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Exploring the Profit Potential of Energy Storage in a Car Park Using Electrolysis, Hydrogen Storage and Fuel Cell Electric Vehicles

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Abstract The Car Park as Power Plant (CPPP) is a main business concept related to a future integrated sustainable mobility and energy system in which hydrogen is a key energy carrier. In order to investigate the uncertain profitability of the CPPP concept, an optimisation model has been developed of a CPPP system that includes an electrolyser, a hydrogen storage tank, and fuel cell electric vehicles, which can produce electricity from hydrogen. The potential profits that can be obtained with electricity price arbitrage through energy storage are explored by means of various energy market scenarios. It is concluded that the CPPP electricity arbitrage business model can be profitable for a future system with a high share of wind and solar power, but that profit levels are highly dependent on electricity prices in hours with low wind and solar power generation.

Keywords: • car park • fuel cell electric vehicle • electrolysis • hydrogen storage • vehicle-to-grid •

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1 Introduction

1.1 Hydrogen as a Main Energy Carrier

To reach the high greenhouse gas emission reductions required to mitigate climate change, our fossil-based economy must transform into a low-carbon economy that makes use of renewable energy sources. For the power sector, this means a system based on variable renewable energy (VRE), notably wind and solar power, while in the mobility sector the main technology option is considered to be the electric vehicle, including battery vehicles, and fuel cell electric vehicles (FCEVs), which convert hydrogen (H_2) into electricity for propulsion [1]. The *Car as Power Plant concept* entails a vision of an integrated sustainable energy and mobility system, based on VRE, hydrogen production and storage, and FCEVs [2]. It offers an energy transition pathway that brings along various technical and economic synergies. Electricity can be converted to hydrogen using electrolysers when VRE generation exceeds demand, hydrogen can be stored on a large scale for periods up to months, and FCEVs can generate power when wind and solar power output are insufficient [3], [4], [5]. In a future power system based on intermittent wind and solar power, the tasks of real-time energy balancing and overall load levelling will become much more substantial. The need for back-up power generation capacity will become particularly pressing in case of multi-day periods without wind or sun. The use of FCEVs for power production results in a more efficient use of passenger cars, which are standing still more than 95% of the time, and reduces the need to invest in little-used back-up power plants [2].

1.2 The Car Park as Power Plant

A main business concept related to the Car as Power Plant concept is that of the *car park as power plant (CPPP)*, which consists of the aggregation of FCEVs parked in a car park into a ‘virtual power plant’ to produce electricity and feed it into the power grid. In contrast to battery vehicles, the availability of FCEVs for driving and power provision is not constrained by VRE output and power line capacities, as they are powered by hydrogen. Advantages of aggregating FCEVs within the boundaries of a car park are that the required vehicle-to-grid (V2G) infrastructure and other system components can be integrated within the car park building, and that possible compensation for drivers can be factored into the parking fee.

The CPPP business concept encompasses many business model options, involving different business developers (e.g., car park operator, energy company, mobility service provider), products and services (e.g., parking, power system services, heat), and related system designs (e.g., V2G infrastructure only, inclusion of hydrogen storage tank, inclusion of electrolyser). In this work, we focus on the business model of *electricity price arbitrage*, where electricity is converted to hydrogen when prices are low and hydrogen is converted back to electricity when prices are high, incorporating hydrogen production and storage within the car park. This particular model was chosen because it represents an elementary CPPP business model design that could play a central part in load levelling in future renewable power systems.

The profitability of the electricity price arbitrage business model (and the CPPP business concept in general) is highly uncertain: It depends on future system costs and electricity market prices. Our research objective is to explore the dependency of profitability of this business model on various energy market conditions. To this end, we perform an optimisation model analysis, in which potential annual profits are explored for different annual power generation, load and price patterns.

2 Model Description

We have developed an optimisation model of the car park as power plant applying the electricity price arbitrage business model, ‘CPPP model’ in short. It has been built in MATLAB, and makes use of the linear programming solver ‘linprog’. Below, we describe the model details.

2.1 Conceptual Design

The conceptual design of the CPPP model primarily concerns the system design, i.e., the system components that the business developer invests in. These consist of an electrolyser, a hydrogen storage tank, a hydrogen compression system, a hydrogen dispenser (to refuel the FCEVs), V2G dischargers, a rainwater collection system (to obtain water needed for electrolysis), and a reverse osmosis (RO) system (to purify the rainwater). The electrolyser, compression system and dischargers are indispensable components for electricity price arbitrage using FCEVs. The hydrogen storage tank increases the arbitrage potential. The dispenser is used to refill the FCEV tanks. The rainwater collection and RO system enable the production of pure, demineralised water.

The modelled system environment is formed by a specific distribution grid or microgrid, which consists of residential and service sector consumption, wind and solar power capacity, and a merit order list of back-up power capacity.

2.2 Model assumptions

The following system-level assumptions apply to the CPPP model:

- The total load of a specific number of households is modelled, along with an equivalent size of service sector load.
- The balance between power production and consumption is not maintained.
- All hydrogen used for V2G is produced within the CPPP system (H_2 balance).
- The CPPP operator makes use of one electricity market only (for both buying and selling).

- The CPPP operator has perfect foresight of electricity prices and VRE surpluses and shortages in future hours.
- The operation of the CPPP system does not influence the electricity price.
- The CPPP system components other than the electrolyser and the ‘FCEV plant’ are not subject to energy losses.
- The electrolyser and the FCEV plant can ramp to full capacity instantaneously.
- A single dispenser is used.
- A certain minimum number of cars is available for power production at all hours.
- Fuel cells do not degrade faster due to V2G operation.
- The energy storage service (electricity price arbitrage) is the only service considered. Therefore, parking costs and benefits are not taken into account, the FCEVs are owned by the individual drivers, and on-board tanks are refuelled to original levels.
- No benefits or costs are associated with the oxygen (by-product of electrolysis), and heat and water (by-products of V2G operation).

One of the most important assumptions concerns the hour-to-hour electricity price, which is determined as follows. First of all, the residual load (MWh) is calculated as the electricity demand minus the PV and wind power generation, for each hour in the modelled year. Negative residual load values are transposed into positive VRE surplus values, and positive residual load values into positive VRE shortage values. Secondly, a back-up power generation bid ladder is constructed. The bid ladder is assumed to be linear. Third, the electricity price for hours with a VRE shortage is set at the back-up bid ladder price that corresponds to the back-up capacity volume equal to the VRE shortage. The electricity price for VRE surplus hours is set at a fixed VRE surplus price.

2.3 Optimisation problem

The goal of the CPPP operator is to maximise gross profit by optimising the control of the electrolyser and the FCEV plant throughout an entire year, with an hourly time resolution. The corresponding objective function is

$$\min_{P_{elk}*, P_{FCEVk}*} \sum_{k=1}^{N_k} p_{ek} \cdot E_{elk} - p_{ek} \cdot E_{FCEVk} \tag{1}$$

, where p_{ek} is the electricity price at hour k (€/MWh), E_{elk} is the energy input of the electrolyser at hour k (MWh), E_{FCEVk} is the energy output of the FCEV plant at hour k (MWh), and N_k is the last hour of the period over which the profit is maximised. P_{elk}* and P_{FCEVk}* are the electrolyser capacity at hour k (MW) and the FCEV plant capacity at hour k (MW), resp.; these are the control variables. The gross profit maximisation is subject to the equality constraint

$$E_{H_{k+1}} = E_{H_k} + \eta_{el} \cdot P_{el_k} \cdot \Delta t - \frac{1}{\eta_{FCEV}} \cdot P_{FCEV_k} \cdot \Delta t \tag{2}$$

,where $E_{H_{k+1}}$ is the hydrogen stored at hour $_{k+1}$ (MWh), η_{el} is the efficiency of the electrolyser, P_{el_k} is the power input of the electrolyser at hour k (MW), η_{FCEV} is the efficiency of the FCEV plant, P_{FCEVk} is the power output of the FCEV plant at hour k (MW), and Δt is the time interval (hours). In addition, the following inequality constraints apply:

$$0 \leq P_{el_k} \leq P_{el\,\max,k} \tag{3}$$

$$0 \leq P_{FCEV_k} \leq P_{FCEV\,\max,k} \tag{4}$$

$$0 \leq E_{H_k} \leq E_{H\,\max,k} \tag{5}$$

Here, $P_{el\,\max,k}$ is the maximum power input of the electrolyser (MW; this is the minimum of the rated electrolyser capacity and the VRE surplus in MW at hour k), and $P_{FCEV\,\max,k}$ is the maximum power output of the FCEV plant (MW; this is the minimum of the rated FCEV plant capacity and the VRE shortage in MW at hour k).

2.4 Model inputs

The following main input data are fed into the CPPP model:

- The number of households. For the analysis this was set at 2,000.
- An electricity demand profile, for all hours in a year. The reference profile is based on residential and service consumption data from the Netherlands in 2014, as developed and used in [6].
- Photovoltaic (PV) and wind power generation profiles in MWh, for all hours in a year. Data from the Netherlands from the years 2013, 2014 and 2015 have been used, obtained from [7].
- Installed PV and wind power capacity values in MW.
- A back-up power bid ladder (€/MWh), based on 2014 data from the Dutch balancing energy market. The size of the bid ladder is assumed to be 3 MW, which is large enough to cover the peak demand of 2.86 MW. The minimum and maximum prices on the bid ladder are based on the average Dutch balancing energy market prices at minimum and maximum activated volumes, which are 52.6 and 235.5 €/MWh, respectively [8].
- The VRE surplus price (€/MWh), i.e., the electricity price for hours with a VRE surplus. This is set at 10 €/MWh.

- Capital cost (in euro per unit of capacity) and O&M cost (in euro per year, expressed as a percentage of total capital cost) for each of the system components. The used values are projections for 2050, described by [4]. These include capital cost values of 250 €/kW for the electrolyser, 575 €/kg of hydrogen for the storage tank, 4,200 €/kg/h for the compression system, 72,890 euro per dispenser, and 3,200 euro per 4-point discharger.
- The weighted average cost of capital (WACC). This was set at 3%.
- Energy efficiencies of the electrolyser and the FCEVs, and the lifetime of the system components, based on projections for 2050 [4]. The electrolyser efficiency is set at 82%, and the FCEV efficiency at 61%, following [4].
- The electrolyser capacity (MW) and the hydrogen storage capacity (MWh). The values of these are calibrated and fixed for the main analysis (see section 3).
- The power output of a single FCEV. This is assumed to be 10 kW.
- The number of fuel cell cars that is assumed to be available for power production at all times. This is set at 100.

2.5 Model outputs

The direct results of the model optimisation consist of the hour-to-hour power input values of the electrolyser (MW), the power output values of the FCEV plant (MW), the stored energy values (MWh), and the gross profit (€).

The main result of interest is the *net profit*, which shows if the investment in the CPPP system is earned back. It is calculated by

$$NP = \sum_{k=1}^{N_k} (E_{FCEV_k} \cdot p_{e_k} - E_{el_k} \cdot p_{e_k}) - \sum_{i=1}^{N_i} TC_i \tag{6}$$

, where *NP* is the total net profit (€/year), E_{FCEV_k} is the energy output of the FCEV plant at hour *k* (MWh), E_{el_k} is the energy input of the electrolyser at hour *k* (MWh), and TC_i is the total cost of individual system component *i* (€/year). The total cost of a component is equal to the sum of the annual capital cost and O&M cost of that component, with annual capital cost being dependent on the economic lifetime of the component and the WACC. The corresponding equations are identical to those used and presented in [4].

The *return on investment* (%) is the gross profit as a share of the total system costs.

Two other important economic performance indicators of the CPPP model are the *system-levelised cost of electricity* produced by the CPPP and the *system-levelised cost of hydrogen* produced by the CPPP. These are calculated by:

$$SLCoE = \frac{\sum_{k=1}^{N_k} (E_{el_k} \cdot p_{e_k}) + \sum_{i=1}^{N_i} TC_i}{\sum_{k=1}^{N_k} E_{FCEVk}} \tag{7}$$

$$SLCoH = \frac{\sum_{k=1}^{N_k} (E_{el_k} \cdot p_{e_k}) + \sum_{j=1}^{N_j} TC_j}{\sum_{k=1}^{N_k} E_{el_k} \cdot \frac{\eta_{el}}{e_H}} \tag{8}$$

, where SLCoE and SLCoH are the system-levelised cost of electricity (€/MWh) and hydrogen (€/kg), resp., TC_j is the total cost of the components j needed for hydrogen production and storage (€/year), and e_H is the specific energy of hydrogen (MWh/kg).

3 Analysis Results

3.1 Calibration of system dimensions

Given that the modelled power market spans 2,000 households and the capacity of the FCEV plant is 1 MW, the capacity of the electrolyser and the hydrogen storage tanks have a certain optimal value. When varying the dimensions of both system components, we find that they should be large enough to utilise the potential for arbitrage with the FCEV plant, but that the profitability of the CPPP business model drops when marginal investment cost surpass marginal revenues. For the reference scenario (4 MW PV, 4 MW wind, 2014 load and generation data), the found optima are an electrolyser capacity of 0.6 MW and a storage capacity of 32 MWh. See Figure 1.

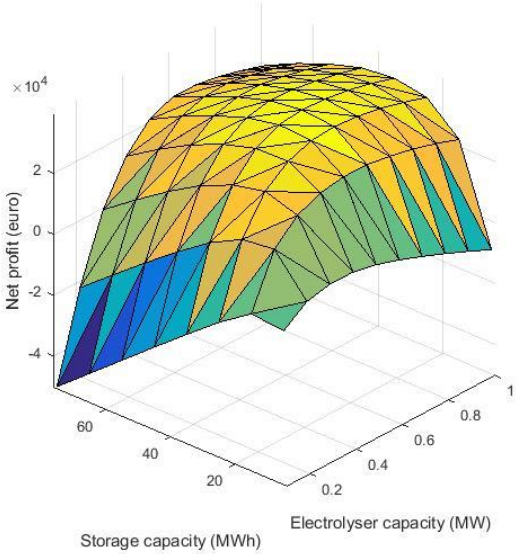

Figure 1. Impact of CPPP system dimensions on profitability for reference scenario

Here, the load factor of the electrolyser is 43%, showing that it can pay off to invest in capacity that enables the sale of more energy in high-price hours.

When performing the same calibration for a scenario with high power production potential (enabled by the load and VRE generation profiles), we found that an electrolyser capacity of 0.9 MW could increase profits by 60% in this scenario. However, in a scenario with minimum power production potential, no profit could be made. To limit the number of optimisation scenarios, we assume an electrolyser capacity of 0.6 MW and a storage capacity of 32 MWh, which produces a net profit in the reference scenario that is close to the average of all scenarios in the main analysis.

3.2 Sensitivity to market conditions

We have run the optimisation for 972 scenarios in which six inputs were varied:

- installed PV capacity (3 MW, 4 MW, 5 MW)
- installed wind power capacity (3 MW, 4 MW, 5 MW)
- PV generation profile (2013, 2014, 2015)
- wind power generation profile (2013, 2014, 2015)
- load profile (residential, mixed minus 10%, mixed, mixed plus 10%)

- back-up power bid ladder (reference minus 25 €/MWh, reference, reference plus 25 €/MWh)[1]

All input value combinations have been included in the analysis. This has led to the overall results presented in Table 1. We find that in 81% of the scenarios a positive profit develop. The distribution of the net profit values resembles a normal distribution, but with smaller tails. The average gross profit is high, which is necessary to obtain a positive business case: The break-even value lies in the range 80-100 €/MWh[2]. The system-levelised cost of hydrogen is in the range of the DOE 2020 target value for electrolysis [9]. Profit levels are proportional to the total electricity produced by the FCEV plant, as well as to the back-up bid ladder prices on which the electricity prices are based, which indeed follows from Equation (6). The total electricity produced increases along with the total VRE shortage over the year, until the first becomes larger than ca. 2,000 MWh, in which case the reducing number of VRE surplus hours and the corresponding opportunities for low-cost electrolysis affect the arbitrage potential. The average total electricity produced is 45% of the average total VRE shortage, which indicates that short-term energy storage has the potential to supply about half of the residual load.

Table 1. Main Results Of Optimisation Over All Scenarios

Output parameter	Mean	Standard deviation
Net profit (€/year)	22,843	24,102
Gross profit (€/MWh)	104.7	22.8
Return on investment (%)	14.4	24.7
Total system cost (M€)	1.68	0
System-levelised cost of electricity (€/kWh)	0.093	0.0067
System-levelised cost of hydrogen (€/kg)	2.0	0.14
Total electricity demand (MWh)	14,210	1,005
VRE surplus hours (%)	67.4	8.4
Total VRE shortage (MWh)	2,185	664
Total electricity produced by FCEV plant (MWh)	982	85.0
Load factor of electrolyser (%)	37.4	3.2
Load factor of FCEV plant (%)	11.2	0.97

Grouping the results by input value generates a series of box plots (Figure 2). How much PV capacity is installed does not have a significant impact on the net profit, but higher wind capacity values lead to lower net profit values, due to lower total VRE shortage values (power production potential). This indicates that PV production peaks do not match well with the load peaks. Wind generation patterns are much more irregular than PV patterns, which is reflected by the differences between (profile data from) different years. The results for different load profiles show that higher electricity consumption leads to higher profits, as the power production potential rises. Because the mixed load profile matches better with VRE output than the residential load profile, the arbitrage potential is lower, which is in line with the results from [6]. The impact of the bid ladder price level on net profit is the highest of the six energy market inputs. Because the bid ladder directly determines the electricity prices, the gross profit per MWh increases by 25 €/MWh if the bid ladder shifts upward by the same value.

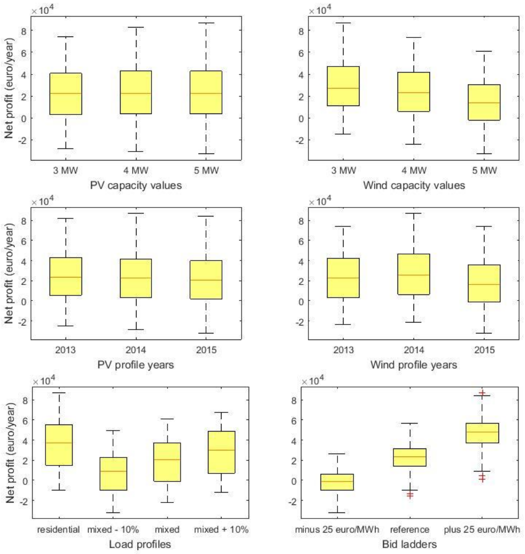

Figure 2. Sensitivity of CPPP profitability to energy market conditions

4 Discussion

The CPPP energy storage business model has been found to be profitable for a power system that is dominated by wind and solar power, as energy storage is highly valuable in such a system. CPPP profitability will depend for an important part on electricity prices at times of low VRE output. These prices will depend on the scarcity and operating costs of back-up power generation capacity and flexible load, but also on the degree to which providers of back-up capacity recover capital costs through energy sales at shortage hours.

The profitability of the CPPP business model may be enhanced by the inclusion of more services, such as the sale of hydrogen to FCEV drivers, and by the sale of the oxygen produced in the electrolysis process. Moreover, the CPPP reduces back-up power investment costs and causes lower local air pollution and noise (although it may prove difficult for the car park operator to capitalise on these benefits).

Valuable extensions of this work include the evaluation of the impact of electricity sale by the CPPP operator on the electricity market prices, and of the impact of limited availability of FCEVs (i.e., taking into account driving patterns).

5 Conclusion

This study provides preliminary results of an optimisation study in which the profit potential of a Car Park as Power Plant energy storage business model has been explored. Based on these results, we can conclude that the CPPP business model has the potential to be profitable in power systems with a high share of wind and solar power, but that the level of profitability highly depends on the electricity prices during VRE shortage hours.

Notes

1 The minimum bid ladder prices (and thus electricity prices) are 34.9, 59.9 and 84.9 €/MWh, respectively. The maximum bid ladder prices are 210.5, 235.5 and 260.5 €/MWh, respectively.
2 Because the break-even value depends on the arbitrage potential provided by the generation and load patterns, it varies between scenarios.

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