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A hydrogen-based integrated energy and transport system

The design and analysis of the Car as Power Plant Concept

Safaei Farahani, Samira; van der Veen, Reinier; Oldenbroek, Vincent; Alavi, Farid; Park Lee, Esther; van de Wouw, Nathan; van Wijk, Ad; De Schutter, Bart; Lukszo, Zofia

DOI
10.1109/MSMC.2018.2873408

Publication date
2019

Document Version
Final published version

Published in
IEEE Systems, Man, and Cybernetics Magazine

Citation (APA)
Safaei Farahani, S., van der Veen, R., Oldenbroek, V., Alavi, F., Park Lee, E., van de Wouw, N., van Wijk, A., De Schutter, B., & Lukszo, Z. (2019). 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*, *5*(1), 37-50. https://doi.org/10.1109/MSMC.2018.2873408

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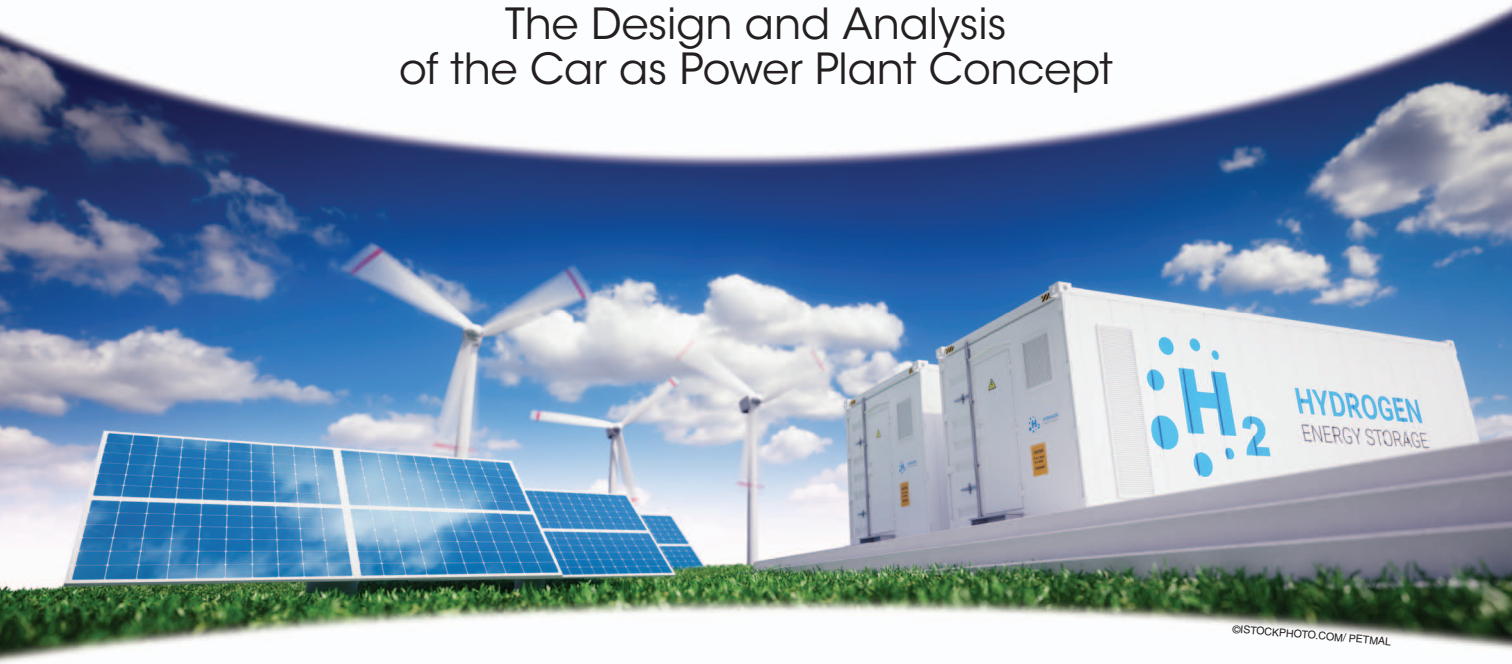
A Hydrogen-Based Integrated Energy and Transport System

The Design and Analysis of the Car as Power Plant Concept



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by Samira S. Farahani, Reinier van der Veen, Vincent Oldenbroek, Farid Alavi, Esther H. Park Lee, Nathan van de Wouw, Ad van Wijk, Bart De Schutter, and Zofia Lukszo

In recent years, the European Union (EU) has set ambitious targets toward 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 toward a sustainable energy system, solar (or green) hydrogen plays many important roles, as it is a clean and safe energy carrier that can also be used as a fuel in transportation and in electricity production. To understand and steer the transition from the current energy system toward an integrated hydrogen-based energy and transport system, we propose a framework that integrates a technical and economic feasibility study, a 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

Digital Object Identifier 10.1109/MSMC.2018.2873408
Date of publication: 16 January 2019

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.

Development of the CaPP Smart City

The urgency to significantly reduce the impacts of climate change is felt around the globe. By signing the Paris Agreement, 195 governments agreed on a long-term goal of keeping the increase in global average temperature lower than 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 energy and transport systems 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 (EVs) [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]. In recent years, it has been shown that the integration of energy and transport systems may solve major problems related to the separate transitions described previously and create synergies [4]–[7].

To integrate electricity and transport systems, we developed a concept known as *CaPP* [8] to utilize automotive fuel cells as stationary power production units during nondriving hours (typically at home or in parking lots during office hours). When a 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 article 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 fuel cell EVs (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 we 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 article aims to provide a single comprehensive framework for designing a complex sociotechnical system from different perspectives. We will 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. Standalone technical analysis is not complete without economic and social analysis. To this end, we introduce a fully renewable energy system for a smart city in 2050, inspired by the city of Hamburg, 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.

System Description

The smart city used as an illustrative example for 2050 is designed in such a way that it fulfils the following design requirements:

1) the city's energy and transport systems use only electricity and hydrogen as energy carriers, and 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 does not depend 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, 2,000 households were selected (since for every 2,000 households, there is a medium-sized supermarket and one gas station) [22]. According to German statistics, 2,000 German households correspond to an average of 4,210 people, with a total of 2,330 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 2,000 households. An average dwelling has a floor area of 92 m^2. Residential and service sector roofs are used for solar electricity systems and for rainwater collection. Solar electricity systems are installed on roof areas: 9 m^2 per person on residential buildings and 4 m^2 per person on service sector buildings. The roof area available for rainwater collection is 22.5 and 10 m^2 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 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 seven major elements:

1) local solar electricity and 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 and smart electric grid control: the smart electric grid is managed by a controller, which connects all buildings, grid-connected 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 EVS
3) hydrogen tube trailer transport: tube trailers towed by tube trailer tractors transport hydrogen either from 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 including passenger cars, vans, buses, or trucks
6) large-scale and 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

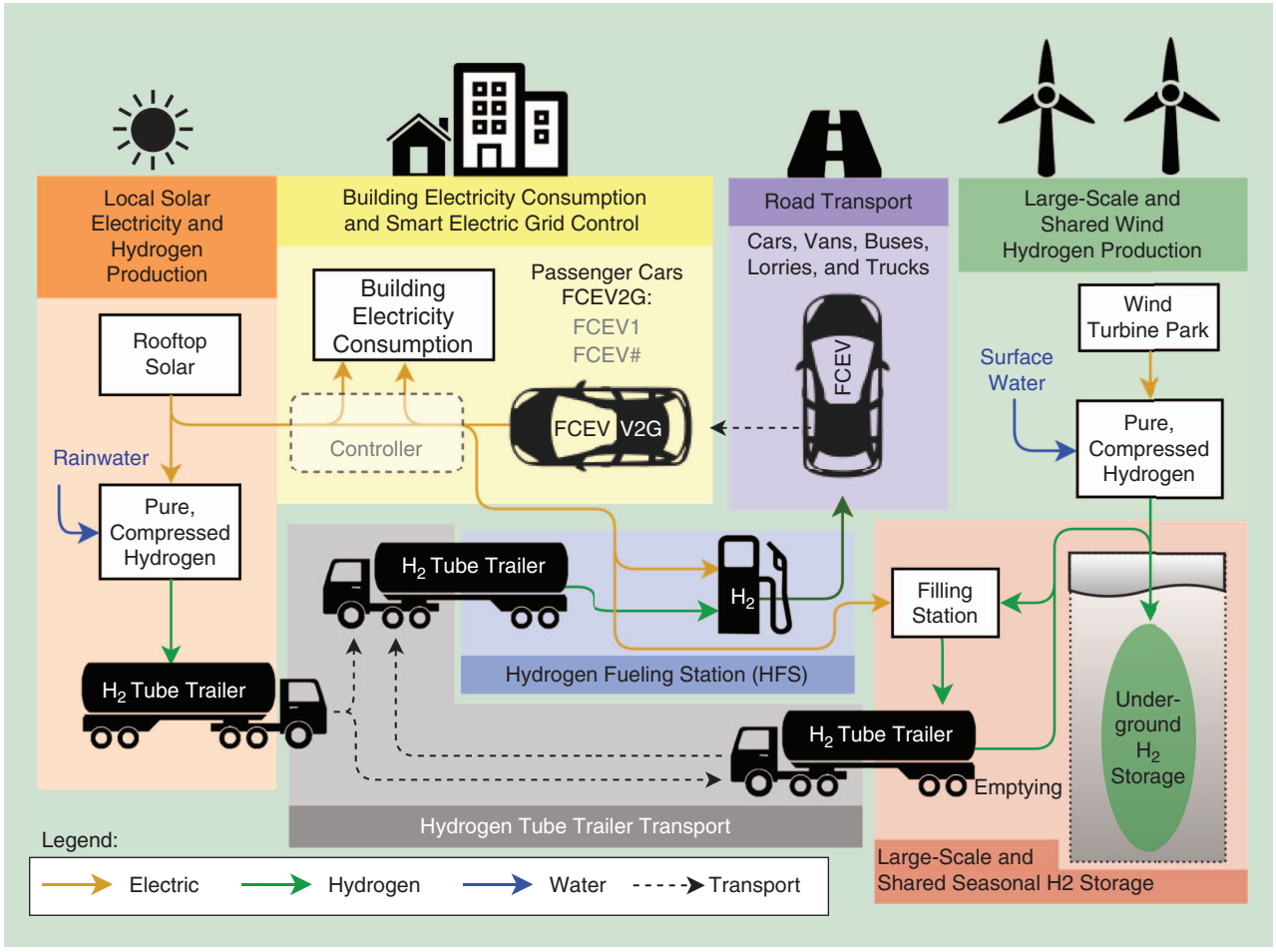

Figure 1. The hydrogen-based integrated energy and transport system and its key elements.

for hydrogen production, which will be reserved in a large-scale seasonal hydrogen storage

7) large-scale and 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 (Figure 2) based on four perspectives: technical, economic, operational and control, and institutional perspectives. In the following sections, we explain how these perspectives will be combined to obtain a complete system design and analysis.

Technoeconomic Analysis

In this section, the technoeconomic 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, and 3) cost of energy calculation based on the sizing and economic characterization of the system components.

Modeling the Hydrogen-Based Integrated Energy and Transport System

Figure 3 displays the simplified simulation scheme of the system and consists of an hourly and annual energy balance. First, the hourly electricity and hydrogen balance has to be met, either by converting surplus electricity into hydrogen or by 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 buildings, 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 and 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.

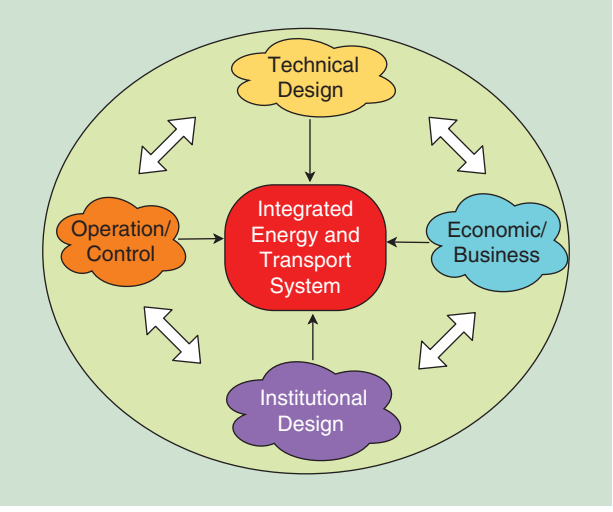

Figure 2. The analysis framework for the design of the future smart city area.

Cost of Energy

We applied the cost calculation methods described in [2], which consider the different economic lifetimes and operation and maintenance costs (OMCs) 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 kiloeuros per year (k€/year) is the sum of the total annual capital costs (CCs) and the OMCs of the individual subsystems. The levelized cost of energy of electricity ($LCoE_e$) from wind and solar does not include energy storage. Therefore, the system levelized cost of energy ($SLCo_e$) is introduced [2]. The system levelized costs of energy built up from cost of energy for electricity consumption in buildings $SLCoE_e$ [euros per kilowatthour (€/kWh)] and hydrogen consumption for driving $SLCoE_H$ [euros per kilograms H_2 (€/kg)] are calculated by allocating a share of the TC of the smart city area energy system [2].

Simulation Results

Energy Balance

Based on the hourly simulation, the annual energy balance is defined and presented in Figure 4. We investigated the production and transport of hydrogen and the seasonal and tube trailer hydrogen storage in analyzing the annual system behavior [Figure 4(a)]. In the October to 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 approximately 2,000 kg is stored in the underground storage (see also Figure 5, H_2 80 MWh).

In Figure 4(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 6 p.m. During the night hours (11 p.m.–4 a.m.), in the summer and winter, on average, between 100 and 200 cars are required (4–9%). Around 4 a.m., FCEV demand starts rising to an average of 280 (12%) at 8 a.m. in the winter and 150 (6%) at 5 a.m. in the summer. At these morning peak hours, solar electricity starts to cover the daytime electricity demand. In the winter, the average minimum is 105 cars (5%) at 1 p.m., and in the summer, it is fewer than 25 cars (1%) from 9 a.m. and 4 p.m. The average evening peak is 350 cars (15%) at 6 p.m. in the winter and 210 cars (9%) at 8 p.m. in the

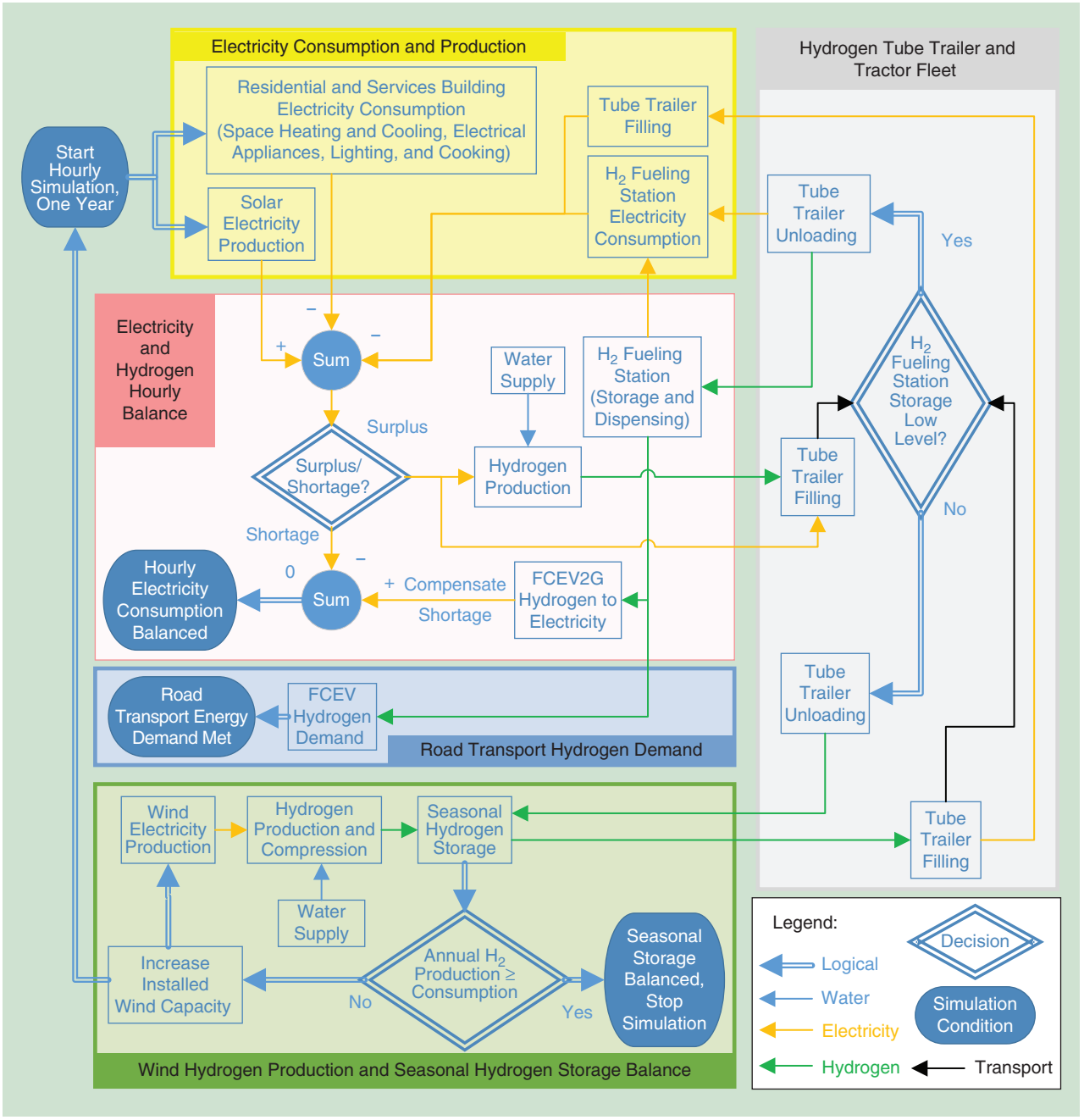

Figure 3. The simplified hourly simulation scheme for a hydrogen-based integrated energy and transport system.

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. The 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 are required to make this system operational and reliable.

Cost Analysis

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

The TC of the smart city area energy system is 3,085 k€/year and is the sum of the total annual CCs of 2,204 k€/year and the OMCs of 881 k€/year of the individual subsystems. The LCoE_e from wind and solar is 0.03 and 0.02 €/kWh, respectively. The SLCo_e is 0.11 €/kWh, and the SLCoE_H is 3.3 €/kg H_2. These values are comparable with those for other future fully renewable integrated energy systems [37].

Optimal Scheduling

Promising conclusions from the technoeconomic 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, $P_{\mathrm{res}}(k)$, i.e., the actual load subtracted by the power

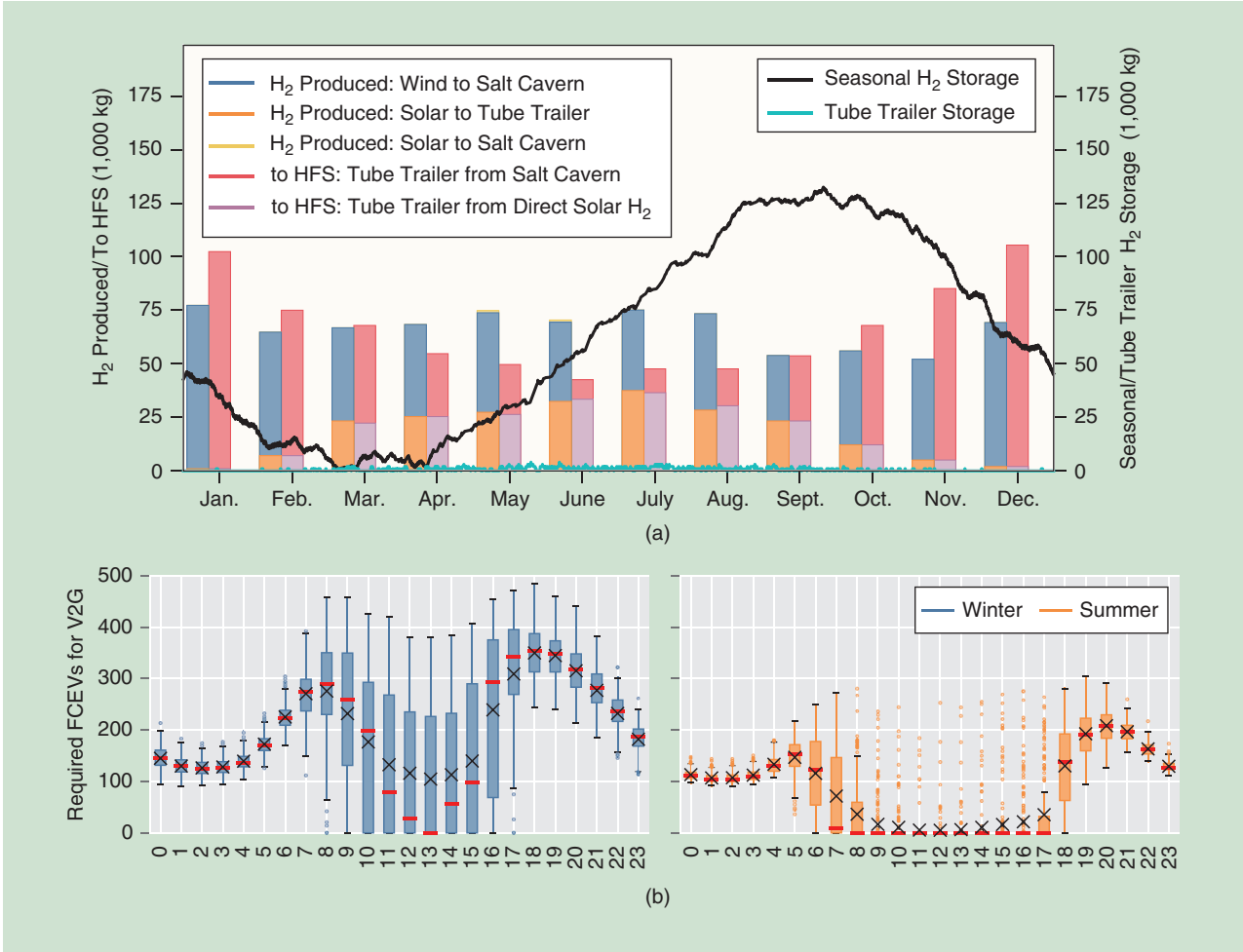

Figure 4. (a) The hydrogen production and transport (left axis) and seasonal and tube trailer hydrogen storage (right axis) and (b) the FCEV2G operation during winter (left) and summer (right, days) period per hour of the day.

generation of the solar photovoltaic (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, and control cost (Table 1).

Discrete-Time Model of the Hydrogen-Based Integrated Energy and 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 $\mathcal{I} = \{1, \ldots, N_v\}$ 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 α_i and β_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, $s_{f,i}(k)$, 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 15-min) 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

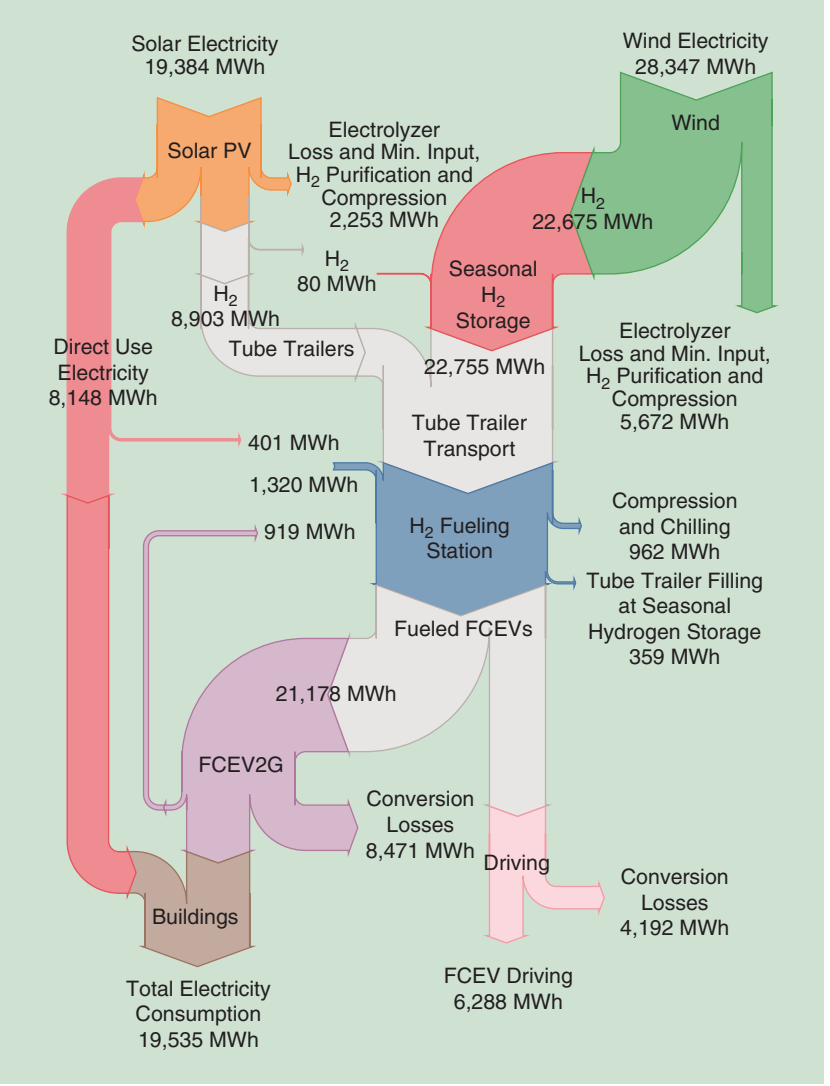

Figure 5. The annual energy balance for a 2050 fully renewable electricity, heating, and road transport system for the city of Hamburg. Min.: minimum.

Table 1. Calculated CC, OMC, and TC for the subsystems in the smart city area.

Subsystems	CC (k€/year)	OMC (k€/year)	TC (k€/year)
Solar electricity	406	199	605
Solar H_2 production	273	70	343
Wind electricity	360	226	586
Wind H_2 production	142	89	231
Hydrogen fueling station	352	63	416
Seasonal H_2 storage	259	11	270
H_2 tube trailers transport	143	151	293
FCEV2G, smart grid, and control	268	72	341
Total system cost of energy	2,204	881	3,085

the car is not in transportation mode at time step k, then $\gamma_i(k) = 0$.

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

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

In (1), $s_{\mathrm{f},i}(k)$ 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 is defined as $u_i(k) = [u_{\mathrm{f},i}(k) \;\; s_{\mathrm{f},i}(k) \;\; s_{\mathrm{r},i}(k)]^T$.

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:

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

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

The operation of the 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 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], (1) and (2) together with the aforementioned constraints can be rewritten as a so-called mixed logical dynamical model of the form

$$x(k+1) = x(k) + B_1 u(k) + B_2 z(k) \times E_1 u(k) + E_4 x(k) + E_5 \geq E_3 z(k). \quad (3)$$

In (3), $x(k)$ and $u(k)$ are the system states and the control inputs and are defined as $x(k) = [x_1^T(k) \ldots x_{N_v}^T(k)\, x_s(k)]^T$ and $u(k) = [u_1^T(k) \ldots u_{N_v}^T(k)]^T$, 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 TC function of the system is

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

where $\mathcal{J} = \{0, \ldots N_{\mathrm{p}} - 1\}$ and $W_{\mathrm{S},i}$, $W_{1,i}$, 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 $\Delta s_{\mathrm{f},i}(k+j)$ indicates the difference in the value of $s_{\mathrm{f},i}$ in two consecutive time steps as $\Delta s_{\mathrm{f},i}(k+j) = s_{\mathrm{f},i}(k+j) - s_{\mathrm{f},i}(k+j-1)$, which represents the switching on and off of the fuel cell.

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 $\tilde{u}(k) = [u^T(k)\, u^T(k+1) \ldots u^T(k+N_{\mathrm{p}}-1)]^T$. 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

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

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].

Simulation Results

Assumptions in the Model Predictive Control Approach

We considered 2,300 fuel cell cars inside the system, where the parameters α_i and β_i in (1) are randomly chosen from a uniform distribution in an interval [0.03, 0.05] kg/kWh for α_i and an interval [0.001, 0.009] kg/h for β_i for all $i \in \mathcal{I}$. The maximum power generation of each fuel cell car, $\bar{u}_{\mathrm{f},i}$ for all $i \in \mathcal{I}$ is assumed to be 10 kW. The

maximum capacity of the 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 to cover the most important dynamics of the system. The sampling time, T_S, is assumed to be 1 h.

Results

The operation of a smart city area with the specifications described in the "System Description" section 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 (6) for 2,300 cars using a normal personal computer. There are generally two approaches to decrease the computation time and make the problem tractable. The first is to use a distributed control architecture (see e.g., [40]). The second 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 does not depend 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. 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 an Intel Xeon central processing unit with 3.7-GHz clock speed and 16 GB of random access memory, it takes, on average, about 0.46 s to solve the optimization problem of each time step. Considering the time step of 1 h, the optimization problems are thus solved fast enough for real-time application. The obtained results show that, in general, the stored hydrogen increases during the spring and summer, while in the fall and winter periods, the stored hydrogen decreases, which confirms the results of Figure 4(a). Also, the simulation results illustrated in Figure 6 show the total number of cars used in the power generation mode is less in the spring and summer compared with other times of the year, which confirms the results of the "Technoeconomic Analysis" section.

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 sociotechnical 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 V2G contracts to show the role of contract parameters in the participation of drivers when supplying power to the smart city.

V2G Contracts

As described in our previous work [42], we build on 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 the "Technoeconomic Analysis" and "Optimal Scheduling" sections, the number of vehicles needed at a certain hour is between 400 and 500 [compare Figures 4(b) and 6]. Therefore, the number of discharging points for V2G is set to 500. Given the large number 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.

Agent-Based Model

As introduced previously, 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 Figure 7, we create agents that represent actors in the social subsystem that own and operate components in the physical subsystem. Buildings

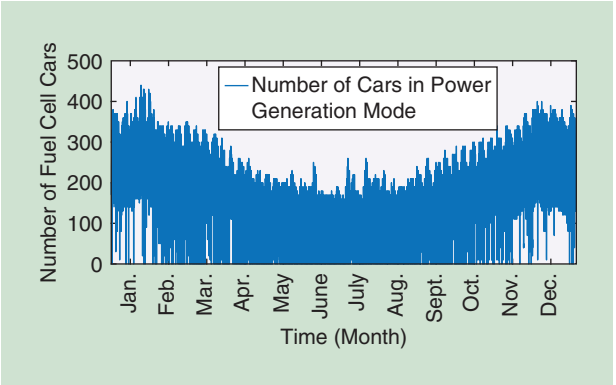

Figure 6. The number of cars in the power generation mode for one year.

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. The description of the agent-based model is given in more detail.

Agents and Objects

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*).

Building Object

Commercial and retail buildings are represented as objects that consume and produce electricity with rooftop PV systems.

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.

Process Overview

The order in which actions take place in the simulation is depicted in Figure 8.

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 it if it is low. Each driver has either a "home" or "work" plug-in profile that indicates whether the driver plugs in his or her vehicle at home or at work.

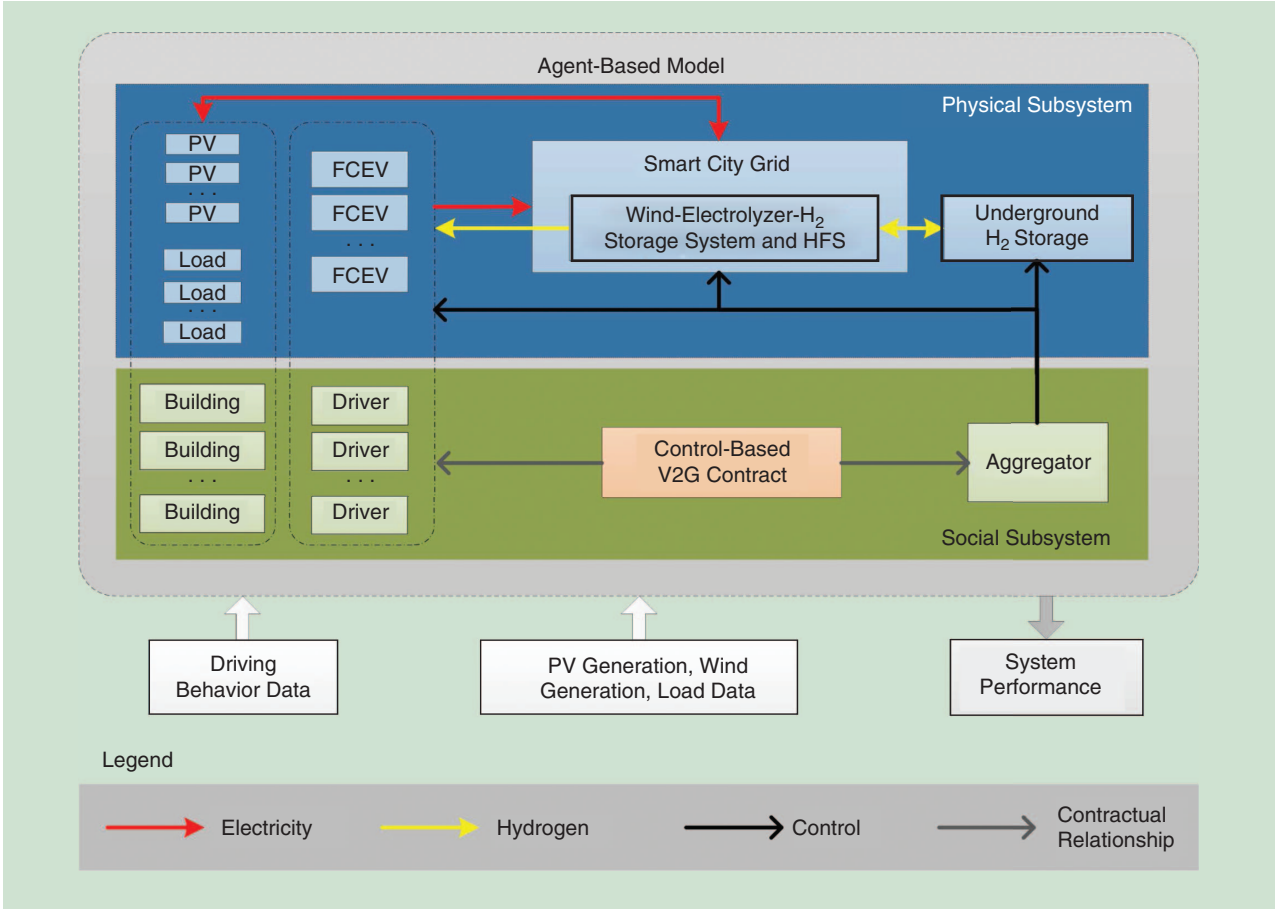

Figure 7. The agent-based model concepts.

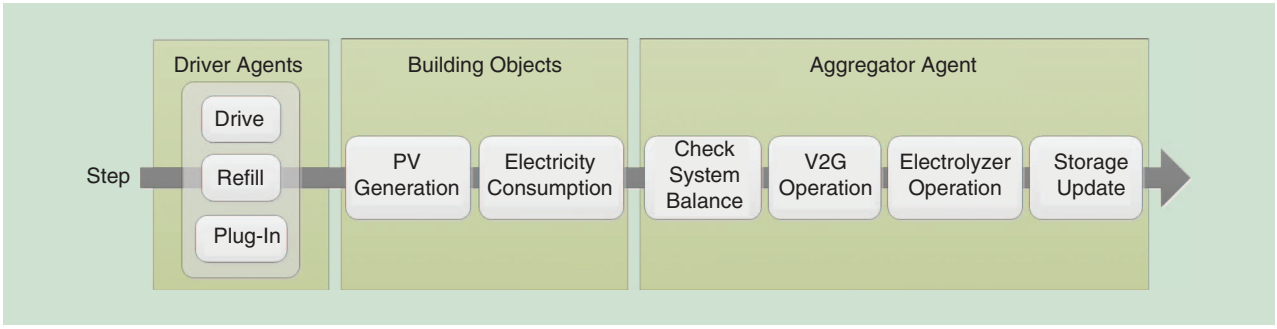

Figure 8. The flowchart of process.

Building Object

Building objects have PV panels that produce electricity, either used for their own consumption or to produce hydrogen when generated in excess.

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] and [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.

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, and so on) are not considered in the contracts or to manage or use the vehicles.
- Only the electricity consumption in the buildings is considered.

Simulation Results

ABMS Initialization

Driver Agents

The properties of the 2,300 driver agents are initialized as follows:

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

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 the "Technoeconomic Analysis" section 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 50,000 kg. The efficiencies of the fuel cell and electrolyzers, as well as the fuel consumption of the FCEV, are also the same as in the "Technoeconomic Analysis" section.

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 2 show the difference in the average (and standard deviation) of the 2,300 driver agents' results in terms of plug-in time, V2G supplied, and number of start-ups at the end of a year.

While the number of discharging points does not influence the aggregate performance of V2G supply in the smart city, the differences between the UD and LD scenarios 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-served rule. While more dischargers allow more equal opportunities for drivers, this circumstance also leads to

Table 2. Drivers' results: average and standard deviation.

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

a higher number of plug-in hours per driver. As seen in Table 2, more plug-in hours per driver are not necessary for the operation of the system, as the average V2G supply is the same.

Figure 9 shows the distribution of start-ups per driver at the end of the year. In the UD scenario, there are around 2,000 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 (around 2,000) reach 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 fairer opportunities for drivers to sell power.

The results of this section are based on the assumption that the actors are willing to participate based on the agreed contract. However, the 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 as self-driving car-sharing platforms). Hence, to make and implement system operational policy interventions, fair chances for actors (FCEV owners, aggregators, energy companies, and so forth) 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.

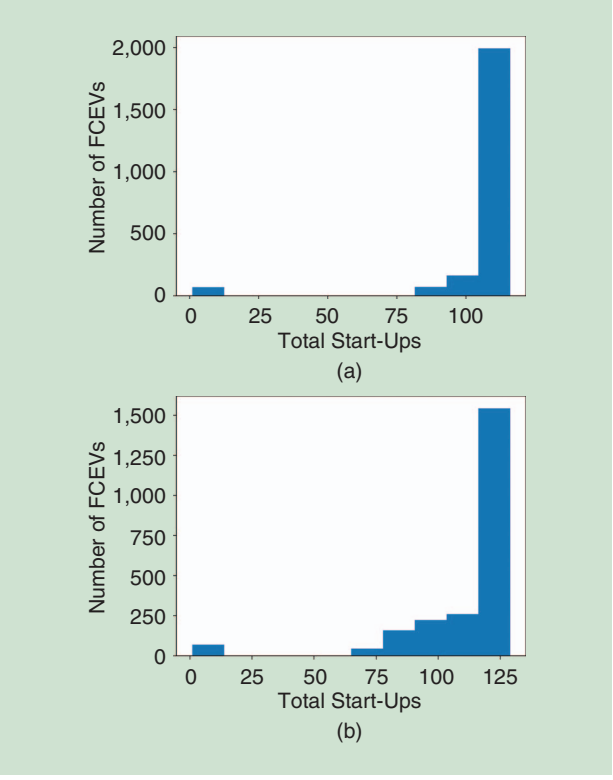

Figure 9. The distribution of the total number of start-ups per driver: (a) the UD scenario and (b) the LD scenario.

Conclusion

In this article, we presented a hydrogen-based integrated energy and transport system named *CaPP*. The CaPP concept is a complex sociotechnical 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 FCEVs inspired by the city of Hamburg, 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 stressed that operation of such an innovative concept should be accompanied by an institutional analysis and by designing an organizational system structure. To this end, we studied the system behavior using different contracts between the system agents, i.e., 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 consider 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 an energy system to policymakers, compared with the individual models. Moreover, to realize a carbon-free energy system, sector coupling is needed, i.e., the 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, in addition to storage, they can operate as dispatchable power plants independent of the electricity grid. The CaPP system and our combined framework are an example of such a 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 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 FCEVs can reduce total system cost even further.

Acknowledgments

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

About the Authors

Samira S. Farahani (s.farahani@tudelft.nl) earned her B.Sc. degree in applied mathematics from the Sharif University of Technology, Iran, in 2005. She earned her M.Sc. degree in applied mathematics and Ph.D. degree in systems and control from the Delft University of Technology, The Netherlands, in 2008 and 2012, respectively. She is a postdoctoral researcher at the Engineering Systems and Services Department at the Delft University of Technology.

Reinier van der Veen (R.A.C.vanderVeen@tudelft.nl) earned his master's degree in systems engineering, policy analysis, and management from the Faculty of Technology, Policy, and Management at the Delft University of Technology, The Netherlands, in 2007. He earned his Ph.D. degree at the same university in 2012 on the topic of design and internationalization of electricity balancing markets in Europe. He is currently working in sustainable fuel projects at the environmental research and consultancy company CE Delft.

Vincent Oldenbroek (V.D.W.M.Oldenbroek@tudelft.nl) earned his M.Sc. degree in process engineering and investigated integrated gasification fuel cell combined cycles with CO_2 capture from the Delft University of Technology, The Netherlands. He is a Ph.D. candidate within the Future Energy Systems group at the Department of Process and Energy, Faculty of 3mE, at the Delft University of Technology, The Netherlands. His research focuses on fully renewable integrated transport and energy systems with electricity and hydrogen as energy carriers.

Farid Alavi (f.alavi@tudelft.nl) earned his B.Sc. degree in 2010 and his M.Sc. degree in 2013, both in electrical engineering control, from the Isfahan University of Technology, Iran. He began his Ph.D. research in October 2014 at the Delft Center for Systems and Control at the Delft University of Technology, The Netherlands. The topic of his current research is model predictive control of energy management systems in the presence of uncertainty.

Esther H. Park Lee (H.ParkLee@tudelft.nl) earned her B.Sc. degree in chemical engineering from the Universitat Ramon Llull, Barcelona, Spain, in 2009 and M.Sc. degrees in industrial ecology from Leiden University, The Netherlands, and the Delft University of Technology (TU Delft), The Netherlands, in 2013. She is currently a Ph.D. candidate within the Energy & Industry group at the Faculty of Technology, Policy, and Management at TU Delft.

Nathan van de Wouw (n.v.d.wouw@tue.nl) earned his M.Sc. degree (honors) and his Ph.D. degree in mechanical engineering from the Eindhoven University of Technology, The Netherlands, in 1994 and 1999, respectively. He currently holds a full professor position in the Mechanical Engineering Department at the Eindhoven University of Technology. He also holds an adjunct full professor position at the University of Minnesota, Minneapolis and a (part-time) full professor position at the Delft University of Technology, The Netherlands.

Ad van Wijk (A.J.M.vanWijk@tudelft.nl) earned his Ph.D. degree for research on wind energy and electricity production in 1990 at the University of Utrecht, The Netherlands, where he studied physics. He is a sustainable energy entrepreneur and part-time professor of future energy systems at Delft University of Technology (TU Delft), The Netherlands. He also works for the KWR Water Research Institute to develop and implement the research program Energy and Water. He is a member of the Northern Netherlands Innovation Board to realize the energy transition.

Bart De Schutter (b.deschutter@tudelft.nl) earned his Ph.D. degree in applied sciences in 1996 at Katholieke Universiteit (KU) Leuven, Belgium. He is currently a full professor and head of a department at the Delft Center for Systems and Control at the Delft University of Technology, The Netherlands. He is the associate editor of *IEEE Transactions on Automatic Control* and the senior editor of *IEEE Transactions on Intelligent Transportation Systems*.

Zofia Lukszo (z.lukszo@tudelft.nl) earned her Ph.D. degreee from the Eindhoven University of Technology, The Netherlands, in 1996, and studied applied mathematics at the Technical University of Lodz and philosophy at the University of Lodz, Poland. She is a full professor of smart energy systems at the Delft University of Technology, The Netherlands, and the Politecnico di Torino, Italy. She is a Steering Board member of PowerWeb, an interfaculty program on smart grids at the Delft University of Technology, The Netherlands. She is a Senior Member of the IEEE.

References

[1] United Nations. (2015). Adoption of the Paris agreement. *United Nations Framework Convention on Climate Change*. [Online]. Available: https://unfccc.int/resource/docs/2015/cop21/eng/l09r01.pdf

[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," *Int. J. Hydrogen Energy*, vol. 42, no. 12, pp. 8166–8196, Mar. 2017.

[3] International Energy Agency. Energy technology perspectives 2016: Towards sustainable urban energy systems, 2016. [Online]. Available: https://www.iea.org/publications/freepublications/publication/EnergyTechnologyPerspectives2016_ExecutiveSummary_EnglishVersion.pdf

[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 Manage.*, vol. 123, pp. 153–173, Sept. 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," *Int. J. Hydrogen Energy*, vol. 41, no. 9, pp. 8337–8346, May 2016.

[6] B. V. Mathiesen, H. Lund, D. Connolly, H. Wenzel, P. A. Østergaard, B. Möller, S. Nielsen, I. Ridjan, P. Karnøek, K. Sperling, F. K. Hvelplund, "Smart energy systems for coherent 100% renewable energy and transport solutions," *Appl. Energy*, vol. 145, pp. 139–154, May 2015.

[7] D. Steward and J. Zuboy, "Community energy: Analysis of hydrogen distributed energy systems with photovoltaics for load leveling and vehicle refueling," Nat. Renewable Energy Lab., Golden, CO, Tech. Rep. NREL/TP-6A20-62781, Oct. 2014.

[8] A. van Wijk and L. Verhoef, *Our Car as Power Plant*. Amsterdam, Netherlands: IOS Press, 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 *Proc. 30th Electric Vehicle Symp.*, Stuttgart, Germany, 2017, pp. 1–11.

[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 *Proc. 6th European PEFC & Electrolyser Forum*, Lucerne, Switzerland, 2017, pp. 1–18.

[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 *Proc. 6th European PEFC & Electrolyser Forum*, Lucerne, Switzerland, 2017, pp. 1–19.

[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," *Appl. Energy*, vol. 192, pp. 296–304, Apr. 2017.

[13] F. Alavi, N. van de Wouw, and B. De Schutter, "Min-max control of fuel-cell-car-based smart energy systems," in *Proc. European Control Conf.*, Aalborg, Denmark, 2016, pp. 1223–1228.

[14] F. Alavi, N. van de Wouw, and B. De Schutter, Power scheduling in islanded-mode microgrids using fuel cell vehicles," in *Proc. 56th IEEE Conf. Decision and Control (CDC)*, Melbourne, Australia, 2017, pp. 5056–5061.

[15] E. H. Park Lee, E. Chappin, Z. Lukszo, and P. Herder, "The car as power plant: Towards socio-technical systems integration," in *Proc. IEEE PowerTech*, Eindhoven, The Netherlands, 2015, pp. 1–6.

[16] E. H. Park Lee and Z. Lukszo, "Scheduling fuel cell electric vehicles as power plants in a community microgrid," in *Proc. IEEE PES Innovative Smart Grid Technologies*, Ljubljana, Slovenia, 2016, pp. 1–6.

[17] E. H. Park Lee, Z. Lukszo, and P. Herder, "Aggregated fuel cell vehicles in electricity markets with high wind penetration," in *Proc. IEEE Int. Conf. Networking, Sensing and Control (ICNSC)*, Zhuhai, China, 2018, pp. 1–6.

[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 *Proc. Int. Conf. Sustainable Energy & Environmental Protection (SEEP2017)*, Bled, Slovenia, 2017, pp. 1–6.

[19] *Smart grid set of standards*, CEN-CENELEC-ETSI Smart Grid Coordination Group Standard SGCG/M490/G, 2014.

[20] J. Andrews and B. Shabani, "Re-envisioning the role of hydrogen in a sustainable energy economy," *Int. J. Hydrogen Energy*, vol. 37, no. 2, pp. 1184–1203, Jan. 2012.

[21] A. Maroufmashat, M. Fowler, S. Sattari Khavas, A. Elkamel, R. Roshandel, and A. Hajimiragha, "Mixed integer linear programing based approach for optimal planning and operation of a smart urban energy network to support the hydrogen economy," *Int. J. Hydrogen Energy*, vol. 41, no. 19, pp. 7700–7716, May 2016.

[22] Enerdata. (2015). Odyssee database - transport, households and services. *Enerdata*. [Online]. Available: http://odyssee.enerdata.net/database/

[23] Eurostat. (2015). Number of private households by household composition, number of children and age of youngest child (1000). *Eurostat*. [Online]. Available: http://ec.europa.eu/eurostat/en/web/products-datasets/-/LFST_HHNHTYCH

[24] U. Bünger, J. Michalski, F. Crotogino, and O. Kruck, "Large-scale underground storage of hydrogen for the grid integration of renewable energy and other applications," *Compendium Hydrogen Energy*, vol. 4 (Woodhead Publishing Series in Energy), pp. 133–163, 2016.

[25] "NEDU," *Profielen Aardgas Elektriciteit*, vol. 2017, 2017. [Online]. Available: https://www.nedu.nl/documenten/verbruiksprofielen/

[26] CIBSE, "Degree-days - Theory and application - TM41: 2006," Chartered Institution of Building Services Engineer, London, United Kingdom, 2006. [Online]. Available: https://www.cibse.org/Knowledge/knowledge-items/detail?id=a0q20000008I73TAAS

[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 Manage.*, vol. 90, pp. 323–335, Jan. 2015.

[28] B. Aebischer, G. Catenazzi, and M. Jakob, "Impact of climate change on thermal comfort, heating and cooling energy demand in Europe," *in Proc. ECEEE*, 2007, pp. 23–26.

[29] W. Deutscher. (2017). Klimadaten Deutschland-Stundenwerte. *FTP server-Hamburg-Fuhlsbüttel-Station ID 1975-2012-2016*. [Online]. Available: ftp://ftp-cdc.dwd.de/pub/CDC/observations_germany/climate/hourly/

[30] M. C. Peel, B. L. Finlayson, and T. A. McMahon, "Updated world map of the Köppen-Geiger climate classification," *Hydrology Earth System Sci.*, vol. 11, no. 5. pp. 1633–1644, Oct. 2007.

[31] U. Persson and S. Werner, "Quantifying the Heating and Cooling Demand in Europe," Work Package 2, Background Report 4, 2015. [Online]. Available: https://heatroadmap.eu/

[32] S. Werner, "European space cooling demands," *Energy*, vol. 110, pp. 148–156, Sept. 2016.

[33] M. Jakubcionis and J. Carlsson, "Estimation of European Union residential sector space cooling potential," *Energy Policy*, vol. 101, pp. 225–235, Feb. 2017.

[34] M. Jakubcionis and J. Carlsson, "Estimation of European Union service sector space cooling potential," *Energy Policy*, vol. 113, pp. 223–231, Feb. 2018.

[35] Kraftfahrt-Bundesamt, Der Fahrzeugbestand im Überblick am 1. Januar 2016 gegenüber 1. Januar 2015, 2016.

[36] Kraftfahrt-Bundesamt, Verkehr 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*, vol. 123, pp. 236–248, Aug. 2018.

[38] IBM. CPLEX optimizer. *IBM*. [Online]. Available: http://www-01.ibm.com/software/commerce/optimization/cplex-optimizer/

[39] Gurobi. Gurobi optimization. *Gurobi*. [Online]. Available: http://www.gurobi.com/

[40] M. Yazdanian and A. Mehrizi-Sani, "Distributed control techniques in microgrids," *IEEE Trans. Smart Grids*, vol. 5, no. 6, pp. 2901–2909, Nov. 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 *Proc. Innovative Smart Grid Technologies (ISGT) European 2017 Conf.*, pp. 1–6.

[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*, vol. 2018, pp. 1–11, Mar. 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*, vol. 42, pp. 313–324, Mar. 2014.

[44] (2015). "Onderzoek Verplaatsingen in Nederland 2014 (Research on movements in the Netherlands 2014) - Data archiving and networked services (in Dutch)." Centraal Bureau voor de Statistiek (CBS) and Rijkswaterstaat (RWS), The Netherlands. [Online]. Available: https://easy.dans.knaw.nl/ui/datasets/id/easy-dataset:61643

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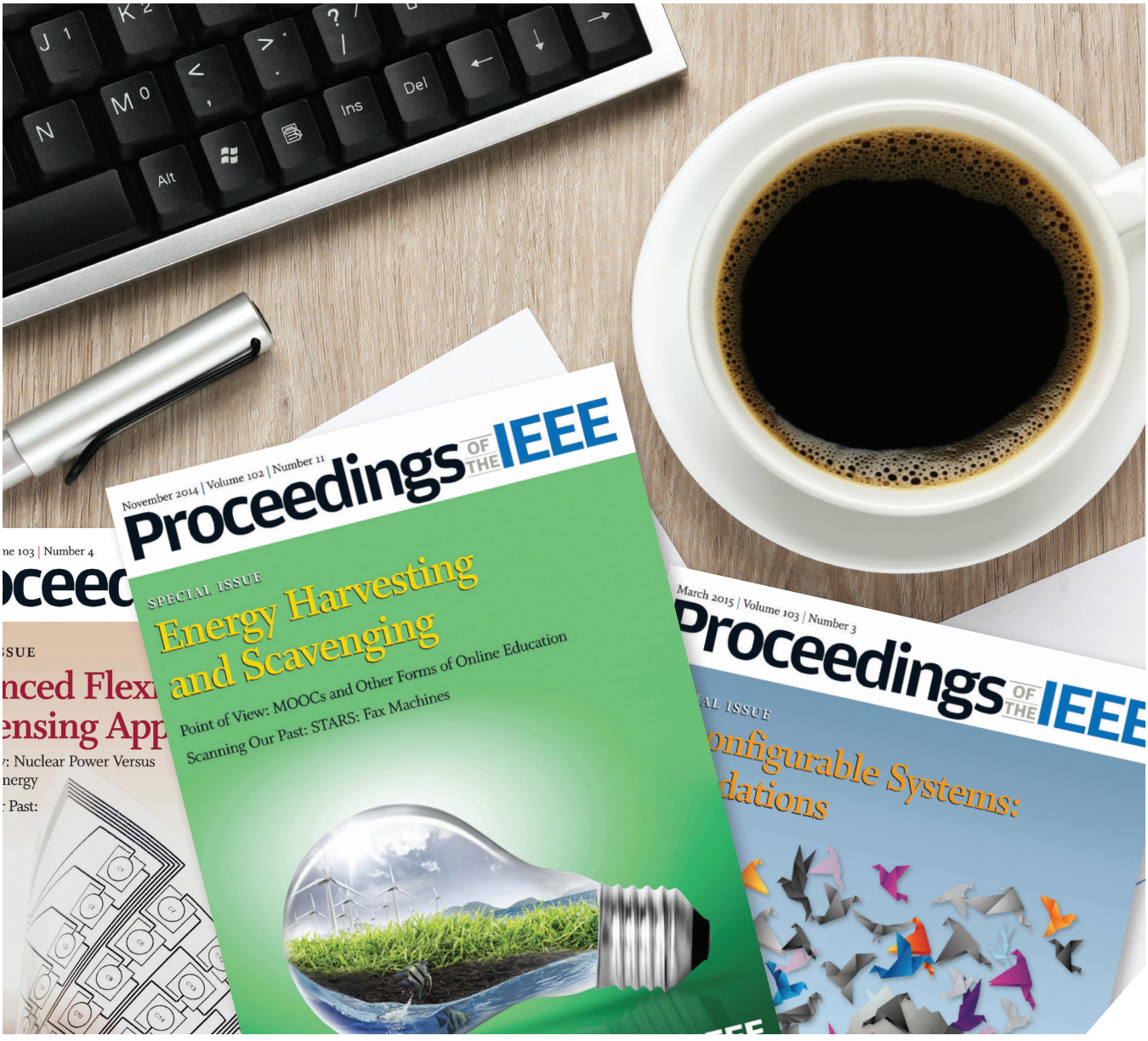

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