indicates the amount of hydrogen used to refuel the fuel cell cars.

The operation of system is subjected to several constraints as follows:

- If a fuel cell is off then its total power generation is zero.
- A fuel cell cannot be in both the refueling and the power generation modes at the same time.
- If a car is used for the transportation, it cannot be connected to the smart city area's power network or be refueled.
- The driver of each fuel cell car can set a minimum level on the remaining fuel of the car. In addition, there is a maximum fuel level for each car.
- If the residual load of the smart city area is lower than zero, the power balance of the smart city area is maintained by the operation of the electrolyzer. In the case that the residual load is more than zero, the total power generation of fuel cell cars should be equal to the residual load of the smart city area, at each time step  $k$ .

By adopting a similar procedure as in [12], equations (1)-(2) together with the above constraints can be rewritten as a so-called mixed logical dynamical model of the form

$$\begin{aligned} x(k+1) &= x(k) + B_1 u(k) + B_2 z(k) \\ E_1 u(k) + E_4 x(k) + E_5 &\geq E_3 z(k). \end{aligned} \quad (3)$$

In (3),  $x(k)$  and  $u(k)$  are the system states and the control inputs and are defined as  $x(k) = [x_1^T(k) \dots x_{N_v}^T(k) x_s(k)]^T$  and  $u(k) = [u_1^T(k) \dots u_{N_v}^T(k)]^T$ , respectively, and  $z(k)$  is a vector of auxiliary variables. For more details on how to derive such a mixed logical dynamical model, see [12]–[14] and the references therein.

The operational cost of a fuel cell car consists mainly of two factors: the degradation of the fuel cell stack and fuel consumed inside the car. Switching the operation mode and the power generation of a fuel cell are considered to be the two important causes of degradation of the fuel cell stack. Fuel consumed inside the car is an affine function of the generated power. Therefore, the total cost function of the system is

$$J(k) = \sum_{i \in \mathcal{I}} \sum_{j \in \mathcal{J}} W_{s,i} |\Delta s_{f,i}(k+j)| + W_{1,i} u_{f,i}(k+j) + W_{0,i} s_{f,i}(k+j), \quad (4)$$

where  $\mathcal{J} = \{0, \dots, N_p - 1\}$  and  $W_{s,i}$ ,  $W_{1,i}$ , and  $W_{0,i}$  are three constant coefficients related to fuel cell car  $i$  that represent the cost of switching the operation mode, the cost of power generation, and the cost of standby mode operation, respectively. In (4), the value of  $\Delta s_{f,i}(k+j)$  indicates the difference in the value of  $s_{f,i}$  in two consecutive time steps as  $\Delta s_{f,i}(k+j) = s_{f,i}(k+j) - s_{f,i}(k+j-1)$ , which represents the switching on and off of the fuel cell.

#### B. Optimization problem of model predictive controller

The vector of optimization variables,  $\tilde{V}(k)$ , has to be determined at time step  $k$  and this vector is defined as follows:

$$\tilde{V}(k) = [\tilde{u}^T(k) \tilde{x}^T(k) \tilde{z}^T(k)]^T, \quad (5)$$

where a tilde notation over a variable means the stacked version of that variable over the prediction window. For example,  $\tilde{u}(k)$  is defined as  $\tilde{u}(k) = [u^T(k) \ u^T(k+1) \ \dots \ u^T(k+N_p-1)]^T$ . By adding some extra auxiliary variables to  $\tilde{z}(k)$  in (5) and by defining a vector  $c$  in an appropriate way, we can rewrite the cost function (4) as  $J(k) = c^T \tilde{V}(k)$ . In addition, we can define the matrix  $A$  and the vector  $b$  such that the constraints in (3) for all the time steps in the prediction window can be expressed as  $A\tilde{V}(k) \leq b$ . Hence, the optimization problem of the model predictive controller at time step  $k$  can be written as

$$\begin{aligned} \min_{\tilde{V}(k)} \quad & c^T \tilde{V}(k) \\ \text{subject to} \quad & A\tilde{V}(k) \leq b \end{aligned} \quad (6)$$

The optimization problem (6) is a mixed integer linear programming problem and can be solved by the standard solvers such as CPLEX [38] or Gurobi [39].

### C. Simulation results

#### 1) Assumptions in the model predictive control approach:

We have considered 2300 fuel cell cars inside the system, where the parameters  $\alpha_i$  and  $\beta_i$  in (1) are randomly chosen from a uniform distribution in an interval  $[0.03, 0.05]$  kg/kWh for  $\alpha_i$  and an interval  $[0.001, 0.009]$  kg/h for  $\beta_i$  for all  $i \in \mathcal{I}$ . The maximum power generation of each fuel cell car,  $\bar{u}_{f,i}$  for all  $i \in \mathcal{I}$  is assumed to be 10 kW. The maximum capacity of hydrogen tank in each car is set at 6.5 kg. In addition, we assume that the minimum level of fuel for the power generation mode is 1.5 kg. The values of  $W_{s,i}$ ,  $W_{1,i}$ , and  $W_{0,i}$  are randomly chosen from a uniform distribution in the interval of  $[0.5, 1.5]$ , and the prediction horizon,  $N_p$ , is assumed to be 4 in order to cover the most important dynamics of the system. The sampling time,  $T_s$ , is assumed to be one hour.

2) *Results:* The operation of a smart city area with the specifications described in Section II is simulated for a year. The computation time required to solve the optimization problem (6) typically grows exponentially when the size of the problem increases. In our case, it is impractical to solve problem (6) for 2300 cars using a normal personal computer. There are generally two approaches to decrease the computation time and to make the problem tractable. The first approach is to use a distributed control architecture, see e.g. [40]. The second approach is to adopt a decentralized control architecture where the overall system is decomposed into several subsystems and each subsystem has its own control system that is not dependent on other subsystems.

In our study we use the latter approach, as it has the advantage of simplicity. Ten subsystems are considered, each consisting of 230 fuel cell cars. In order to maintain the power balance condition of the smart city area, each subsystem is assigned to generate one tenth of the total residual load of the smart city area. As a result, the computation time is decreased significantly. For a Linux machine with Intel Xeon CPU with 3.7 GHz clock speed and 16 GB of RAM memory, it takes on average about 0.46 seconds to solve the optimization problem of each time step. Considering the time step of one hour, the optimization problems are thus solved fast enough for real-time application. The obtained results show that in general the stored hydrogen increases during spring and summer, while in

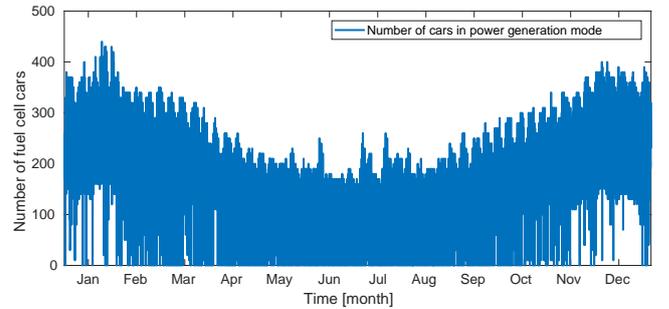


Fig. 6. Number of cars in the power generation mode during one year.

the fall and winter period the stored hydrogen decreases, which confirms the results of Figure 5(a). Also, the simulation results illustrated in Figure 6 show the total number of cars used in the power generation mode is less in spring and summer compared to other times of the year, which confirms the results of Section III

## V. INSTITUTIONAL ANALYSIS

To arrive at a complete design and operational system, it is essential to also consider social aspects and interactions influencing the system. From a socio-technical system perspective, the smart city area is viewed as a combination of physical and social subsystems [41], in which actors in the social subsystem make decisions or take actions that influence the operation of the physical system. The use of an FCEV as a power plant, thus, depends on both the driver (to make the car available) and the aggregator (to start-up the car), which then calls for new institutions. To operate FCEVs while considering drivers' needs, we focus on the contractual relationship between drivers and the aggregator. We, then, use another modeling technique, i.e. Agent-Based Modeling and Simulation (ABMS), and formalize the vehicle-to-grid contracts to show the role of contract parameters in the participation of drivers when supplying power to the smart city.

### A. Vehicle-to-grid contracts

As described in our previous work [42], we build upon the V2G literature [43] and conceptualize three contract types: price-based, volume-based, and control-based contracts. As the name indicates, a price signal is used to activate the V2G power from a vehicle in price-based contracts. In volume-based contracts, the amount of volume committed is used as a boundary condition. Finally, with control-based contracts, any connected vehicle may be used to support the system as long as there is enough fuel available for driving. Each contract type consists of parameters that define the availability and the conditions under which the aggregator may use the vehicle.

Based on the analyses of Section III and Section IV the amount of vehicles needed at a certain hour is between 400 and 500 (cf. Fig. 5(b) and Fig. 6). Therefore, the number of discharging points for V2G is set to 500. Given the large amount of vehicles in the system and the limited number of connections, we consider the use of control-based contracts with voluntary plug-in. We expect that there will be a need for plug-in time and volume commitment, since the limited discharging points would lead to unfulfilled contracts.

## B. Agent-based model

As introduced above, we use agent-based modeling and simulation to explore the agents' actions and their effects on the aggregated vehicle availability and system performance. As shown in Fig. 7, we create agents that represent actors in the social subsystem that own and operate components in the physical subsystem. Buildings produce electricity with PV panels for their own consumption and feed the excess to the grid. Together with the wind energy produced outside and transported to the smart city grid, the excess PV generation is used for hydrogen production. Drivers refill their FCEVs at the hydrogen fueling station. Whenever the PV generated in the buildings is not sufficient, FCEVs are used to supply V2G power. To manage the availability of FCEVs in the system for V2G, the drivers sign a control-based V2G contract with the aggregator. This defines when the vehicles will be plugged in, and to what extent the aggregator is allowed to use them.

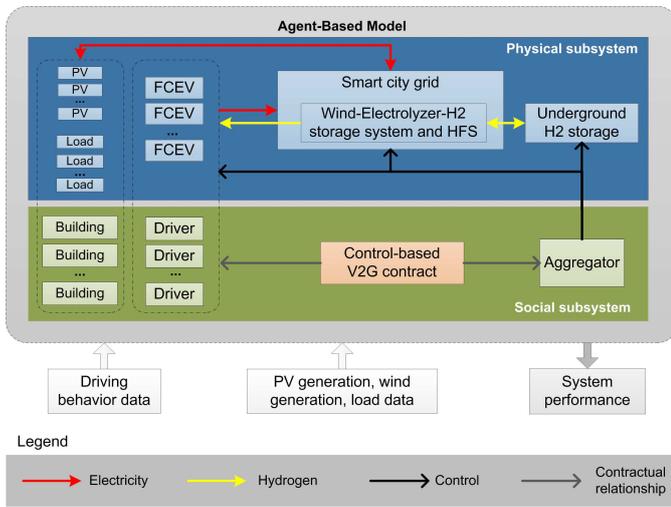


Fig. 7. Agent-based model concepts.

Below is the description of the agent-based model in more details:

### 1) Agents and objects:

a) *Driver agent*: This agent type represents the driver's characteristics as well as the characteristics of their car. The main states of the agent include driving schedule (weekdays and weekends), plug-in profile (either home or work hours), fuel level, and state of the vehicle (driving, refilling, plugged in, V2G). The driver agent also has a control-based V2G contract that consists of the guaranteed fuel (*guarFuel*).

b) *Building object*: Commercial and retail buildings are represented as objects that consume and produce electricity with rooftop photovoltaic (PV) systems.

c) *Aggregator agent*: The aggregator manages the supply and demand in the smart city. It owns an electrolyzer-hydrogen storage system (Hydrogen Fueling Station), which is used to produce hydrogen using electricity and provide hydrogen to drivers. An underground hydrogen storage is also operated by the aggregator to exchange hydrogen in the case of surplus or shortage.

2) *Process overview*: The order in which actions take place in the simulation is depicted in Fig. 8.

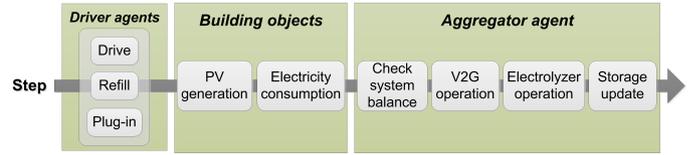


Fig. 8. Flowchart of process.

a) *Driver*: Drivers follow their driving schedule to drive from home to work and vice versa. After arrival, drivers check the fuel level in their vehicle and refill if it is low. Each driver has either a “home” or “work” plug-in profile which indicates whether they plug-in their vehicle at home or at work.

b) *Building object*: Building objects have PV panels that produce electricity, either used for own consumption or to produce hydrogen when generated in excess.

c) *Aggregator*: Every hour the aggregator checks the system balance and determines the residual demand. If needed, available FCEVs are used for V2G. Similarly as in [16], [41], we use a fair scheduling mechanism for the aggregator to operate available vehicles based on their total number of start-ups. Thus, available vehicles that have been used less frequently will be started up first. When there is a surplus solar generation from the buildings and whenever wind power is being generated, the electrolyzers are used to produce hydrogen. Finally, the hydrogen storage is updated and if needed, hydrogen is exchanged with the underground hydrogen storage.

### 3) AMB model assumptions:

- Drivers live and work within the smart city.
- Drivers have constant driving schedules throughout the simulation.
- The use of dischargers for plugging in is based on a first-come first-serve rule.
- Once plugged in, cars are not disconnected until they leave for their next trip.
- Costs (of V2G, hydrogen production, etc.) are not considered in the contracts or to manage or use the vehicles.
- Only the electricity consumption in the buildings is considered.

## C. Simulation results

### 1) ABMS Initialization:

a) *Driver agents*: The properties of the 2300 driver agents are initialized as follows:

- Driving schedule: distribution derived from [44] (average 45 km/day).
- Plug-in profile: 50% drivers during work hours, 50% drivers during home hours.
- Initial fuel level (kg): random number from uniform distribution in the interval [3.0,6.5].
- V2G contract- *guarFuel*: hydrogen requirement for daily driving distance.

b) *Building object and Aggregator agent*: One aggregator agent and one building object that represents all buildings are also created. For the PV, wind, electrolyzers and hydrogen storage, the same capacities as presented in Section III are

used. At the beginning of the simulation, the hydrogen storage system is initialized at 50% of its capacity, and the underground storage is initialized at 50000 kg. The efficiencies of the fuel cell and electrolyzers, as well as the fuel consumption of the FCEV are also the same as in Section III.

2) *Results*: Hourly simulations for two scenarios are run for a year: 1) Unlimited number of Discharging points (UD scenario) and, 2) Limited number of Discharging points (LD scenario). The results in Table II show the difference in the average (and standard deviation) of the 2300 driver agents' results in terms of plug-in time, V2G supplied, and number of start-ups at the end of a year.

|                      | UD Scenario               | LD Scenario               |
|----------------------|---------------------------|---------------------------|
| Plug-in time (hours) | 3,203.8 ( $\pm 1,297$ )   | 1,903.6 ( $\pm 831$ )     |
| V2G supplied (kWh)   | 5,105.0 ( $\pm 2,929.1$ ) | 5,105.0 ( $\pm 3,188.6$ ) |
| Start-ups            | 109.1 ( $\pm 19.9$ )      | 114.9 ( $\pm 25.0$ )      |

TABLE II  
DRIVERS' RESULTS: AVERAGE AND STANDARD DEVIATION

While the number of discharging point does not influence the aggregate performance of vehicle-to-grid supply in the smart city, the differences between the UD and LD scenario indicate that the choice in the number of dischargers influences the participation for individual drivers, as the use of the dischargers follows a first-come first-serve rule. While more dischargers allow more equal opportunities for drivers, it also leads to a higher number of plug-in hours per driver. As seen in Table II, more plug-in hours per driver are not necessary for the operation of the system, as the average V2G supply is the same.

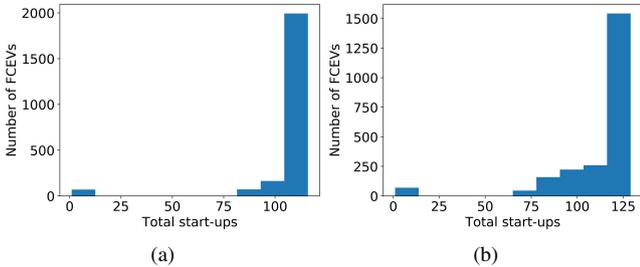


Fig. 9. Distribution of total number of start-ups per driver: (a) UD scenario; (b) LD scenario.

Fig. 9 shows the distribution of start-ups per driver at the end of the year. In the UD scenario, there are around 2000 drivers with the same number of start-ups, while in the LD scenario the distribution is a bit more skewed. Therefore, while at the system level the performance may be the same, there are differences in the participation of drivers at the individual level. There are more equal opportunities for drivers in the UD scenario to provide V2G, as most of them reach (around 2,000) the same number of start-ups at the end of the year. In the LD scenario, there are more drivers that have had fewer opportunities to participate due to the lack of free dischargers. A limited number of discharging points may be appropriate to reduce costs, but additional rules may be needed to provide more fair opportunities for drivers to sell power.

*Remark 1*: The results of this section are based on the assumption that the actors are willing to participate based on the agreed contract. However, participation of actors in the future may be more financial driven than a personal choice since the ownership of the EVs can be shifted from individuals to corporations (such a self-driving car sharing platforms). Hence, to make and implement system operational policy interventions, fair chances for actors (FCEV owners, aggregators, energy companies, etc.) must be ensured. To make this possible incentives and policy measures are needed. Here we can think about mandates and/or subsidies as a way to support the V2G technology and to develop V2G standardization and infrastructure.

## VI. CONCLUSIONS

In this paper, we have presented a hydrogen-based integrated energy and transport system named Car as Power Plant (CaPP). The CaPP concept is a complex socio-technical system. A large network of players is involved in the development and operation of its technical infrastructure and physical components. To illustrate how the CaPP system will work, we designed a 100% renewable integrated energy and transport system for a smart city area based on wind, solar, hydrogen and fuel cell electric vehicles (FCEVs) inspired by the city of Hamburg in Germany. Using techno-economic analysis, we have shown that such a design is technically feasible. However, technical feasibility cannot be guaranteed without considering the controllability of the system. So, the next challenge was to maintain the supply-demand balance as well as to minimize the operational costs of the FCEVs, which we have done by using advanced control techniques. We have stressed that operation of such an innovative concept should be accompanied by an institutional analysis and designing an organizational system structure. To this end, we have studied the system behavior using different contracts between the system agents, namely the owners of FCEVs and the aggregators.

New policies to be defined for carbon-free energy transition are manifold and policymakers require broader knowledge from different disciplines to address the challenges of such system transition. Our framework stresses the need to take into account different aspects such as technology, economics, control, institutional and social perspectives in modeling energy systems. As such, it provides a clearer and more comprehensive insight into the realization of such energy system to policymakers, compared to the individual models. Moreover, to realize a carbon-free energy system, sector coupling is needed, i.e., energy and transport sectors should support each other. For this matter, V2G is a promising technology and FCEVs give more flexibility than standard battery EVs since beside storage, they can operate as dispatchable power plants independent of the electricity grid. The CaPP system and our combined framework is an example of such carbon-free energy system offering sector coupling and facilitating the penetration of 100% intermittent renewables without any compromise on reliability of energy supply for power, heat and transport and at the same time reducing system cost. Moreover, our approach will engage consumers to have a more active role in the energy transition as prosumers. The future research will also include

the grid modeling to explore different system configurations, e.g. hydrogen pipeline grids next to electricity grids, and to investigate whether a combination of battery and fuel cell electric vehicles can reduce total system cost even further.

## ACKNOWLEDGMENTS

This research is supported by the NWO-URSES project Car as Power Plant, which is financed by the Netherlands Organization for Scientific Research (NWO). The authors would like to thank Gilbert Smink and Tijmen Salet for their contribution to the techno-economic analysis of the smart cities.

## REFERENCES

- [1] United Nations (UN). Adoption of the Paris agreement eframework convention on climate change. <https://unfccc.int/resource/docs/2015/cop21/eng/l09r01.pdf>, 2015.
- [2] V. Oldenbroek, L. A. Verhoef, and A. J. M. van Wijk. Fuel cell electric vehicle as a power plant: Fully renewable integrated transport and energy system design and analysis for smart city areas. *International Journal of Hydrogen Energy*, 42:8166–8196, 2017.
- [3] International Energy Agency (IEA). Energy technology perspectives 2016: towards sustainable urban energy systems, 2016.
- [4] S. Cao. Comparison of the energy and environmental impact by integrating a H2 vehicle and an electric vehicle into a zero-energy building. *Energy Conversion and Management*, 123:153–173, 2016.
- [5] S. Garmsiri, S. Koohi-Fayegh, M. A. Rosen, and G. R. Smith. Integration of transportation energy processes with a net zero energy community using captured waste hydrogen from electrochemical plants. *International Journal of Hydrogen Energy*, 41:8337–8346, 2016.
- [6] B. V. Mathiesen, H. Lund, D. Connolly, H. Wenzel, P. A. Østergaard, B. Möller, and et al. Smart energy systems for coherent 100% renewable energy and transport solutions. *Applied Energy*, 145:139–154, 2015.
- [7] D. Steward and J. Zuboy. Community energy: analysis of hydrogen distributed energy systems with photovoltaics for load leveling and vehicle refueling. *National Renewable Energy Laboratory*, 2014.
- [8] A. van Wijk and L. Verhoef. *Our Car as Power Plant*. IOS Press BV, Amsterdam, Netherlands, 2014.
- [9] V. Oldenbroek, S. Alva, B. Pyman, L. B. Buning, P. A. Veenhuizen, and A. J. M. van Wijk. Hyundai ix35 fuel cell electric vehicles: degradation analysis for driving and vehicle-to-grid usage. In *The 30th Electric Vehicle Symposium*, Stuttgart, Germany, October 2017.
- [10] V. Oldenbroek, V. Hamoen, S. Alva, C. Robledo, L. Verhoef, and A. J. M. van Wijk. Fuel cell electric vehicle-to-grid : Experimental feasibility and operational performance. In *Proceedings of the 6th European PEFC & Electrolyser Forum*, Lucerne, Switzerland, June 2017.
- [11] V. Oldenbroek, L. Nordin, and A. J. M. van Wijk. Fuel cell electric vehicle-to-grid: emergency and balancing power for a 100% renewable hospital. In *Proceedings of the 6th European PEFC & Electrolyser Forum*, Lucerne, Switzerland, June 2017.
- [12] F. Alavi, E. H. Park Lee, N. van de Wouw, B. De Schutter, and Z. Lukszo. Fuel cell cars in a microgrid for synergies between hydrogen and electricity networks. *Applied Energy*, 192:296–304, 2017.
- [13] F. Alavi, N. van de Wouw, and B. De Schutter. Min-max control of fuel-cell-car-based smart energy systems. In *Proceedings of the European Control Conference*, Aalborg, Denmark, June 2016.
- [14] F. Alavi, N. van de Wouw, and B. De Schutter. Power scheduling in islanded-mode microgrids using fuel cell vehicles. In *Proceedings of the 56th IEEE Conference on Decision and Control (CDC)*, Melbourne, Australia, December 2017.
- [15] E. H. Park Lee, E. Chappin, Z. Lukszo, and P. Herder. The car as power plant: Towards socio-technical systems integration. In *Proceedings of IEEE PowerTech*, Eindhoven, the Netherlands, June-July 2017.
- [16] E. H. Park Lee and Z. Lukszo. Scheduling fuel cell electric vehicles as power plants in a community microgrid. In *Proceedings of IEEE PES Innovative Smart Grid Technologies, Europe*, Ljubljana, Slovenia, October 2016.
- [17] E. H. Park Lee, Z. Lukszo, and P. Herder. Aggregated fuel cell vehicles in electricity markets with high wind penetration. In *Proceedings of IEEE International Conference of Networking, Sensing and Control (ICNSC)*, Zhuhai, China, March 2018.
- [18] R. van der Veen, R. Verzijlbergh, and Z. Lukszo. Exploring the profit potential of energy storage in a car park using electrolysis, hydrogen storage and fuel cell electric vehicles. In *Proceedings of the International Conference on Sustainable Energy & Environmental Protection (SEEP2017)*, Bled, Slovenia, June 2017.
- [19] CEN-CENELEC-ETSI Smart Grid Coordination Group. Smart grid set of standards. <https://www.dke.de/resource/blob/765952/e020d215ac4edae2f77a22fa146a4583/extended-set-of-standards-support-smart-grids-deployment-data.pdf>, 2014.
- [20] J. Andrews and B. Shabani. Re-envisioning the role of hydrogen in a sustainable energy economy. *International Journal of Hydrogen Energy*, 37:1184–1203, 2012.
- [21] A. Maroufmashat, M. Fowler, S. Sattari Khavas, A. Elkamel, R. Roshandel, and A. Hajimiragha. Mixed integer linear programming based approach for optimal planning and operation of a smart urban energy network to support the hydrogen economy. *International Journal of Hydrogen Energy*, 41:7700–7716, 2016.
- [22] Enerdata. Odyssee database - transport, households and services. <http://odyssee.enerdata.net/database/>, 2015.
- [23] Eurostat. Number of private households by household composition, number of children and age of youngest child (1000). [http://ec.europa.eu/eurostat/en/web/products-datasets/-/LFST\\_HHNHTYCH](http://ec.europa.eu/eurostat/en/web/products-datasets/-/LFST_HHNHTYCH), 2015.
- [24] U. Bünger, J. Michalski, F. Crotagino, and O. Kruck. Large-scale underground storage of hydrogen for the grid integration of renewable energy and other applications. *Compendium of Hydrogen Energy*, 4:133–163, 2016.
- [25] NEDU. Profielen Aardgas & Elektriciteit 2017, 2017.
- [26] CIBSE. *Degree-Days - Theory and Application - TM41: 2006*. Chartered Institution of Building Services Engineer, 2006.
- [27] M. De Rosa, V. Bianco, F. Scarpa, and L. Tagliafico. Historical trends and current state of heating and cooling degree days in Italy. *Energy Conversion and Management*, 90:323–335, 2015.
- [28] B. Aebischer, G. Catenazzi, and M. Jakob. Impact of climate change on thermal comfort, heating and cooling energy demand in Europe. In *in Proceedings of ECEEE*, pages 23–26, 2007.
- [29] Deutscher Wetterdienst. Klimadaten Deutschland-Stundenwerte-FTP server-Hamburg-Fuhlsbüttel-Station ID 1975-2012-2016. [ftp://ftp-cdc.dwd.de/pub/CDC/observations\\_germany/climate/hourly/](ftp://ftp-cdc.dwd.de/pub/CDC/observations_germany/climate/hourly/), 2017.
- [30] M. C. Peel, B. L. Finlayson, and T. A. McMahon. Updated world map of the Köppen-Geiger climate classification. *Hydrology and Earth System Sciences*, 11:1633–1644, 2007.
- [31] U. Persson and S. Werner. Quantifying the Heating and Cooling Demand in Europe: Work Package 2, Background Report 4, 2015.
- [32] S. Werner. European space cooling demands. *Energy*, 110:148–156, 2016.
- [33] M. Jakubcionis and J. Carlsson. Estimation of European Union residential sector space cooling potential. *Energy Policy*, 101:225–235, 2017.
- [34] M. Jakubcionis and J. Carlsson. Estimation of European Union service sector space cooling potential. *Energy Policy*, 113:223–231, 2018.
- [35] Kraftfahrt-Bundesamt. Der Fahrzeugbestand im Überblick am 1. Januar 2016 gegenüber 1. Januar 2015, 2016.
- [36] Kraftfahrt-Bundesamt. Verkehr in Kilometern der deutschen Kraftfahrzeuge im Jahr 2015, 2016.
- [37] M. Jacobson, M. Delucchi, M. Cameron, and B. Mathiesen. Matching demand with supply at low cost in 139 countries among 20 world regions with 100% intermittent wind, water, and sunlight (WWS) for all purposes. *Renewable Energy*, 123:236–248, 2018.
- [38] CPLEX optimizer. <http://www-01.ibm.com/software/commerce/optimization/cplex-optimizer/>.
- [39] Gurobi optimization. <http://www.gurobi.com/>.
- [40] M. Yazdani and A. Mehrizi-Sani. Distributed control techniques in microgrids. *IEEE Transactions on Smart Grids*, 5(6), November 2014.
- [41] E. H. Park Lee, Z. Lukszo, and P. Herder. Static volume-based and control-based contracts for coordinating vehicle-to-grid supply in a microgrid. In *Proceedings of Innovative Smart Grid Technologies (ISGT) European 2017 Conference*, pages 1–6, 2017.
- [42] E. H. Park Lee, Z. Lukszo, and P. Herder. Conceptualization of vehicle-to-grid contract types and their formalization in agent-based models. *Complexity*, 2018, 2018.
- [43] G. R. Parsons, M. K. Hidrue, W. Kempton, and M. P. Gardner. Willingness to pay for vehicle-to-grid (v2g) electric vehicles and their contract terms. *Energy Economics*, 42(0):313–324, mar 2014.
- [44] Centraal Bureau voor de Statistiek (CBS) and Rijkswaterstaat (RWS). Onderzoek Verplaatsingen in Nederland 2014 (Research on Movements in the Netherlands 2014) - Data Archiving and Networked Services (in Dutch), 2015.