# Multidimensional Assessment of Reverse-feeding of Hydrogen Fuel Cell Vehicles

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# Abstract

The transition to a carbon-free energy system in Europe is underway. The European Union's 28-member states have signed and approved the Paris Agreement of the Conference of the Parties (COP21) to keep global warming "far below 2 degrees Celsius over preindustrial levels, and to pursue measures to restrict temperature increases even further to 1.5 degrees Celsius". The way the EU generates, distributes, stores, and converts energy will be drastically altered as a result of this shift. It will necessitate carbon-free electricity generation, better energy efficiency, and deep decarbonization of transportation, buildings, and industry. Passenger vehicles account for the majority of energy used in road transport, and when not in use they are typically parked close to buildings. Additionally, passenger cars are idle for about 90% of the time in urban cities. If they are incorporated into the built environment and buildings, significant energy and environmental savings can be realized. In the context of battery electric vehicles (BEV), the vehicle to grid (V2G) and vehicle to home (V2H) concept has proven to be useful as it can lower the total cost of ownership, and it can also be used locally as a residential energy storage and emergency backup storage. Hydrogen fuel cell vehicles (FCV) are in principle also electric vehicles with the additional feature of producing heat, which can be used for room heating. However, in the context of FCVs, there are technical issues to be resolved (use of inverter, heat management, load profiles and the availability of the vehicle for V2G). Furthermore, because costs are uncertain, learning more about the application might provide insights into how practical it may be and what is required to make it competitive.

These are major reasons why combining a V2G or V2H scenario with FCEV is a promising area of research. Therefore, the objective of this study is to conduct a multi-dimensional analysis of this concept in order to determine its economic and technical feasibility, as well as to compare it to other viable initiatives and to forecast future possibilities. For the economic analysis a life cycle costing (LCC) analysis was performed and for the technical analysis the indicators autarky and self-consumption were calculated. The results show that for some cases and conditions the concept of V2G and V2H are in fact economically viable and the technical indicators are promising as well. However, a lot of future work still needs to be performed to have a better outlook.

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# Self-Declaration

I hereby certify that I have written this thesis independently and have not used any sources or aids other than those indicated, and that the thesis has not yet been submitted to any other examination authority in the same or similar form.

Brandenburg/H., 30. October 2022 Rajal Makwana

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# List of Abbreviations

| | |
|---|---|
| AC | Alternating Current |
| BEV | Battery Electric Vehicle(s) |
| COP21 | Conference of the Parties |
| COP | Coefficient of Performance |
| DC | Direct Current |
| DLR | Deutsch Zentrum für Luft und Raumfahrt |
| DWD | Deutscher Wetterdienst |
| EU | European Union |
| FCEV | Fuel Cell Electric Vehicle(s) |
| FCV | Fuel Cell Vehicle(s) |
| FCV2G | Fuel Cell Vehicle to Grid |
| ICEV | Internal Combustion Engine Vehicle(s) |
| IEC | International Electrotechnical Commission |
| IPCC | Intergovernmental Panel on Climate Change |
| IRENA | International Renewable Energy Agency |
| ISO | International Organization for Standardization |
| LCC | Life Cycle Costing |
| LCOE | Levelized Cost of Electricity |
| LPG | LoadProfileGenerator |
| NDC | Nationally Determined Contribution |
| NPV | Net Present Value |
| OAT | One-parameter-At-a-Time |
| PEV | Plug-in Electric Vehicle |
| PV | Photovoltaic |
| SC | Self-Consumption |
| SOC | State of Charge |

| | |
|---|---|
| V2G | Vehicle to Grid |
| V2H | Vehicle to Home |
| V2L | Vehicle to Load |
| TCO | Total Cost of Ownership |
| TUD | Technology University Delft |

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# 1. Introduction

## 1.1 Motivation

The 12th of December of 2015 marked an important milestone in climate change mitigation, as 196 parties signed the so-called "Paris Agreement" at COP21 in Paris. This is a legally binding document whose goal is to limit global warming to below 2, or preferably to 1.5 degrees Celsius, in comparison to the pre-industrial levels. Most parties, aim to achieve net zero by 2050 to achieve this long-term goal set by the Paris Agreement [1]. Net zero refers to a situation in which all greenhouse gas emissions produced are balanced out by an equivalent number of emissions eliminated [2, 3]. Rapid decarbonization will be necessary to accomplish this.

Decarbonization has two components. The first is lowering the amount of greenhouse gases released when fossil fuels are burned. The reduction of carbon emissions mostly achieved through widespread use of renewable resources and increased efficiency in carbon-intensive regions. The second is strengthening carbon sinks, either naturally through afforestation and replanting or artificially [4].

In industrialisation most of the energy supply was done by converting fossil fuels to other forms of energy, with the side effect of releasing greenhouse gas emissions. Global energy conversion, storage, and use should therefore undergo a significant transition in the twenty-first century. Changes with respect to the energy supply are already apparent at this stage in the 21st century, which is about one-fifth of the way complete, but more significant ones are still to come. The obstacles we must overcome to implement these changes span from scientific and technological to societal, cultural, and economic in terms of how we work, play, and live. The driving forces behind these changes are the profound effects that developed and emerging societies have had on the ecosystem of our globe over the last century and the predictions of what will happen to the world if we do nothing. It is obvious that we need to take action right away given the actual and predicted levels of urbanization and the rising world population. [5]

Some driving forces for changing the energy supply and decarbonization are:

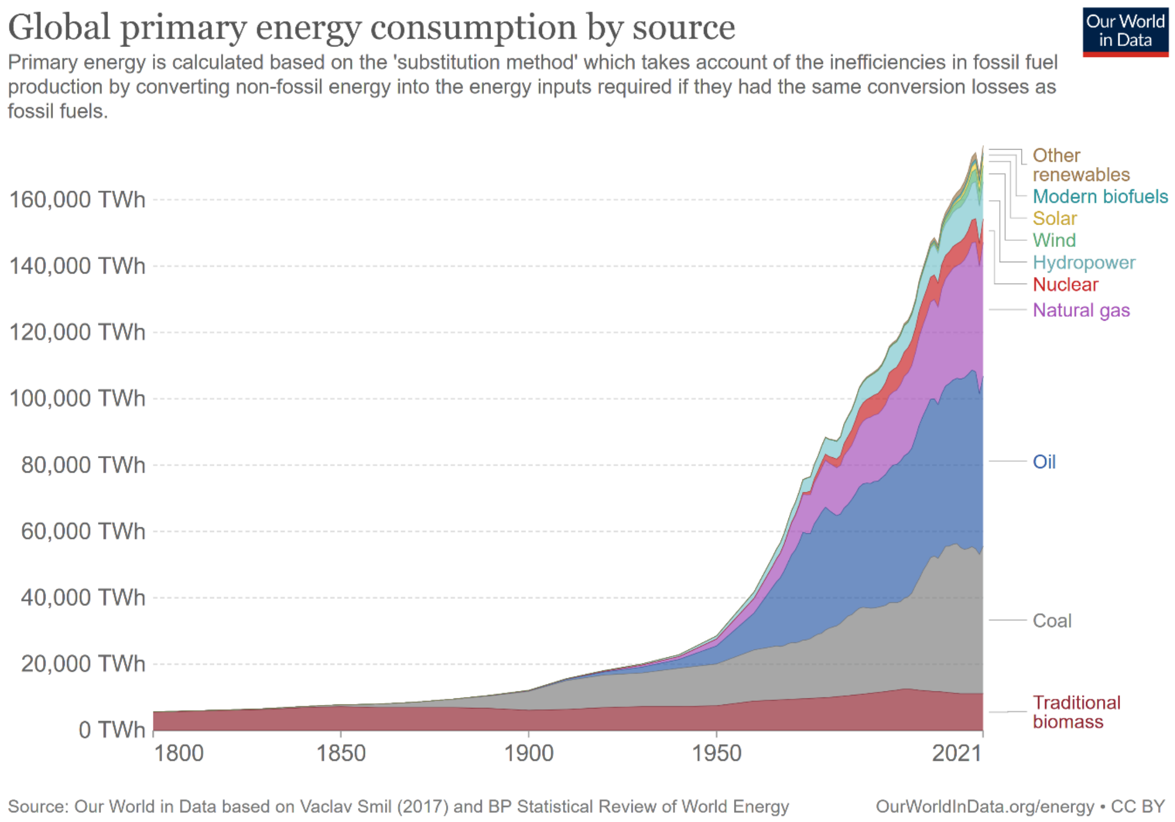
- Rapid reduction in renewable energy costs: The weighted average cost of electricity generated using all commercially accessible renewable energy technology has decreased over the past few years. For instance, since 2010, the cost of power generated by utility-scale solar photovoltaic (PV) plants has decreased significantly. Global weighted average levelized cost of electricity (LCOE) from solar PV decreased 45% to 52.8 USD/MWh between 2010 and 2019, whereas LCOE from onshore wind decreased 82% to 68.4 USD/MWh. Global corporate purchases of solar energy have increased 44% in the past two years, reaching 5.4 GW in 2018 and 9.6 GW in 2019. (Martin, 2020).
- A severe public health concern, air pollution is mostly brought on by unregulated, ineffective, and highly polluting energy sources (such as combustion of fossil fuels and chemical-related pollutants). Lowering costs and switching to clean renewable energy sources would enhance city air quality and increase prosperity by lowering illness. Additionally, it would improve productivity and provide rural communities with cleaner energy access.

- Impacts of climate change and reduction of carbon emissions: Using renewable energy sources instead of fossil fuels will enhance societal and economic conditions while also reducing carbon emissions. Renewable energy projects for example provide various benefits since they make use of local labour, local business and raw materials. Another example is the PV (photovoltaic) panels, which are usually installed on rooftops. The installation and production of PV systems increases job opportunities, improves regional development and renewable energy usage in rural areas [6, 7].
- Access to clean energy for everyone would be made possible by changing the current global energy system. Great inequality is a result of millions of people's current inability to obtain electricity. Rural electrification, community energy projects, and distributed energy resources, which can significantly enhance people's lives and boost local economies, can be implemented in rural areas where the grid has not yet reached.
- Increasing energy security: Energy security is a major concern for nations that rely significantly on imported fossil fuels. By increasing the variety of energy sources through local generation, which increases the system's flexibility and shock resilience, renewables can offer a more secure substitute for fossil fuels.
- Socio-economic advantages: Changing the world's energy system would also have significant social and economic benefits, which are essential for swaying political decisions. [8]

There has been much written and spoken about the effects of industrialisation and modern society on the global environment. The Intergovernmental Panel on Climate Change (IPCC) released an updated analysis [9] of the global situation in October 2018 with a more severe global warming projection than it had previously made [10]. The IPCC emphasized the need to limit the average temperature increase in their most recent report.

> Pathways consistent with 1.5 °C of warming above pre-industrial levels can be identified under a range of assumptions about economic growth, technology developments and lifestyles. However, lack of global cooperation, lack of governance of the required energy and land transformation, and increases in resource-intensive consumption are key impediments to achieving 1.5 °C pathways. … Under emissions in line with current pledges under the Paris Agreement (known as Nationally Determined Contributions, or NDCs), global warming is expected to surpass 1.5 °C above pre-industrial levels, even if these pledges are supplemented with very challenging increases in the scale and ambition of mitigation after 2030. … This increased action would need to achieve peak CO2 emissions in less than 15 years [11].

The IPCC report puts an emphasis on how urgently we need to address climate change. Global carbon emissions must reach their peak by 2020 to 2030, reach zero by 2050, and turn negative (i.e., we must remove carbon dioxide from the atmosphere) after 2050 if we want to avoid the worst effects of climate change.



Global primary energy consumption by source

Primary energy is calculated based on the 'substitution method' which takes account of the inefficiencies in fossil fuel production by converting non-fossil energy into the energy inputs required if they had the same conversion losses as fossil fuels.

Source: Our World in Data based on Vaclav Smil (2017) and BP Statistical Review of World Energy

OurWorldInData.org/energy • CC BY

Figure 1.1: Global primary energy consumption by source [12]

More over 82% of the primary energy use globally in 2021 originated from fossil fuels that contained carbon (oil, coal, and natural gas) with the consequence of emitting greenhouse gas emissions for the conversion of chemical energy into other types of energy [12]. It is logical that the urgent need to decarbonize global energy while meeting energy needs for global development is a common factor in attempts to limit climate change and the crucial issue of atmospheric $CO_2$ levels.

As a response to climate change, the European Union (EU) produced a roadmap named “European Green Deal” to become a climate-neutral continent by 2050. The European Climate Law 3 codified this vision, which was also supported by the climate emergency declaration made by the European Parliament in November 2019. This upped the EU's 2030 emissions reduction target from 40% to at least 55% compared to 1990 levels and turned the EU's commitment to climate neutrality into a legally binding requirement. The European Union's 28-member states have signed and approved the Paris Agreement of the Conference of the Parties (COP21) to keep global warming "*far below 2 degrees Celsius over preindustrial levels, and to pursue measures to restrict temperature increases even further to 1.5 degrees Celsius*". [13] It will necessitate carbon-free electricity generation, better energy efficiency, and deep decarbonization of transportation, buildings, and industry. Some notable strategies and commitments from European countries include: The Netherlands mandated that all Dutch vehicles be emission-free by 2030 [14]; Germany planned to phase out coal power plants by 2038 [15]; and the Danish government decided to meet all of Denmark's energy needs for electricity, heating, and transportation with renewable energy by the year 2050 [16]. Renewable energy sources are thus increasing their contribution towards electricity production steadily, due to energy policies, environment concerns and changing social opinions. In the renewable energy sphere, hydropower, solar and wind are the biggest sources [12]. Solar and wind are especially known to be intermittent, i.e. they fluctuate highly based on weather conditions and thus require storages for a stable and reliable energy supply [17]. There are various ways to implement storages, one way is storing the energy in energy carriers, which are substances or phenomena that contain energy like heat and electricity as well as gaseous, liquid and solid fuels. They occupy the transitional stages in the energy supply chain, between primary sources and end-use applications [18].

Hydrogen is an energy carrier that can store energy in chemical form and with a high mass density. Hydrogen is rarely found in elemental form in Earth, but can be obtained from hydrogen rich molecules like water via electrolysis. The energy necessary for the electrolysis can be supplied by electricity produced from renewable resources. Pure hydrogen does not contain any carbon. If this substance reacts with oxygen, only water and heat is produced, although the combustion at high temperatures might additionally release nitrogen oxides that are air pollutants and greenhouse gases [19]. Additionally, this substance can also be used in fuel cells, which are electrochemical devices that convert chemical energy into electricity directly. It allows stakeholders to convert and store energy as a renewable gas or liquid, allowing for large-scale renewable integration. Additionally, it can be used as a buffer for renewables and for energy distribution between industries and regions. Finally, it allows the decarbonization of power, transportation, buildings, and industry areas that otherwise would be difficult to decarbonize[13].

The EU's energy transformation necessitates almost entirely decarbonized power generation, which requires grid construction and integration of renewables into it. Linking the energy sector with transport, industry and building sectors and optimizing them together is the goal of sector coupling. This concept states that if all sectors are interconnected, $CO_2$ emissions can be decreased via renewable energy sources [20]. Hydrogen is the sole at-scale energy carrier for "sector coupling," which allows generated power to be converted into usable form, stored, and channelled to end-use sectors to satisfy demand[13]. Hydrogen can be also used as energy carrier for transport applications. Some particular types of fuel cells, especially proton exchange membrane fuel cells, have been tested for transport applications in what is commonly named fuel cell vehicles. The electricity produced by these fuel cells is used to supply the vehicle propulsion system and all the other consumers from the vehicle [21]. However, fuel cells also produce a considerable amount of heat, which can be used in buildings.

Fuel cell vehicles are anticipated to offer high-quality environmental and energy benefits. However, hydrogen fuel cells are now being used to meet commercial needs in early marketplace packages such as material handling with the help of forklifts and backup power[22]. These applications are furthering the improvement of fuel cells and associated hydrogen infrastructure, as well as expanding the market for these technologies[23].

## 1.2 State of the Art

In Germany there are 67.7 million vehicles, out of which 48.5 million are passenger vehicles [24]. In addition to this passenger vehicles are unused 95% of the time and usually parked closer to buildings [25]. Battery electric vehicles and fuel cell vehicles, besides public transport are the ones expected to replace the vehicles based on internal combustion engines in the near future. These vehicles could potentially be used during the idle parking time, if buildings and homes were designed to integrate these passenger vehicles [26]. In the context of BEV's as discussed in the previous section, the V2G and V2H concept has proven to be useful as it can lower the total cost of ownership for BEV, and it can also be used locally as a residential energy storage and emergency backup storage. Additionally, it provides and enables a solution to fluctuation caused by the large proportion of renewable energy in the grid, as well as a solution to grid congestion and avoids the need to expand grid infrastructure. Finally, it can help with local peak shaving, load balancing, and electrical demand balance. As a result, the overall cost of electricity could be reduced [26]. However, in the context of FCVs, there are technical issues to be resolved (use of inverter, heat management, load profiles and the availability of the vehicle for V2G). Furthermore, because costs are uncertain, learning more about the application at a high level might provide insights into how practical it may be and what is required to make it competitive. These are major reasons why combining a V2G or V2H scenario with FCV is a promising area of research. Yet, technical and economic feasibility should be proven, and that's the main reason to study the concept of the FCV2G (fuel cell vehicle to grid).

For the EU to realize its goals for complete decarbonization, the use of fuel cell vehicles (FCEV's) as well as their grid integration in the form of vehicle to grid (V2G) and vehicle to home (V2H) could be one innovative solution. V2G and V2H are concepts that were introduced in the 90's, but they are still in very much a testing phase and have not been implemented. The majority of the studies that have performed an economic assessment of the V2G and V2H concepts were performed for battery electric vehicles (BEV's). There are very few studies that actually deal with the FCEV integration with V2G and V2H.

Ravi and Aziz 2022 [27] deals with integrating BEV's with V2G and discussing the potential impacts, challenges, future market penetration insights and possible ancillary service potentials. There is however, no economic assessment to determine the economic feasibility of this concept. Moreover, Los Rios et al. 2012 [28], explores V2G economic assessment of a fleet of BEV's and FCEV delivery trucks. Assessment of costs and benefits of this technology was done with a ten-year cash flow model. A longer time period is necessary for a deeper understanding and prediction of future cash flows. According to the ISO 15686 the period of analysis should cover the life cycle of the asset and for this particular case 10 years although appropriate falls short of the life cycle of the fleet. Additionally, Tiedemann et al. 2022 [29] Investigates how the energy demand of a combined German neighbourhood can be met by FCEV's and identifies potential technical problems. It only deals with the energy aspects of the vehicles and V2G, V2H concepts, however it is also emphasised that for such a concept to work in reality, the owners of the FCEV's are benefited economically. Finally, Robledo et al. 2018 [26] assesses the end-user's potential of implementing FCEV's in V2G scenario to act as a local energy source. Real data was collected and analysed for the FCEV power production in the V2G mode and based on this data one-year simulations of a microgrid consisting of a fleet of 5 vehicles and 10 houses were also performed. The simulations were mostly evaluated on technical indicators and results from this study shows that such a microgrid scenario can potentially reduce electricity consumption from the grid by up to 71% for a year. Furthermore, savings for a year, hydrogen costs for running the FCEV's and during V2G mode were calculated and based on these costs it was concluded that the scenario could be economically beneficial for the end user if hydrogen prices drop below 8.24 EUR/kg. However, this paper does not shed light on the total cost of ownership of the FCEV's, infrastructure costs as well as maintenance costs. For this reason, it is essential to conduct an economic analysis for the V2G scenario that considers the total costs associated with owning an FCEV over a period longer than 10 years to get a prognose on the economic viability.

The above-mentioned studies mostly deal with fleet vehicles, there is no study that considers the total costs associated from the vehicle owner, and how much savings could be made with V2G for electricity as well as reusing heat generated from the FCEV. Additionally, no prosumer model is explored and how much revenue could be generated when electricity is supplied to the grid. There is also no comparison between the costs of FCEV's and ICEV's, this is necessary to have a better outlook on system and component costs as well as possible savings.

The goal of this study is thus to conduct a multidimensional analysis of the V2G and V2H concept in order to determine its economic and technical feasibility. Furthermore, to answer the following questions:

- What are the costs associated with this concept?
- How does this concept compare with the traditional energy supply for households based on electricity from the grid and natural gas for heating?
- What is the degree of autarky and self-consumption achieved with the concept?

## 1.3 Approach and Structure of Thesis

Chapter 2 describes the foundations and theoretical definitions that are required to understand the thesis. Additionally, the life cycle costing (LCC) is also explained in detail along with the concepts of V2G and V2H and finally the sensitivity analysis. Chapter 3 explains in detail the methodology for the life cycle costing and how it was implemented, along with boundaries, scope, inputs of each of the cases considered in the study along with the system description of components and the full scope of each case. The boundaries and limitations of each case are also explored. Moreover, load profile generator and how it was utilized is also described. Finally, the sensitivity analysis methodology is explained. Chapter 4 presents and compares the LCC analysis results for the selected cases. Additionally, some technical indicators are analysed. Chapter 5 presents the results of the sensitivity analysis. Chapter 6 discusses the final results from the LCC and the sensitivity analysis. Chapter 7 summarizes the results of the thesis and gives an outlook on possible future prospects and work that could improve this study.

# 2. Theoretical Background

## 2.1 V2H

Vehicle to Home (V2H) capability refers to a situation in which a fuel cell electric vehicle (FCEV) or plug-in electric vehicle (PEV) supplies backup power to an islanded load, such as a home, during an outage, comparable to a stand-alone emergency generator [30, 31].
Additionally, a V2H-capable vehicle could offer continuous backup power for more frequent but often transient grid distribution problems. As a result, a V2H-capable car coupled to a home might permit completely off-grid operation or the vehicle could be used as a practical, secure, and potent backup generator to power a home or other isolated load. In the case of FCEV’s this application can be extended by also reusing the heat generated during electric power generation [32–34].

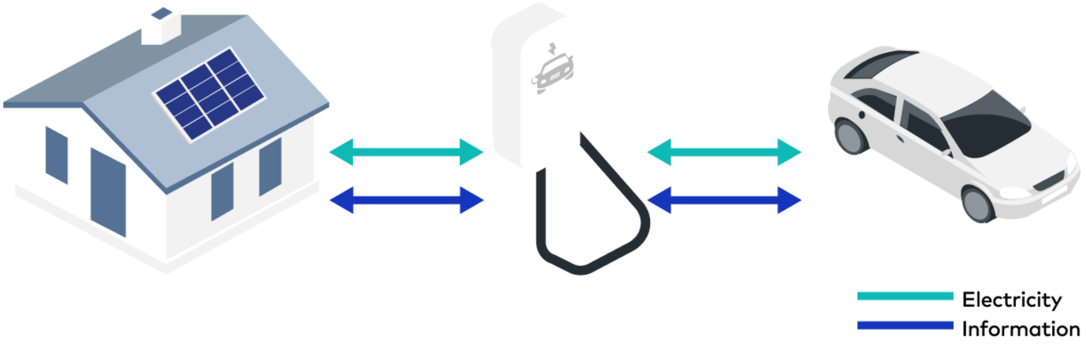


Figure 2.1: Vehicle to home concept [35]

Recent years have seen a rise in interest in V2H technology, and the concept may be widely deployed in the next years. From an economic perspective, costs could be reduced by shifting energy use from cheap to expensive times of the day. In addition, the V2H can sustain important loads of houses and buildings like data servers, computers, emergency lights, water pumps, elevators, etc. Hospitals, universities, hotels, office buildings, retail centres, sports facilities, among others, can also profit from this technology. Finally, transferring energy to the grid during emergencies like power outages will increase the building's and the grid system's overall resilience [36].

For a better understanding of the proposal figure 2.1 is presented, which consists of a simplified flow diagram of the process for supplying energy to the building. To perform the V2H strategy the energy demand for the house and buildings is calculated, later the battery charging and discharging model is used considering the fixed parameters. State of Charge (SOC) of the battery is calculated in order to guarantee the maximum DOD that ensures remaining energy for the travel and not damaging the battery [37].

## 2.2 V2G

Vehicles can be linked to the electrical grid using Vehicle to Grid (V2G) technology, allowing BEVs and FCEVs to provide electricity from their onboard storage (batteries for EVs and compressed hydrogen storage for FCEVs) to the grid when there is a shortage. In Europe there are around 250 million vehicles [38], and 95% of the time these vehicles are unused or parked [25]. However, most of these vehicles are currently powered by internal combustion engine and have a limited electrical supply for vehicle's onboard loads. In the near future, if most of these vehicles are replaced by BEVs and FCEVs, these can be utilized as a highly dynamic power plant that can stabilize and support the electrical grid at the distribution level. In the particular case of BEVs, these could also store electricity in their batteries, therefore stabilizing the grid when overproduction of electricity from renewables is available and releasing it later when is needed. Despite FCEVs cannot be charged, they can on the other hand provide useful heat, which can be used for room heating.

There are various potential benefits and advantages of the V2G for different stakeholders:
• For the vehicle owner: V2G can lower the total cost of ownership (TCO) of a vehicle since it can have additional functions of home energy storage and backup system.

• For the grid operator: V2G offers the possibility of having distributed and mobile energy storages or electricity feeders, which could supply local consumers with electricity that otherwise would have to be supplied by the grid. This can in turn diminish the congestion of the distribution grid. Additionally, especially the BEVs can buffer the electricity produced locally by renewable energy or both BEVs and FCVs can feed to grid in moments of high demand.

• For the government: V2G increases energy security (supply and quality) and supports environmental sustainability if considerable amount of renewable energies that otherwise would be curtailed, are stored for later use. The lifestyle and infrastructure of the city will change as a result of BEVs, FCEVs and V2G, creating a significant shift in economic activity by adding in new infrastructure for charging/refuelling.

• For the vehicle operator: Grid balancing services which are mainly applicable to BEVs (in connection to utilities, grid operators, and customers) and renewable energy storage services (such as storage and minimizing curtailment and volatility) are two new business opportunities in the electricity sector that are presented by V2G.

• For the office and real estate owners and business entities (e.g., office, factory): V2G can help with load levelling, local peak shaving, and balancing the demand for electricity. As a result, the overall cost of electricity could be decreased because a part of the load could be supplied by the vehicles, therefore avoiding the purchase of electricity in peak hours.

There are some drawbacks of the V2G as well:

- Without a smart grid system the charging and discharging of BEV's is harmful to the battery and causes degradation [39].
- To cope with the demands of increasing V2G services large infrastructure and technology investments are needed [39].

- Standardization of charging points and stations is another challenge with different vehicle models that needs to be dealt with [39].
- Vehicles are mobile and it is not possible to guarantee that they will always be there to supply or store electricity, so the implementation comes with certain degree of uncertainty.

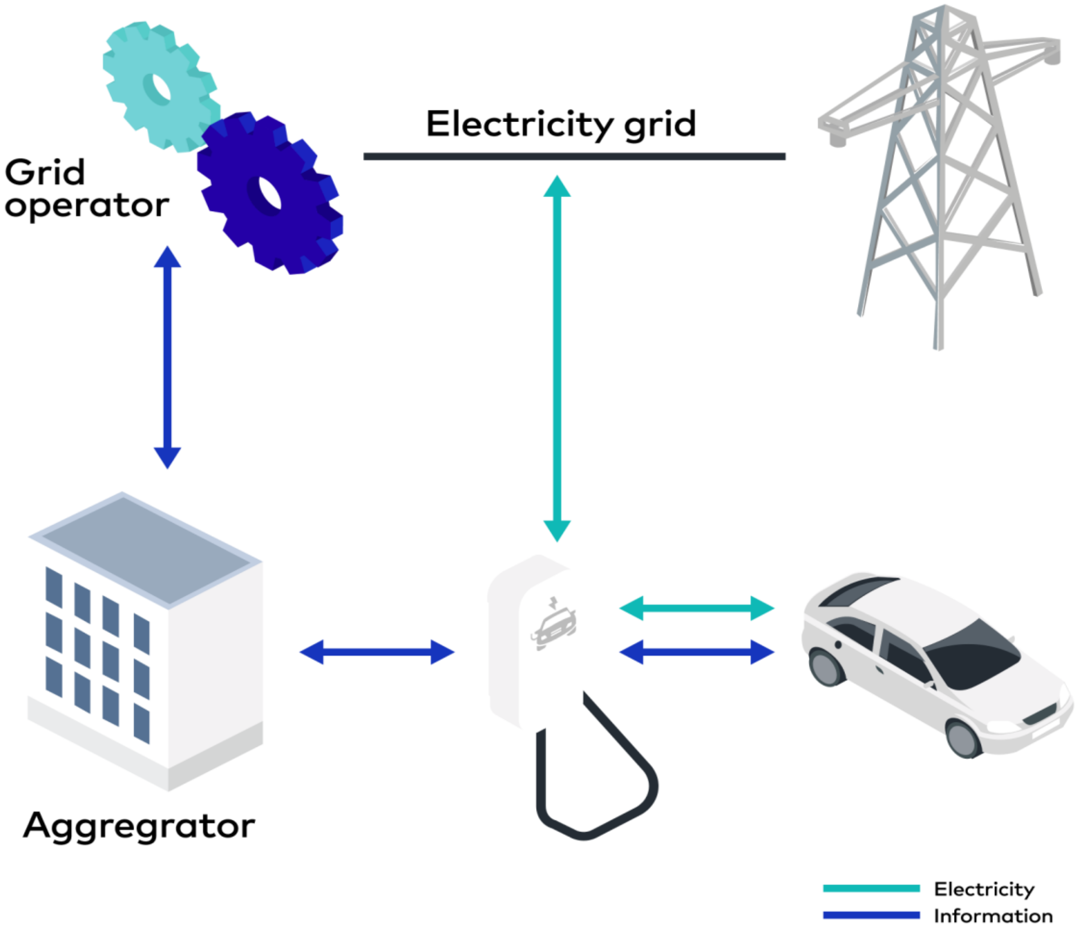


Figure 2.2: Vehicle to grid concept [35]

Previous studies have explored the use of BEV for V2G concepts [39–44]. Most of the research was focused on small balancing activities for the current grid, where passenger car owners can sell their onboard electricity during peak time and high prices, buying it and storing it during off peak hours. However, fewer studies have dealt with the use of FCEV's for V2G applications. For example, one V2G application connected the commercially available Hyundai ix35 FCEV with an all-electric home, and was used in a small-scale demonstration on the Technology University Delft (TUD) campus to illustrate how FCEVs can provide grid services when parked [26]. Several FCEV manufacturers are developing FCEVs that can power electric appliances, small grids, or homes (Vehicle-to-Home V2H) [45], however none of them claimed to have linked an FCEV to a low voltage national AC grid.

A total of 18 V2G pilot projects have been started, most of them with the goal to regulate grid frequency. Already in 2014, a trans-European project was started with V2G pilots in 6 cities in 5 different countries. In the United Kingdom, in 2016 the largest V2G project until now was started by Nissan with 100 bi-directional chargers [46]. A few small projects in the Netherlands are running (in Amsterdam, Utrecht, Lochem) [47], where successful Vehicle to Home and V2G bidirectional charge installations are built. Next to grid connected BEVs for V2G service, there is a project of FCEVs providing grid services when parked is already demonstrated on a small scale with one V2G ready commercial Hyundai ix35 FCEV and an all-electric house, on the Technology University Delft (TUD) [26]. FCEVs providing power to electric appliances (so called Vehicle-to-Load V2L), small grids or homes (Vehicle-to-Home V2H) [45] are being developed by several FCEV manufacturers, although none of them reported to have connected an FCEV to a low voltage national AC grid. As discussed in the above paragraph and the subsection 1.2 State of the Art, an economic assessment is necessary to understand the costs associated with the V2G and V2H concepts. For this purpose, we utilize life cycle costing to determine the economic feasibility of these concepts with an FCEV.

## 2.3 Life Cycle Costing

Life Cycle Costing (LCC) is a technique used to assess all pertinent costs associated with a project, a product, or a measure over time. It accounts for all costs, including initial costs like capital investment, purchase, and installation. Future costs like energy, operating, capital replacement, financing and any costs associated with resale, salvage, or disposal over the course of the project or product. Thus, LCC is a tool for economic analysis (EA) that can be used to compare the relative merit of project alternatives that are in competition. Initial costs and future costs are the two main cost categories by which projects are to be assessed in an LCC. Initial costs are any costs incurred before the facility or product is acquired. All costs accrued following the facility or products possession are considered future expenses. At the time of the LCC study, defining the precise expenses of each spending category can be challenging. However, a reliable LCC can be created by using acceptable, consistent, and well-documented assumptions [48].

In this study the standard of ISO 15686-5 was used for the LCC analysis, the next subsection gives a brief description and outlook on important sections of the standard necessary to understand the performed analysis.

## 2.4 ISO 15686-5

ISO (the International Organization for Standardization) is a worldwide federation of national standards bodies (ISO member bodies). Technical committees within ISO are typically used to develop or create International Standards. The right to be represented on a technical committee exists for any member body interested in a topic for which one has been created. Governmental and non-governmental international groups collaborate with ISO to complete the task. On all issues relating to electrotechnical standardization, ISO works closely with the International Electrotechnical Commission (IEC). Technical Committee ISO/TC 59, Building construction, Subcommittee SC 14, *Design life* prepared the ISO 15686-5.

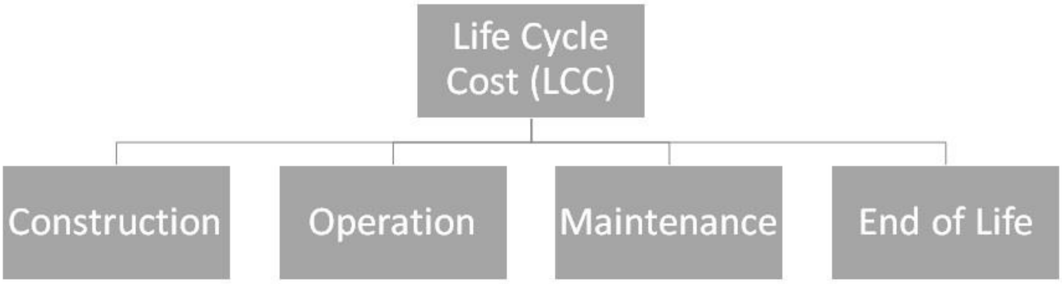


Figure 2.3: Elements of an LCC [49]

According to ISO 15686-5, LCC is a useful method for forecasting and evaluating the cost performance of developed or developing assets. It is useful for determining if a project satisfies the client's performance and is important primarily for decision-making and for evaluating project options. The use of LCC enables congruous comparisons to be made across options with various cash flows and temporal horizons. Regarding the client-specified brief and the project-specific service-life performance requirements, the analysis considers pertinent elements from across the service life. The subsections below define some important terms and parts of the LCC according to the ISO 15686-5 and are necessary to have a complete understanding of the LCC analysis.

### 2.4.1 Scope

This section of ISO 15686 provides instructions for carrying out life-cycle cost (LCC) evaluations of developed assets, including buildings, and their component elements. In life-cycle costing, relevant costs are considered from procurement through operation and disposal, together with income and externalities, if they are included in the agreed-upon scope. A comparison of possibilities or an estimation of future costs at the portfolio, project, or component level is frequently included in life-cycle costing. The study is conducted over a predetermined time period for life-cycle costing. It is best to be explicit about whether the analysis covers the complete life cycle of the constructed asset or just a portion of it. In order to quantify the life-cycle cost (LCC) for use in a decision-making or evaluation process, life-cycle costing typically also incorporates inputs from other evaluations (such as functionality assessment, safety assessment, environmental assessment, design assessment, and regulatory compliance assessment). The quantification should be done with the level of specificity needed for the important project stages [49].

### 2.4.2 Costs

**a) Capital cost**

Initial building, construction costs and costs of early adaptation are considered capital costs.

**b) Discounted cost**

Cost when the nominal cost is discounted by the nominal discount rate or when the real cost is discounted by the real discount rate.

**c) Disposal cost**

Cost of disposing of the asset at the end of its life cycle, considering any responsibilities for asset transfers.

**d) Maintenance cost**

Amount of labor, materials, and other expenses that must be incurred in order to keep an asset or one of its components in a condition that allows it to continue serving its intended purpose.

Maintenance entails performing corrective, responsive, and preventative maintenance on built-in assets, or their components, as well as all related management, cleaning, servicing, repainting, repairing, and replacing parts as necessary to enable the built-in asset to be used for its intended purposes.

**e) Nominal cost**

Expected cost, which includes anticipated price changes resulting from, for instance, forecasted changes in efficiency, inflation or deflation, and technology.

**f) Operation cost**

Costs associated with maintaining and operating the asset or environment, such as support services for administration. Rent, rates, insurances, energy prices, other costs associated with environmental and regulatory inspections, and municipal taxes and fees are examples of operational expenses.

### 2.4.3 Importance of Setting Parameters for the LCC

The scope, form, degree, and period of the LCC study, as well as the amount of anticipated uncertainty and hazards associated with the LCC analysis and reporting, should all be clearly defined. The LCC analysis's parameters ought to be determined by the goal and application of the desired outcomes. The parameters chosen can affect the analysis's reliability and applicability. People that have extensive knowledge of facilities management, maintenance, and repair in particular should contribute to the appraisal [49].

### 2.4.4 Decision Variables

**a) Real costs**

Regardless of when the expenses are incurred, real costs should generally be utilized in LCC analysis to assure accuracy. Real costs enable the utilization of current information. A recent past or future date should be chosen as the base date.

**b) Nominal Costs**

The real cost should be multiplied by the inflation/deflation factor,$q_{i,d}$ which should be estimated using Equation (1), to get the nominal cost.

$$q_{i,d} = (1+a)^n \qquad \text{Equation (1)}$$

Where

$a$ is the expected annual price growth in percentage.

$n$ is the period of time between the base date and the cost's occurrence.

### c) Discounted Costs

Future-year costs should be added up and then reduced by a number determined from the discount rate in order to calculate discounted costs. If nominal costs are employed, an inflation/deflation factor should be included in the discount rate. The discount rate shouldn't factor in inflation or deflation if real costs are being used.

Discount factor, $q_d$, is calculated from *d*, the discount rate from the Equation (2)

$$q_d = \frac{1}{(1+d)^n} \qquad \text{Equation (2)}$$

Where

*d* is the expected real discount rate per annum;

*n* is the number of years between the base date and the occurrence of the cost.

When converting a real cost to a discounted cost, the factor $q_d$ should be used as in Equation (2).

When converting nominal cost to discounted cost the factor $q_{d,nc}$ should be used as in Equation (3).

$$q_{d,n} = \frac{1}{(1+\mathrm{d})^n(1+a)^n} \qquad \text{Equation (3)}$$

Where

*d* is the expected real discount rate per annum;

*a* is the expected inflation rate per annum;

*n* is the period of time(years) between the base date and the cost's occurrence.

### d) Present Value

The present value should be used to compare options over the same period of analysis by discounting future cash flows to the base date. Calculating the current amount of money that should be set aside for future expenditures on an asset should be done using present value calculations.

### e) Net Present Value (NPV)

The net present value (NPV) is the difference between present value of revenue and present value of costs. In our case it represents the difference between the present value of costs and present value of revenue. Equation (4), is used to calculate stream of future expenses and benefits into a net present value ($X_{NPV}$):

$$X_{NPV} = \sum(C_n \times q_n) = \sum_{n=1}^{p} \frac{1}{(1+d)^n} \qquad \text{Equation (4)}$$

Where

$C$ is the cost in year $n$;

$q$ is the discount factor;

$d$ is the expected real discount rate per annum;

$n$ is the period of time(years) between the base date and the cost's occurrence;

$p$ is the period of analysis.

If the nominal costs rather than the real costs are used, the discount rate allows for any potential future inflation or deflation. The NPV should be a single figure that accounts for all pertinent future revenues and expenses across the analysis period.

### 2.4.4 Sensitivity Analysis

Sensitivity analysis can be used to investigate how changes in a (plausible) range of uncertainty may impact the relative merits of the options being thought about and contrasted. These ranges ought to be realistic, within the bounds of what is expected. This analysis can aid in determining which inputs have the greatest influence on the outcome of the LCC and how reliable the final decision is. Some examples of assumptions that affect these uncertainties are period of analysis, discount rate, incomplete maintenance, repair and replacement costs data based on assumptions etc. Sensitivity analysis can be a valuable tool for determining what extra data is crucial to gather and what are the most important assumptions that must be made. Additionally, it can be utilized to consider how adaptable or changing requirements may be during the course of the study or life cycle [49].

Throughout the analysis, some of the parameters can stay unchanged because they are known with a high degree of accuracy. The degree of uncertainty may vary for other parameters or assumptions. The ones that should be changed are these parameters. Setting these parameters at the values thought to be most likely to be accurate serves as the starting point for the analysis [50].

Sensitivity analysis can be divided into two types:

- **Global sensitivity methods:** These are approaches that evaluate output variability due to one input parameter by varying all other input parameters, and consider the range and shape of their probability density function [51]. Global methods do not require any restriction on the parameter range of the input variable. The associated sensitivity measures are computed over the entire range of values of the input and output variables. A simple global method is based on graphic representation and analysis using scatter plots. The effect of varying individual input variables can be determined qualitatively. At the same time, the clarity decreases significantly with increasing number of parameters [52].

- **Local sensitivity methods:** These are a one-parameter-at-a-time (OAT) approach, in which output variability evaluation is based on the variation of one input parameter while holding all other input parameters constant. This method is useful for comparing the relative importance of different input parameters. The input-output relationship is linear in assumption and the relation between the input parameters is not considered [51]. An important feature of local sensitivity analysis is the consideration of limited local output variables in the presence of small changes in individual input variables [52].

For the purpose of this study, the local sensitivity method was selected and an OAT approach was used to perform the sensitivity analysis. Two main sensitivity analysis were performed, first only the $H_2$ fuel prices were changed keeping all other inputs constant to find the effect on the NPV and find the breakeven point for the relevant cases compared to the base case. In the second sensitivity analysis the inputs of electricity prices, vehicle investment costs, fuel prices and heating gas price were varied by $\pm20\%$ and the NPV for all the cases were compared to see which input has the highest impact.

# 3. Methodology

An economic analysis by means of life cycle costing according to the standard ISO 15686-5 was performed. A technical analysis by finding the values of system autarky and self-consumption was performed.

Four cases were considered here and LCC is performed on each of them. First the scope and boundaries were set for the LCC and each of the cases that we considered. Second, a market research was done to gather the system and component cost for each of the cases considered. Third, LoadProfileGenerator© 5.1 (LPG) [53] was used to model the electrical and thermal profiles of the house. These quantities were subsequently linked to the heating gas and electricity demand. Additionally, as the concept of V2H makes of a vehicle to partly supply the electricity and heat loads of a household, calculations of the fuel consumption for the different cases and estimations of the corresponding costs were also done. Fourth, based on the simulated inputs and cost variables the output variables were calculated. Microsoft excel® was used to carry out the LCC calculations in which the nominal and discounted cash flows were calculated along with the net present value (NPV) for each case. Fifth, a sensitivity analysis was carried out to find out how the NPV varied with the changing of some inputs. Finally, for the technical analysis the indicators of autarky and self-consumption were calculated for cases 3 and 4.

This section will describe the boundaries, assumption, scope and indicators used followed by a detailed description of each of the cases.

## 3.1 Boundaries and Assumptions

The following points specify in detail the boundaries and assumptions of the analysis and the drivers behind these assumptions.

1. The electric heating loads are corresponding to those of one household (120 $m^2$) with a parking space and inhabited by two working adults. This is a preset household size already present in the LPG whose heat and electricity demand were simulated in the program according to the chosen location.
2. Docking station is the infrastructure needed to integrate the FCEV to the household, in order to supply the heat and electricity demand for the household. For the purpose of this LCC the docking station costs were excluded. The reason behind this is that there are no market estimates at this point of time for constructing such an infrastructure for the purpose of V2H or V2G, specifically for an FCEV.
3. Two types of vehicles were chosen for the analysis, namely, the Hyundai Nexo (FCEV) and Hyundai i40, the latter an internal combustion engine vehicle (ICEV). Both of these vehicles are from the same manufacturer and similar vehicle class. Additionally, there was performance data available for the Hyundai Nexo and other studies in the same field have also considered the Nexo making it a more appropriate choice for the FCEV because of the data available.
4. The $H_2$ refueling station was considered to be en-route to work, which means no additional driving distance was considered for refueling purposes.

5. Period of the LCC was 30 years from 2020-2050. Since there were a lot of market uncertainties from the year 2020 until 2022 because of the pandemic and other global events, it was thought to be more logical to start off with the beginning of 2020 before these events.
6. Discount and inflation rate of components were calculated based on the past trends. Discount rate of 3% is assumed if the real value cannot be calculated. According to the standard of ISO 15686-5, a discount rate between 1%-10% can be chosen when the real discount rate is unknown.
7. Heat and electricity demand for the house was simulated by the LPG 5.1 and based on the chosen household which is called H01 in HT18. For the purpose of this study a standard house instead of an apartment was chosen, since it would have parking space in the house and docking the FCEV would not be complicated.
8. The FCEV is assumed to be docked every day at the house between the times 19:00-07:00. A total of 12 hours every day, reason being that in Germany 90% of the vehicles are either parked or remain idle during this time [29].
9. For the main analysis two power outputs of electricity from the FCEV were chosen. 3kW and 1kW which was based on a former project conducted at TU delft. (Add source)
10. Maintenance costs take care of the replacement of components of the vehicle and heating systems. This ensures proper functioning of the system so that the 30 years lifetime is achievable.
11. Only the fuel cell stack and inverter replacement were considered. These are not included in the maintenance costs. Fuel cell stack was replaced every 8 years and the inverter every 15 years.
12. Heat and electricity demand were simulated with the LPG for one year and was assumed to be constant for the next 30 years.

## 3.2 Scope

This section deals with the scope of each of the cases involved. The study is from the perspective of the owner of the vehicle and house.

### 3.2.1 Case 1: ICEV Owner (reference case)

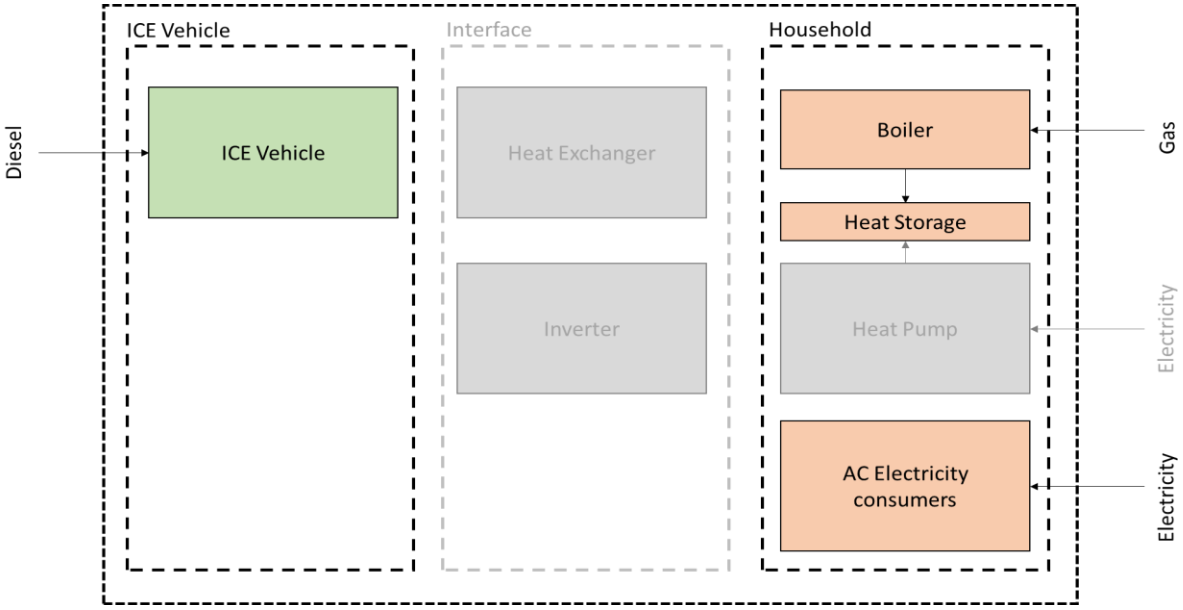


Figure 3.1: Scope of case 1 (own illustration)

One internal combustion engine vehicle (ICEV) was considered along with the household. The costs of the vehicle and some household components were considered (figure 3.1). Investment costs include the vehicle investment. Operating costs include fuel costs for the vehicle, gas for heating and electricity from the grid. This was based on the heat and electricity demand data generated from the LPG. Maintenance costs include vehicle and heating systems maintenance. Following this the nominal costs for the period of 30 years were calculated and discounted to get the NPV of the system.

### 3.2.2 Case 2: FCV Owner

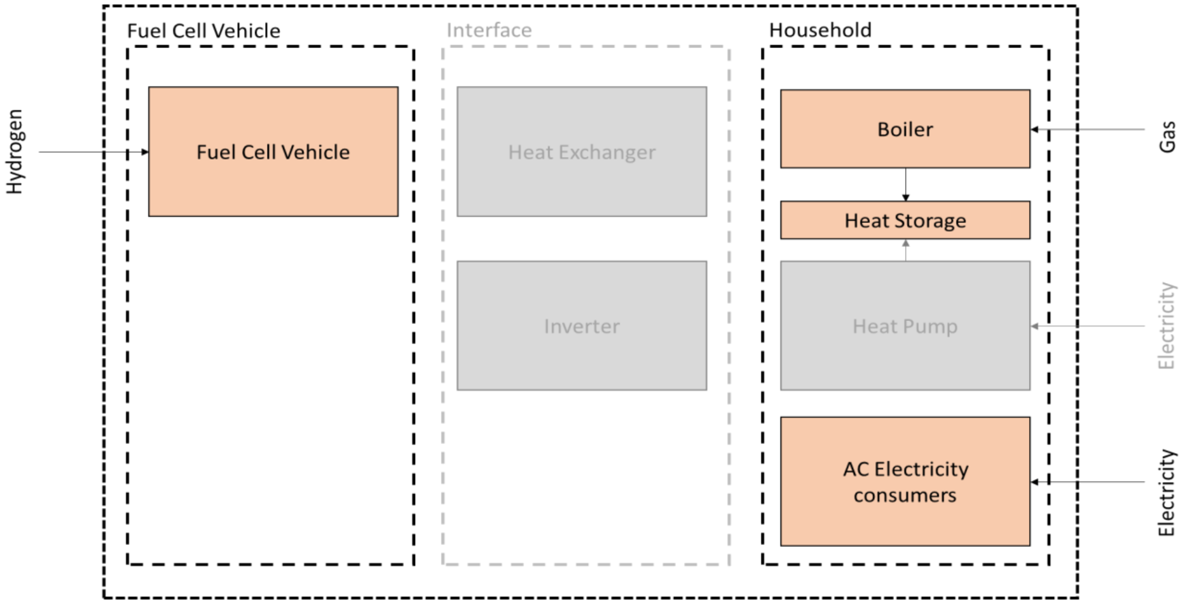


Figure 3.2: Scope of case 2 (own illustration)

One FCEV and the household components instead of the ICEV were considered (figure 3.2). No coupling of the heat or electricity was considered for this case. Costs of the FCEV and household were considered. Investment costs include only the FCEV investment. Operating costs include fuel costs for the vehicle, gas for heating and electricity from the grid. Similar to the first case the gas and electricity costs were based on load profile of the household generated with LPG. Maintenance costs include that of vehicle and heating systems. Following this the nominal costs for the period of 30 years were calculated and then discounted to get the NPV of the system.

### 3.2.3 Case 3: FCV with Energy Autarky (V2H scenario)

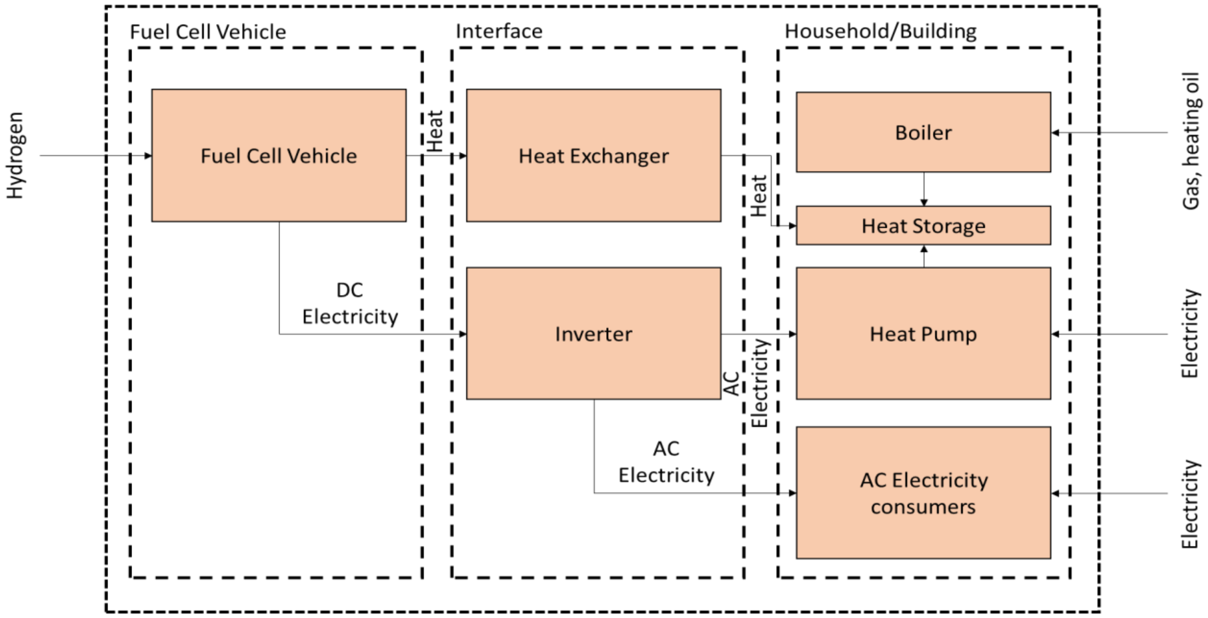


Figure 3.3: Scope of Case 3. (own illustration)

System comprises of one FCV and household components as showed in figure 3.3. Additionally, this is the case for V2H as the heat and electricity generated from the FCV is reused. No electricity was fed to the grid. FCV was assumed to be docked at the docking station daily between 19:00-07:00. 3 kW and 1 kW power output of the fuel cell was considered. Electricity generated in docking mode covers the household demand and excess electricity was supplied to the heat pump. The coefficient of performance of the heat pump was assumed to be 3.5. The calculation the of $H_2$ consumed is shown in section 3.5.1. Investment costs of vehicle, inverter and the heat pump were considered. Operating costs include fuel costs for the vehicle, gas for heating and electricity from the grid. Based on the load profile generated with the LPG, the heat and electricity generated from the FCV is compared with the load profile of the household. Following this, the amount of heat and electricity demand covered with the outputs of the FCV were calculated. Maintenance costs include that of the vehicle and heating systems.

### 3.2.4 Case 4: FCV Prosumer

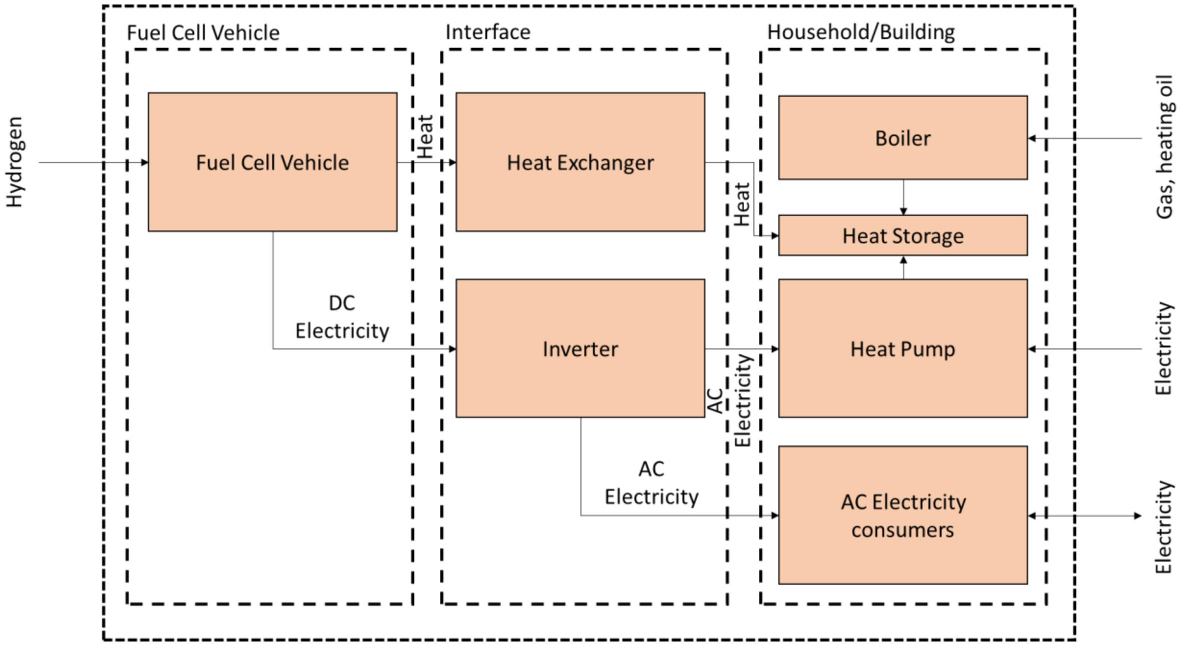


Figure 3.4: Scope of Case 4. (own illustration)

The system comprises of one FCV and the household components. System components of the household are as shown in figure 3.4 and comprise of the heating system, electrical appliances and the interface to transfer the heat and electricity from the docking station. This is the case for V2G as electricity was supplied back to the grid (notice double arrow in figure 3.4). Investment costs include the vehicle, heat pump and inverter. Operating costs include the $H_2$ costs for the household and vehicle, electricity from the grid and gas for heating. Maintenance costs include that of the vehicle and heating systems. The load profile of the household was simulated for 1-hour intervals for the year 2020. With the load profile, how much of the demand that can be covered during the docking hours was calculated. Additionally, excess of the generated electricity was being supplied back to the grid for revenue.

## 3.3 Load Profile Generator

For the generation of the load profile of the household the software LoadProfileGenerator© (LPG) 5.1 was used. The LPG creates load profiles based on behavior simulation of the inhabitants in a house. It is a program that was developed by Noah Pflugradt [53]. The following settings were used to simulate the load profiles for the duration of one year.

1. House type, weather conditions, behavior patterns of the inhabitants, heat and electricity demands were modeled according to the predefined household settings and chosen location.
2. Household chosen was the H01 in HT18(120 $m^2$) with a 20,000 kWh yearly gas heating demand. Household plan was the default for the given house i.e. CHR01 couple (both working, under 30). Energy demand was set as the default for the chosen household.
3. Location chosen was Hamburg according to the weather conditions of 2007 from Deutscher Wetterdienst DWD [6]. Availability of statistical and hourly modelling data in the load profile generator and proximity to Oldenburg were the deciding factors in choosing Hamburg.
4. Load profile was calculated for a year (01.01.2020-01.01.2021) and it is assumed that the following years up till 2050 will have the same demand and weather conditions.

The simulated load profiles of heat and electricity are shown in the subsection 3.3.1.

### 3.3.1 Electricity Load Profile for the year 2020

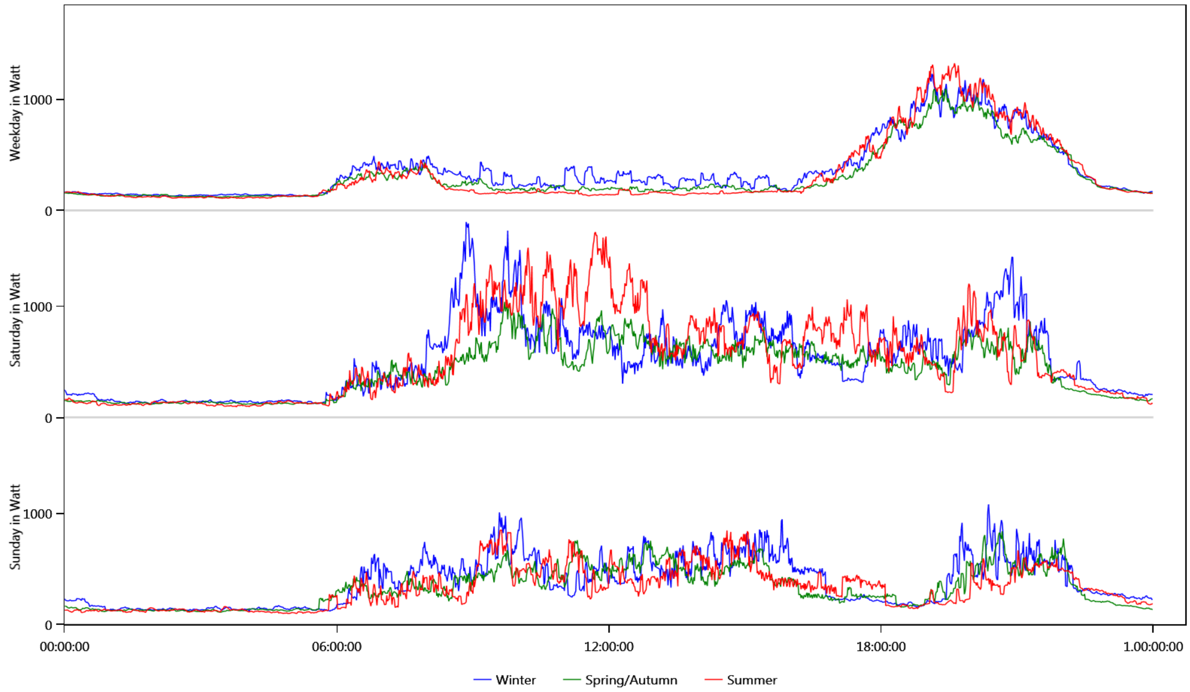


Figure 3.5: Electricity profile for the year 2020. Electricity load profiles for typical weekdays (top), Saturdays (middle) and Sundays (bottom) as assumed for year 2020. Year seasons are shown in different colours. Generated with Load Profile Generator [53].

According to the simulations the yearly total electricity demand for the household is 3059.33 kWh for the year 2020. The load profile was generated with a time step resolution of 1 hour for the entire year and compared to the power being generated by the FCV (1 kW and 3 kW) between the times 19:00 and 07:00. The docking station was assumed to contains an inverter which converts the DC power to AC with an assumed 95% efficiency [29]. Thus, the AC power converted is 2.85 $kW_{el}$ and 0.95 $kW_{el}$ with the power outputs 3 kW and 1 kW of the fuel cell respectively. When the difference between the electricity demand and fuel cell electric energy is negative electricity is taken from the grid. Thus, with the power output of 3 kW the total electric energy from the FCV supplied to the household is 1,447.46 kWh, electricity supplied from the grid is 1,692.43 kWh. For the power output of 1 kW total electric energy from FCV to the household is 1,246.08 kWh and from the grid is 1813.26 kWh.

### 3.3.2 Heating Load Profile for the year 2020

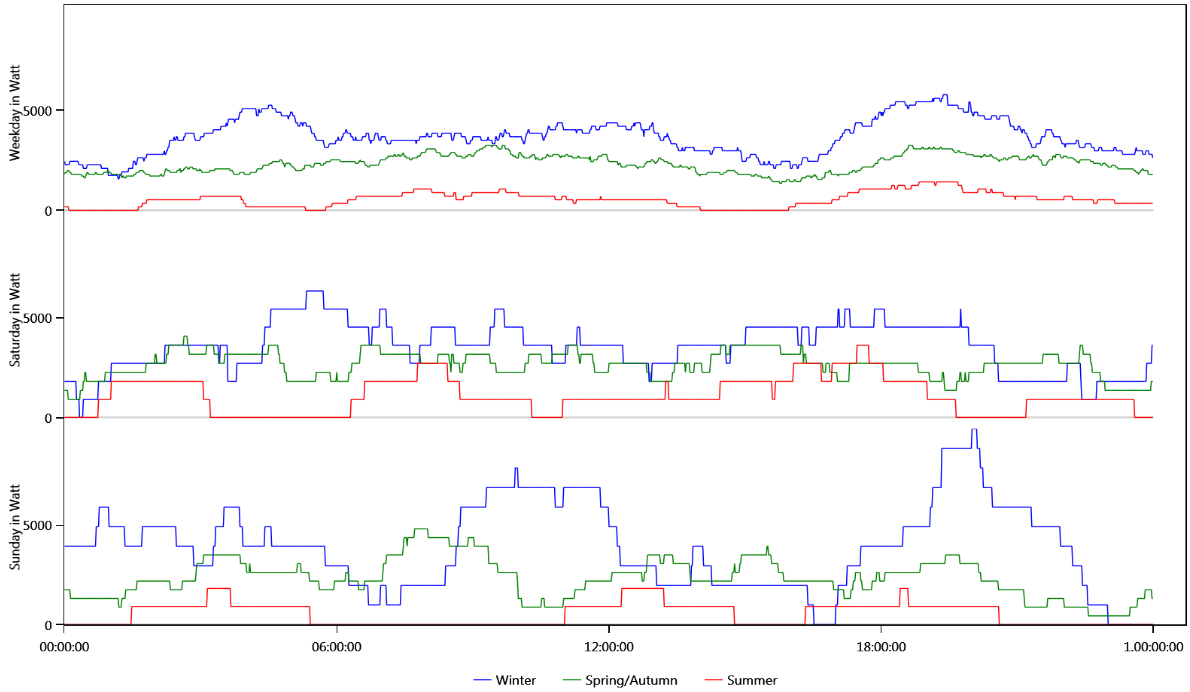


Figure 3.6: Heating profile for the year 2020. Heating load profiles for typical weekdays (top), Saturdays (middle) and Sundays (bottom) as assumed for year 2020. Year seasons are shown in different colours. Generated with Load Profile Generator [53].

The yearly heat demand of the household was estimated as 19,922.92 kWh. According to Tobias et al. [29], for every 100 kWh of chemical energy contained in hydrogen and converted in a vehicle fuel cell, 41.87 kWh is converted to electrical energy, whereas 29.77 kWh to thermal energy can be recovered. This implies a thermal efficiency of 29.77%. Thus, with an electric power output of 3kW and 1kW of the fuel cell corresponds to 2.13$kWh_{th}$ and 0.71$kWh_{th}$ thermal energy converted respectively. Efficiency for heat conversion is assumed at 90% after conversion losses [29], which brings the thermal energy converted to 1.92 $kWh_{th}$ and 0.64 $kWh_{th}$ for the power output modes 3kW and 1kW respectively. For the 3kW output the total thermal energy converted from the FCV for the year 2020 is 8,419 $kWh_{th}$. For the 1kW output the total thermal energy generated from the FCV is 2806 $kWh_{th}$. A heat pump is also used in the cases 3 and 4. For the study the heat pump selected has a COP of 3.5 which implies for every 1kWh of electric energy the thermal energy converted from the heat pump is 3.5 $kWh_{th}$. The total heat generated from the heat pump for the year 2020 is thus 33,024 $kWh_{th}$ and 10,242 $kWh_{th}$ for the power output of 3 kW and 1 kW respectively. For the case 3 the electric energy remaining after covering the demand of the household is used by the heat pump.

The same goes for case 4 but half of the electric energy is sold to the grid and the remaining half is used by the heat pump.

## 3.4 Model Inputs

This section covers the inputs used in each of the cases as well as the costs associated with them.

| Inputs | Case 1 | Case 2 | Case 3 | Case 4 | Units | Source |
|---|---|---|---|---|---|---|
| Electricity Price | 0.32 | 0.32 | 0.32 | 0.32 | EUR/kWh | [54] |
| Heating Gas Price | 13.13 | 13.13 | 13.13 | 13.13 | Ct/kWh | [55] |
| Diesel Price | 1.1 | - | - | - | EUR/l | [56] |
| Hydrogen Price | - | 9.5 | 9.5 | 9.5 | EUR/kg | [57] |
| Electricity Demand | 3,059.33 | 3,059.33 | 3,059.33 | 3,059.33 | kWh/yr | [53] |
| Heating Gas Demand | 19,922.9 | 19,922.9 | 19,922.9 | 19,922.9 | kWh/yr | [53] |
| Mileage of FCV | 16.5 | 105.47 | 105.47 | 105.47 | km/kg | [58] |
| Household Area | 120 | 120 | 120 | 120 | $m^2$ | [53] |
| Average Distance travelled per year | 13,220 | 13,220 | 13,220 | 13,220 | km | [59] |
| FCV Tank Capacity | - | 5.6 | 5.6 | 5.6 | kg | [58] |
| Vehicle Investment Cost | 31,400 | 77,290 | 77,290 | 77,290 | EUR | [60] |
| Investment Cost (Inverter) | - | - | 536 | 536 | EUR | [61] |
| Investment Cost (Heatpump) | | | 4,700 | 4,700 | EUR | [62] |
| Maintenance Cost (vehicle) | 744 | 301 | 301 | 301 | EUR | [63] |
| Maintenance Costs (heating) | 465 | 465 | 465 | 465 | EUR | [64] |
| Fuel Cell Stack Costs | - | 2,000 | 2,000 | 2,000 | EUR | assumption |
| Discount Rate General | 0.03 | 0.03 | 0.03 | 0.03 | - | [65] |
| Discount Rate $H_2$ Fuel | 0.078 | 0.078 | 0.078 | 0.078 | - | - |
| Inflation Rate Gas | 0.013 | 0.013 | 0.013 | 0.013 | - | - |
| Inflation Rate Diesel | 0.027 | 0.027 | 0.027 | 0.027 | - | - |

Table 3.1: Summary of inputs for all the cases. Own table

Maintenance cost for the ICEV is assumed to be 7% of ICEV investment costs per year. For the FCEV the average of all the maintenance categories from [63] is calculated to get the value of 301 EUR as the yearly maintenance cost. The discount rate was calculated by using equation 2 for $H_2$ fuel costs. According to the International Renewable Energy Agency (IRENA) May 2022 report in the less optimistic cost assumptions scenario the cost of $H_2$ fuel by 2050 reaches 1.18 EUR/kg [66]and at year 2020 the cost is 9.5 EUR/kg [57]. This brings the discount rate at around 7.8% for $H_2$ fuel costs. The inflation rate for gas and diesel was calculated similarly by comparing the prices from year 2000 to 2020 [67][68].

## 3.5 Variables

This section shows the different variables that were calculated using the inputs and the load profile data generated from the LPG for both the power outputs of 1 kW and 3 kW.

| **Variables** | **Case1** | **Case 2** | **Case 3** | **Case 4** | **Units** |
|---|---|---|---|---|---|
| Electricity Generated FCV Annually | - | - | 1,447.46 | 1,447.46 | kWh/yr |
| Electricity Consumption Grid | 3,059.3 | 3,059.3 | 1,614.22 | 1,692.00 | kWh/yr |
| Annual Heat Generated FCV | - | - | 8,419.46 | 8,419.46 | kWh |
| Annual Heat Generated from Heat Pump | - | - | 30,324 | 30,324 | kWh |
| Annual Heat Generated Gas Heater | 19,922.92 | 19,922.92 | 0 | 0 | kWh |
| Annual Gas Costs | 2,615.88 | 2,615.88 | 0 | 0 | EUR |
| Annual Electricity Costs (incl. Heating) | 989.39 | 989.39 | 522.04 | 541.57 | EUR/yr |
| Lifetime of the Analysis (n) | 30 | 30 | 30 | 30 | yrs |
| Average Distance Travelled per Year | 13,220 | 13,220 | 13,220 | 13,220 | Km |
| $H_2$ Annual Consumption without Electricity Generation | - | 125.34 | 125.34 | 125.34 | Kg |
| $H_2$ Price Annual without V2H | - | 1,190.77 | 1,190.77 | 1,190.77 | EUR |
| $H_2$ V2H Consumption Rate | - | - | 0.19 | 0.19 | Kg/h |
| Daily $H_2$ Consumption with Electricity Generation | - | - | 2.28 | 2.28 | Kg |
| $H_2$ Annual Consumption with Electricity Generation | - | - | 832.20 | 832.20 | Kg |
| $H_2$ Annual Price with Electricity Consumption | - | - | 7,905.90 | 7,905.90 | EUR |
| FCV Power Output | - | - | 3.00 | 3.00 | kW |

Table 3.2: Variables for the 3kW power output.

| **Variables/Indicators** | **Case1** | **Case 2** | **Case 3** | **Case 4** | **Units** |
|---|---|---|---|---|---|
| Electricity Generated FCV Annually | - | - | 1,447.46 | 1,447.46 | kWh/yr |
| Electricity Consumption Grid | 3,059.33 | 3,059.33 | 1,813.26 | 1,813.26 | KWh/yr |
| Annual Heat Generated FCV | - | - | 2,806.49 | 2,806.49 | kWh |
| Annual Heat Generated from Heat Pump | - | - | 10,242.13 | - | kWh |
| Annual Heat Generated Gas Heater | 19,922.92 | 19,922.92 | 6,874.30 | 17,116.43 | kWh |
| Annual Gas Costs | 2,615.88 | 2615.88 | 902.60 | 2,247.39 | EUR/kWh |
| Annual Electricity Costs (incl. Heating) | 989.39 | 989.39 | 586.41 | 586.41 | EUR/yr |
| Lifetime of the Analysis (n) | 30.00 | 30.00 | 30.00 | 30.00 | yr |
| Avg. Distance travelled per year | 13,220.00 | 13,220.00 | 13,220.00 | 13,220.00 | Km |
| $H_2$ Annual Consumption without electricity generation | - | 125.34 | 125.34 | 125.34 | kg |
| $H_2$ Price Annual without V2H | - | 1,190.77 | 1,190.77 | 1,190.77 | EUR |
| $H_2$ V2H Consumption rate | - | - | 0.09 | 0.09 | kg/h |
| Daily $H_2$ Consumption with electricity generation | - | - | 1.08 | 1.08 | kg |
| $H_2$ Annual Consumption with electricity generation | - | - | 394.20 | 394.20 | kg |

| | | | | | |
|---|---|---|---|---|---|
| $H_2$ Annual Price with electricity consumption | - | - | 3,744.90 | 3,744.90 | Eur |
| FCV power output | - | - | 1.00 | 1.00 | kW |

Table 3.3: Variables for the 1kW power output.

### 3.5.1 $H_2$ Consumption Rate

According to the study Robledo et. al. the hydrogen consumption rate increases linearly with the power output. The hydrogen consumption can be calculated using equation 5.

$$H_{2rate}[\text{kg/h}] = 0.04 + 0.05 \times P_{FCV} \qquad \text{Equation (5)}$$

Where

$H_{2rate}$ is the hourly rate of consumption of $H_2$.

$P_{FCV}$ is the power output of the FCV [kW].

The annual $H_2$ consumption is thus the sum of the $H_2$ annual consumption for normal vehicle operation and the consumption for the supply of electricity and heat to the household.

The above sections form the basis of the LCC and with the help of the inputs and variables the NPV of all the cases were calculated after determining the nominal costs and discounted costs using the equations (1), (2) and (3).

# 4. Results

## 4.1 LCC Results for the 3kW Power Output

The outcome of the LCC analysis presents the total costs overtaken by the owner of the vehicle for 30 years for each of the cases in the form of NPV (net present value). Table 4.1 shows the total life cycle costs from investment costs to operating and maintenance and for each of the cases. The table also highlights the total NPV for each of the cases in the LCC. Case 1 is the reference case, compared to this case the case 2 NPV is 7.26% higher, case 3 is almost breaking even with a 2.66% increased difference and case 4 is lower by around 4.94%. Table 4.1 and figure 4.1 underlines that the highest costs associated with the LCC are the gas costs for cases 1 and 2, and operational costs of the vehicle for cases 3 and 4. Operational costs include the amount of hydrogen used in the FCV for driving as well as when the vehicle is in the docking state and converting electricity plus heat. The next cost that has a significant impact on the NPV is the investment costs for the vehicle. Case 4 is also the prosumer case meaning the owner is selling electricity back to the grid. For case 4 this is shown by the revenue grid row in table 4.1. Case 3 and 4 have no gas costs since the heat from the heat pump and the heat recovered from the fuel cell cover the entire household heat demand.

| **Parameter** | **Case 1** | **Case 2** | **Case 3** | **Case 4** |
|---|---|---|---|---|
| **Investment Costs(vehicle)** | 31,400 | 77,290 | 77,290 | 77,290 |
| **Running Costs(vehicle)** | 40,959 | 13,662 | 104,371 | 104,371 |
| **Maint. Costs(vehicle)** | 14,583 | 7,575 | 7,575 | 7,575 |
| **Electricity** | 19,392 | 19,392 | 10,232 | 10,728 |
| **Gas** | 96,471 | 96,467 | 0 | 0 |
| **Heating maint. Costs** | 9,114 | 9,114 | 9,114 | 9,114 |
| **Stack replacement costs** | 0 | 3,809 | 3,809 | 3,809 |
| **Heat Pump Costs** | 0 | 0 | 4,700 | 4,700 |
| **Inverter Costs** | 0 | 0 | 880 | 880 |
| **Revenue Grid** | 0 | 0 | 0 | -17,320 |
| **NPV** | 211,919 | 227,310 | 217,971 | 201,147 |
| | | 7.26% | 2.86% | -5.08% |

Table 4.1: Total discounted life cycle costs and NPV for each case

Figure 4.1 compares the cash flows for each of the cases that take place every year from 2020 to 2050. Stack for the FCV are replaced every 8 years, which accounts to slight increase in the costs at year 8, 16 and 24. Case 1 costs increase slightly with time. This is based on the inflation rate for the heating gas prices and the diesel prices and therefore increasing running costs every year for the ICEV. Case 4 also involves revenue being generated, and therefore in figure 4.2 it is negative and falls below the y axis.

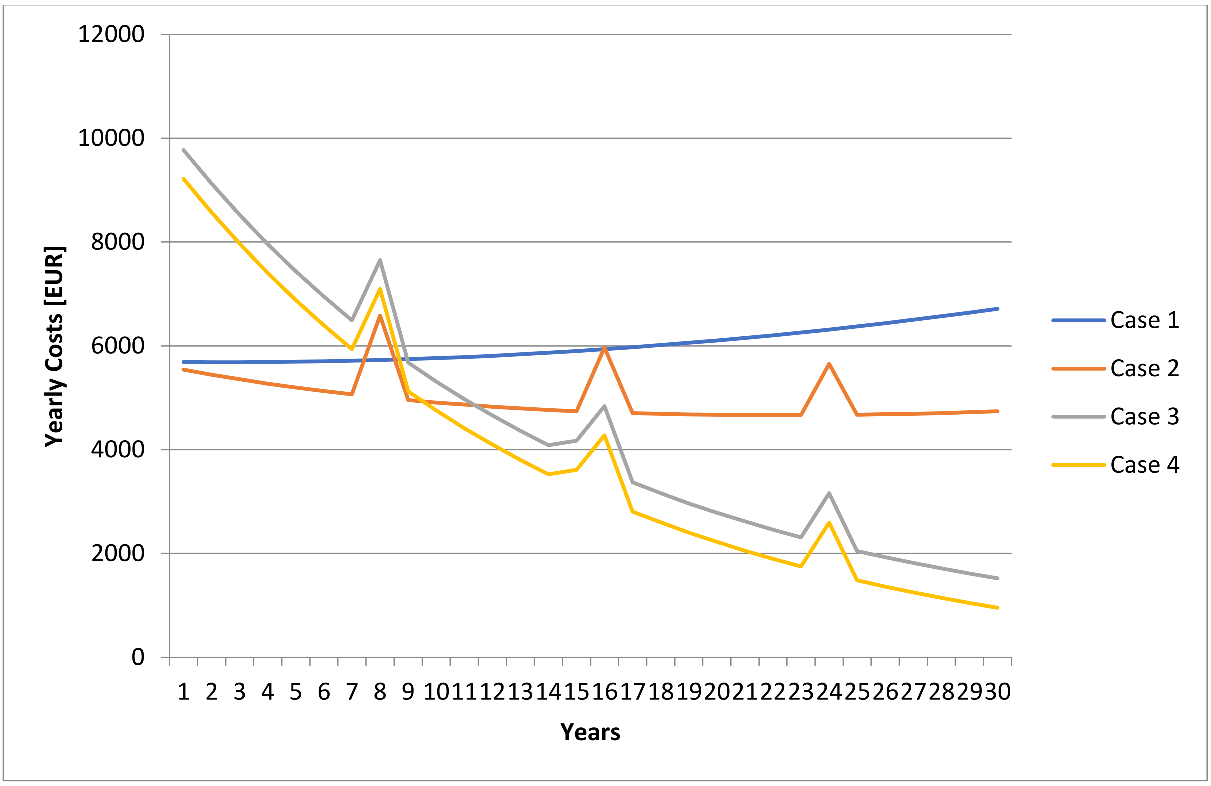


Figure 4.1: Yearly discounted costs for each case excluding the investment costs.

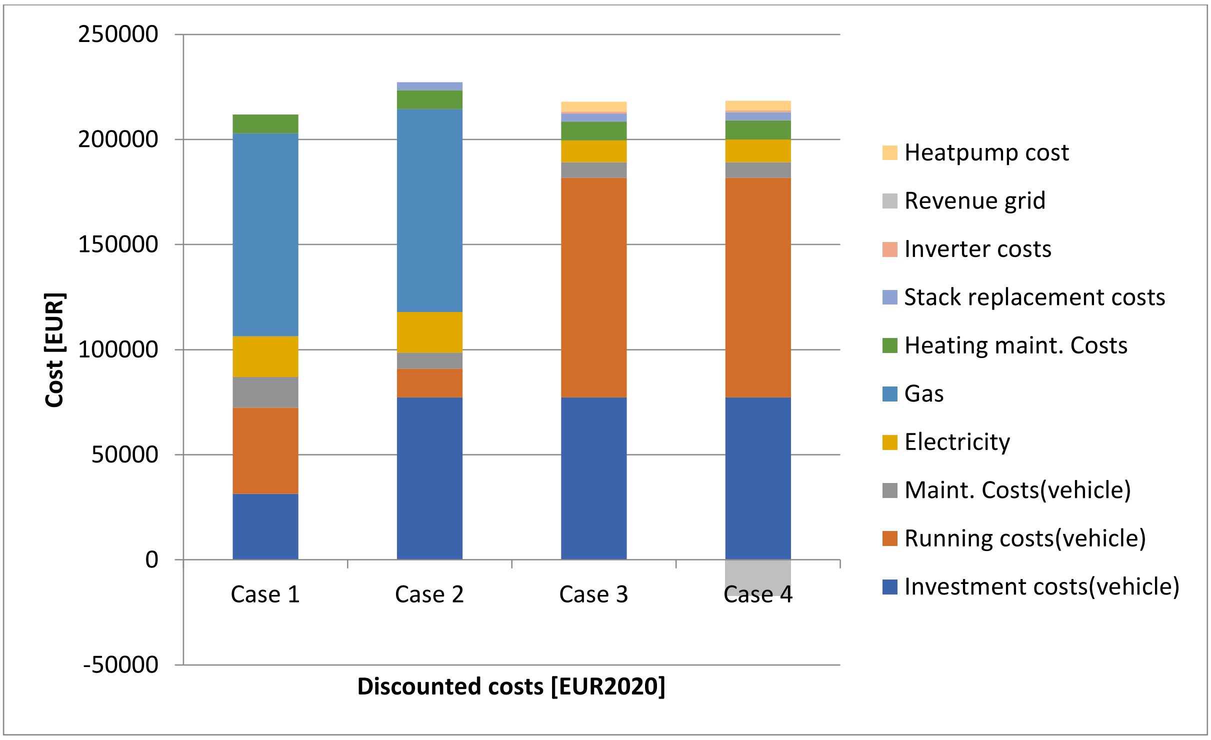


Figure 4.2: NPV for each case along with contribution to the NPV from all associated costs.

## 4.2 LCC Results for the 1kW power output

Table 4.2 displays the NPV and cost from each category and from each case that contributes to the NPV for the 1kW power output of the FCV, cases 1 and 2 are not influenced by this. Gas prices for the heater from cases 1 and 2 contribute the most for their respective NPV, followed by running and investment costs. For case 3 the investment costs for the vehicle are the highest contributor at 77,290 Euro followed by running costs of the vehicle at 56,630 Euro and the gas for heating at 33,287 Euro. Despite the reduction in gas heating, for case 4 gas costs are the highest contributor with 82,881 Euro followed by the investment costs at 77,290 Euro and then the running costs of the vehicle at 56,630 Euro. The difference in gas costs between case 3 and 4 is due to the fact that excess electrical energy in case 3 is transferred to the heat pump, whereas in case 4 it is fed to the grid. There is no reason to use a heat pump in case 4 because excess of electricity is sold to the grid. It was possible to use a heat pump with the 3 kW power output mode of the FCV since even after dividing the electric power towards heat pump and the grid there was enough revenue as well as heat generated from the heat pump to justify this. For the 1 kW power output there is not enough electricity being generated so that heat pump and grid coupling can be used together for case 4. The main difference between the 3 kW and 1 kW subcases is that the running costs of the FCV for cases 3 and 4 are almost halved from 104,371 to 56,630 Euros. This is a significant impact on the overall NPV as well by just reducing the power output of the FCV while it is docked. Another difference is between the gas costs for heating, which is 0 for case 3 and 4 for the 3 kW FCV power output and 33,287, 82,881 EUR2020 for the 1 kW power output. Gas costs for heating have a considerable impact on the NPV in all the cases, eliminating them makes the cases 3 and 4 economically competitive with our reference case, which is case 1. Figure 4.3 shows the cash flow trends for each of the cases with the 1 kW power output. Case 1 cash flow increases because of the inflation on diesel and heating gas prices which increase the running costs of the vehicle and heating costs of the house every year. Case 2 tends to also increase at the end due to the inflation rate for the gas prices for heating. Cases 3 and 4 follow a similar trend, major difference being the gas prices for heating that increases the costs for case 4. The sudden increase in the cash flow for cases 2, 3 and 4 every 8 years is due to the stack replacement of the FCV.

| | **Case 1** | **Case 2** | **Case 3** | **Case 4** |
|---|---|---|---|---|
| **Investment costs(vehicle)** | 31,400 | 77,290 | 77,290 | 77,290 |
| **Running costs(vehicle)** | 40,959 | 13,662 | 56,630 | 56,630 |
| **Maint. Costs(vehicle)** | 14,583 | 7,575 | 7,575 | 7,575 |
| **Electricity** | 19,392 | 19,392 | 11,494 | 11,494 |
| **Gas** | 96,471 | 96,467 | 33,287 | 82,881 |
| **Heating maint. Costs** | 9,114 | 9,114 | 9,114 | 9,114 |
| **Stack replacement costs** | 0 | 3,809 | 3,809 | 3,809 |
| **Heat Pump Costs** | 0 | 0 | 4,700 | 0 |
| **Inverter costs** | 0 | 0 | 880 | 880 |
| **Revenue grid** | 0 | 0 | 0 | -10,535 |
| **NPV** | 211,919 | 227,310 | 204,778 | 239,138 |
| **Difference** | | 7.26% | -3.37% | 12.96% |

Table 4.2: Total discounted life cycle costs and NPV for each case with 1 kW power output.

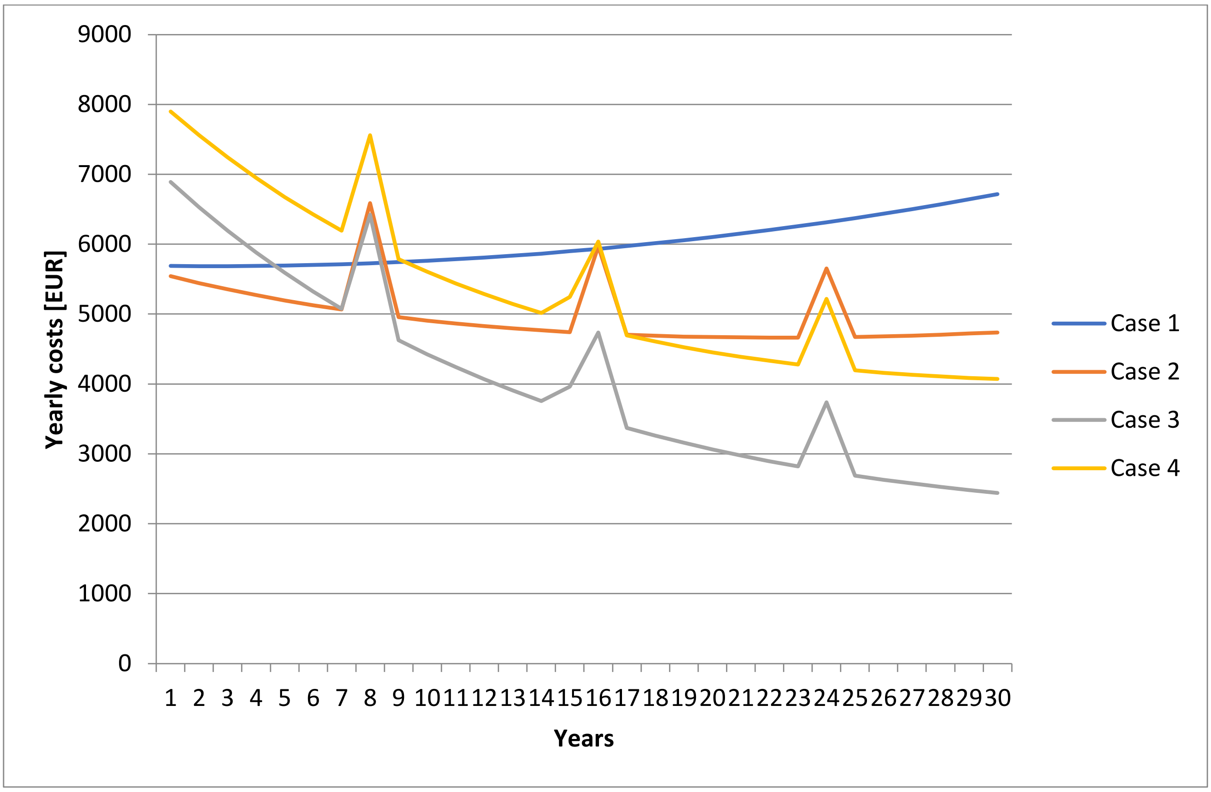


Figure 4.3: Discounted cash flow for all the cases for each year without the investment costs at year 0.

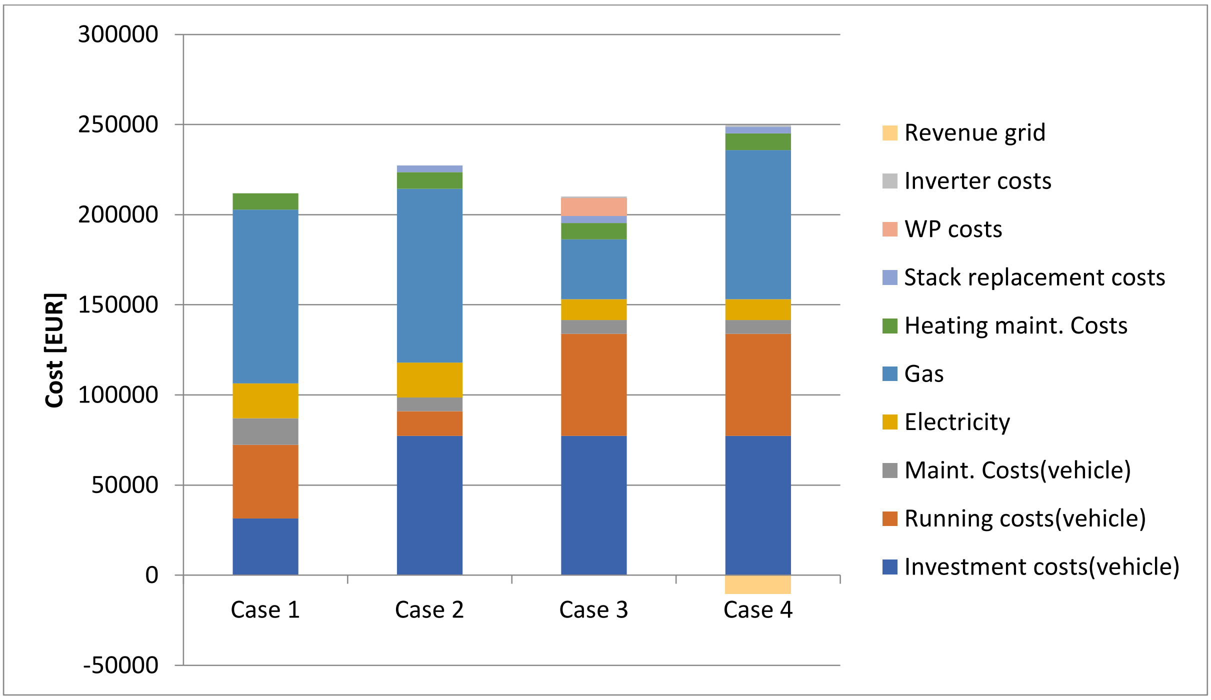


Figure 4.4: NPV for each case along with contribution to the NPV from all associated costs for the 1 kW power output.

## 4.3 Technical Analysis Results

### 4.3.1 Self Consumption

Self-consumption is the ratio of locally generated electricity which is consumed to the total electricity generated [69].

$$SC = \frac{E_{lgc}}{E_{gen}} \qquad \text{Equation (6)}$$

Where,

$SC$ is the self-consumption

$E_{lgc}$ is the electricity locally generated and consumed [kWh]

$E_{gen}$ is the total local electricity generation [kWh].

By using equation 6 and tables 3.2 and 3.3, the total annual SC values are:

| | Case 3a | Case 4a | Case 3b | Case 4b |
|---|---|---|---|---|
| Self-Consumption | 0.95 | 0.95 | 0.58 | 0.43 |

Table 4.3: Self consumption values for cases 3 and 4. Case 3a and 4a correspond to the 3 kW power output of the FCEV. Cases 3b and 4b correspond to the 1 kW power output of the FCEV.

### 4.3.2 Autarky

Autarky is the ratio of locally generated electricity which is consumed with respect to the total electricity consumption [69].

$$A_t = \frac{E_{lgc}}{E_{load}} \qquad \text{Equation (7)}$$

Where,

$E_{lgc}$ is the electricity locally generated and consumed [kWh]

$E_{load}$ is the total electricity load [kWh]

By using equation 7 and the variables from table 3.2 and 3.3, the total annual autarky values are:

| | Case 3a | Case 4a | Case 3b | Case 4b |
|---|---|---|---|---|
| Autarky | 0.95 | 0.70 | 0.83 | 0.41 |

Table 4.4: Autarky values for cases 3 and 4. Case 3a and 4a correspond to the 3 kW power output of the FCEV. Cases 3b and 4b correspond to the 1 kW power output of the FCEV.

# 5. Sensitivity Analysis

Data uncertainty cannot be completely avoided. Costs at which the probability of occurrence is unclear are referred to as being uncertain. The method most frequently employed to cope with uncertainty is sensitivity analysis. Finding and identifying the key assumptions or cost variables that can influence the economic analysis is the methodology [70]. This analysis's goal is to examine expensive input variables that could have an impact on the net present value (NPV) of each case. Sensitivity analysis for the cost variables like electricity costs, heating gas costs, vehicle investment costs and fuel costs were performed using the local sensitivity method and an OAT approach. A ±20% cost change on the price of the cost variables, for example the buying price of electricity, heating gas and $H_2$ price was calculated to find out the change in the NPV for each case and for both the power output scenarios. These costs were considered because they contribute the most for the NPV in each case.

## 5.1 Sensitivity Analysis for input Parameters with 3 kW power output

For case 1, the highest change in NPV is 9.1% after changing the heating gas prices, followed by 3.87% with ICEV fuel costs, 2.96% vehicle investment costs and 1.91% with -20% electricity cost and 1.71% with 20% electricity cost change.

| Case 1 | Electricity cost | invest. costs | Fuel costs | Gas costs(heating) |
|---|---|---|---|---|
| 80% | 207,878 | 205,639 | 203,727 | 192,625 |
| 100% | 211,919 | 211,919 | 211,919 | 211,919 |
| 120% | 215,553 | 218,199 | 220,111 | 231,213 |

Table 5.1: NPV variation for the sensitivity analysis for case 1. The row corresponding to 80% are the NPV after changing the input prices of each input by 80%. Similarly, the row corresponding to 120% are the NPV after changing the input prices by 120%. Own source.

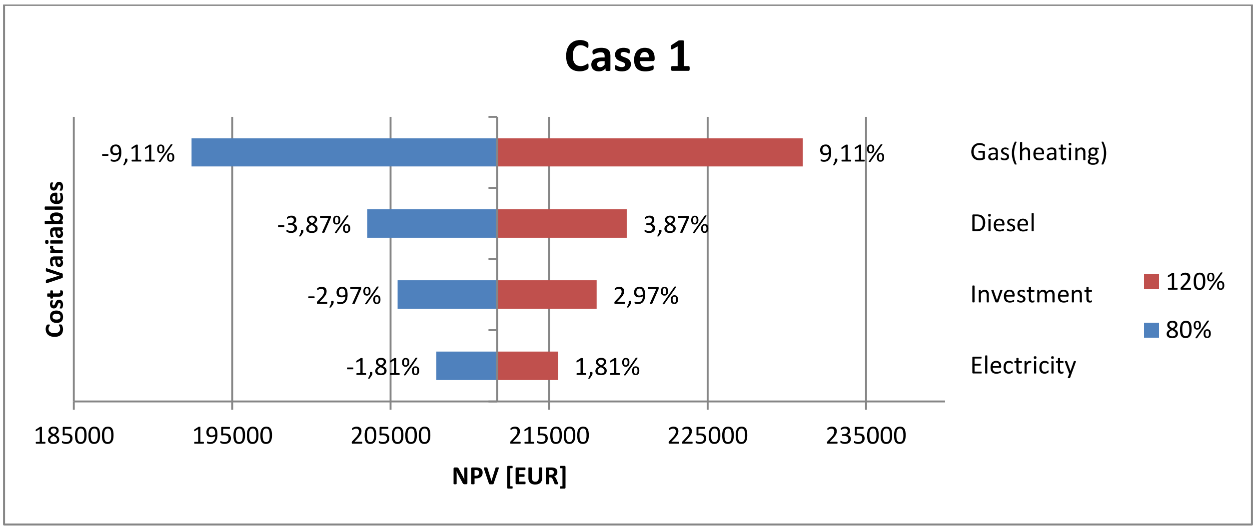


Figure 5.1: Percentage change in NPV for the respective input parameter. Own plot.

For case 2, the highest change in NPV is 8.49% after changing the heating gas prices, followed by vehicle investment costs at 6.8%, electricity costs which are 1.78% with -20% cost change and 1.60% at 20% cost change and 1.2% change in NPV with $H_2$ fuel price.

| Case 2 | H2 fuel costs | Electricity costs | invest. Costs | Gas costs(heating) |
|---|---|---|---|---|
| 80% | 224,578 | 223,268 | 211,852 | 208,017 |
| 100% | 227,310 | 227,310 | 227,310 | 227,310 |
| 120% | 230,042 | 230,944 | 242,768 | 246,604 |

Table 5.2: NPV values for each input parameter changed. Own source.

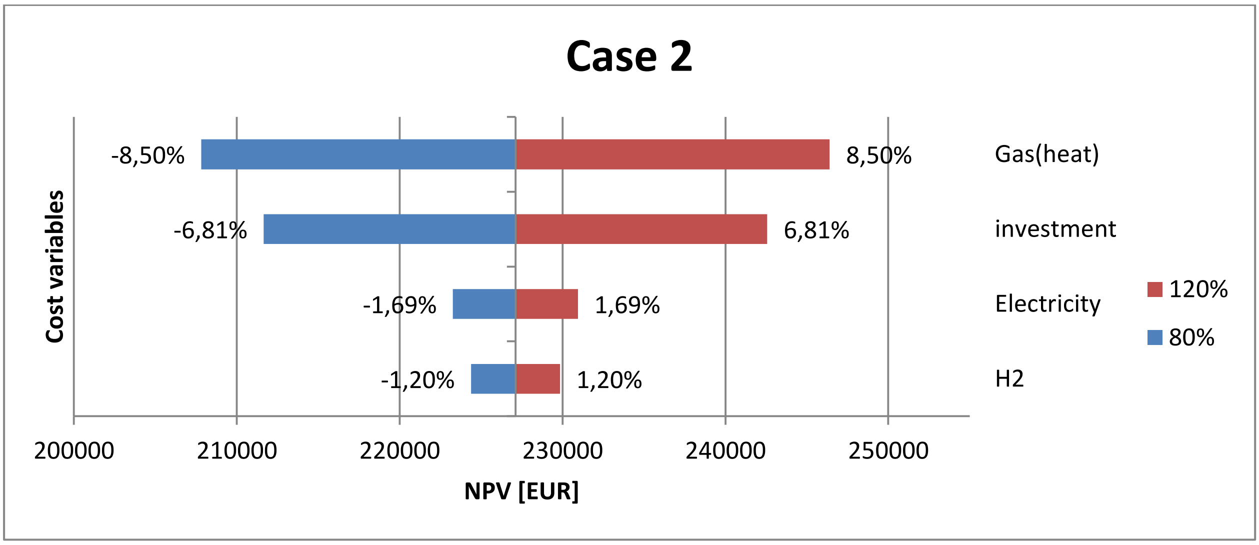


Figure 5.2: Percentage change in NPV for the respective input parameters for case 2. Own plot.

For case 3, the highest change in NPV is ±9.58% corresponding to $H_2$ fuel prices, followed by vehicle investment costs at 7.04% with +20% cost variation and -7.14% with -20% cost variation. For electricity NPV is varied by -0.98% with -20% cost variation and 0.88% with a +20% cost variation. Gas prices do not change the NPV for case 3 with the 3 kW power output. The reason being that the entire heat demand is covered with the heat supplied through the heat pump and FCEV, and therefore no heating gas needs to be bought in order to run the heating boiler.

| Case 3_3kW | Gas (Heat) | Electricity | Investment | H2 fuel costs |
|---|---|---|---|---|
| 80% | 217,971 | 215,839 | 202,406 | 197,097 |
| 100% | 217,971 | 217,971 | 217,971 | 217,971 |
| 120% | 217,971 | 219,889 | 233,322 | 238,846 |

Table 5.3: NPV for each input parameter varied. Own source.

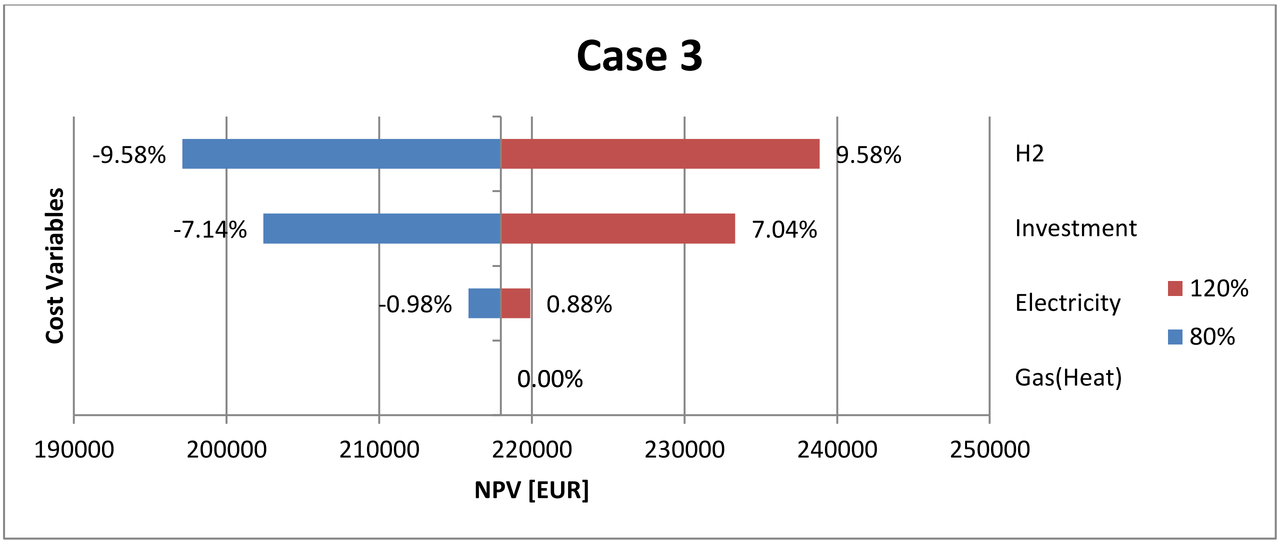


Figure 5.3: Percentage change in NPV for the respective input parameters in case 3. Own plot.

For Case 4, highest change in NPV is ±10.38% corresponding to $H_2$ fuel price variation, followed by vehicle investment cost at ±7.68%. Electricity price variation of -20% and +20% varies the NPV by -1.11% and 1% respectively. Gas prices do not have any effect on the NPV for the same reason as case 3 above.

| Case 4_3kW | Gas(heat) | Electricity | Investment | H2 fuel costs |
|---|---|---|---|---|
| 80% | 201,147 | 198,911 | 185,689 | 180,273 |
| 100% | 201,147 | 201,147 | 201,147 | 201,147 |
| 120% | 201,147 | 203,157 | 216,605 | 222,021 |

Table 5.4: NPV variation for the sensitivity analysis in case 4. Own source.

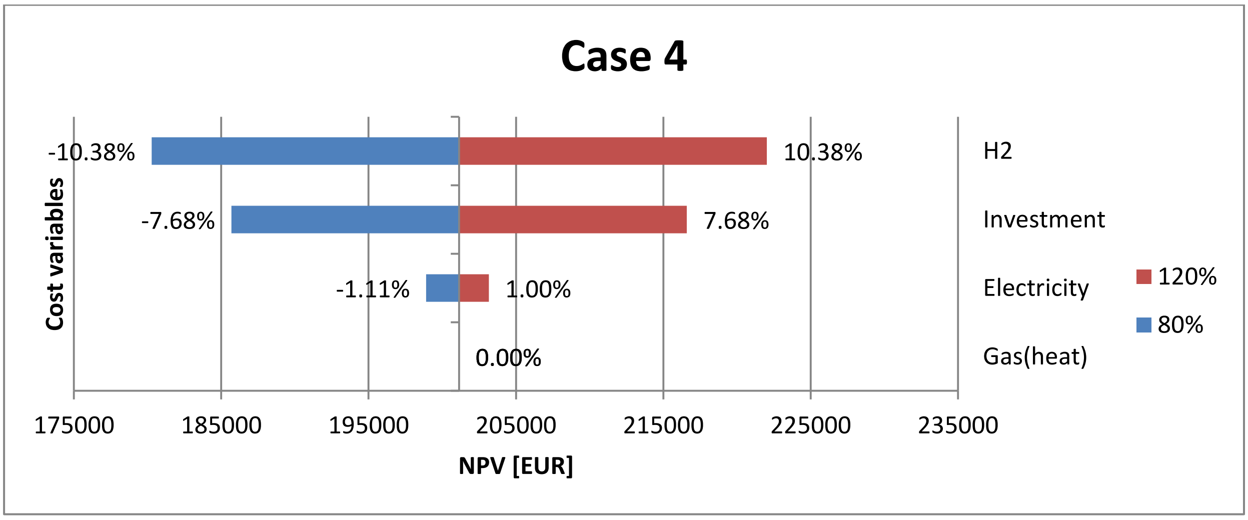


Figure 5.4: Variation in NPV for the respective input cost variables in case 3. Own plot.

## 5.2 Sensitivity Analysis with input parameters for the 1 kW output

The sensitivity analysis for cases 1 and 2 in the 1 kW power output mode are the exact same as the 3 kW power output. Table 5.1 and 5.2 and figure 5.1 and 5.2 showcase those results.

For case 3 the highest change in NPV is 7.36% with vehicle investment costs, 5.39% with $H_2$ fuel price, 3.17% with heating gas costs and 1.14% with the -20% electricity costs and 1.03% with 20% costs.

| Case 3_1kW | Electricity costs | Gas costs(heating) | H2 fuel costs | invest. Costs |
|---|---|---|---|---|
| 80% | 207,683 | 203,421 | 198,752 | 194,620 |
| 100% | 210,078 | 210,078 | 210,078 | 210,078 |
| 120% | 212,232 | 216,736 | 221,404 | 225,536 |

Table 5.5: NPV values for each input parameters change for case 3. Own source.

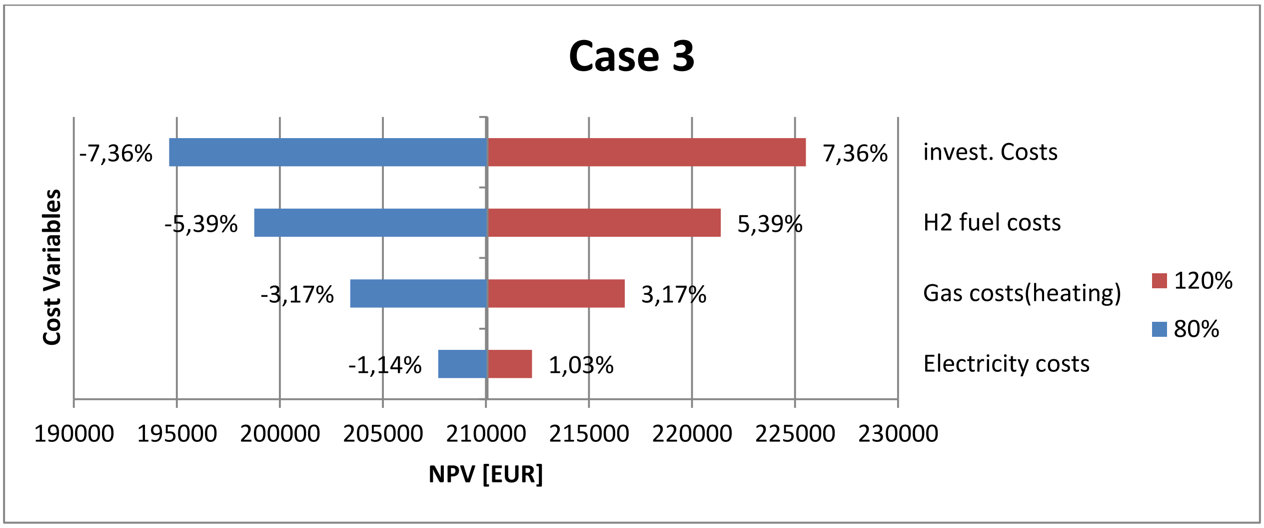


Figure 5.5: percentage change in NPV for the respective input parameters for case 3. Own plot.

For case 4 the highest change in NPV is 6.65% with heating gas costs, 6.2% with vehicle investment costs, 3.45% with $H_2$ fuel costs and 0.96% with -20% electricity cost change and 0.86% with 20% electricity cost change.

| Case 4_1kW | Electricity costs | H2 fuel costs | invest. Costs | Gas costs(heating) |
|---|---|---|---|---|
| 80% | 246,743 | 240,544 | 233,680 | 232,562 |
| 100% | 249,138 | 249,138 | 249,138 | 249,138 |
| 120% | 251,292 | 257,731 | 264,596 | 265,714 |

Table 5.6: NPV values for each input parameter changed for case 4. Own source.

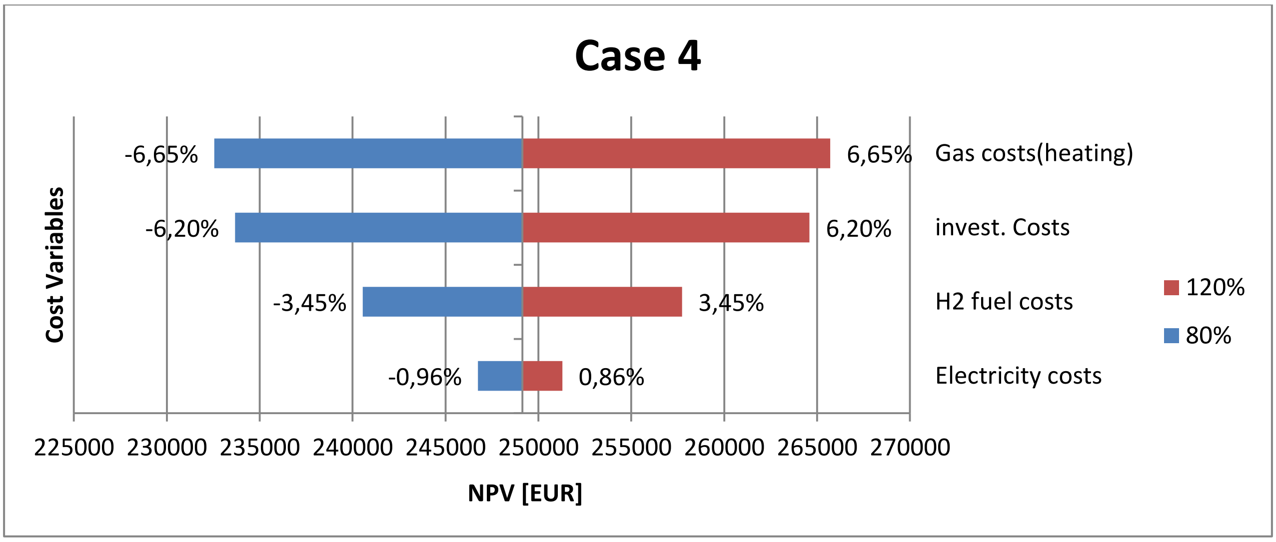


Figure 5.6: percentage change in NPV for the respective input parameters for case 4. Own plot.

# 6. Discussion

The objective of this study is to conduct a multidimensional analysis of the V2G and V2H concept for an FCEV in order to determine its economic and technical feasibility. For the economic analysis an LCC using the standard of ISO 15686-5 was performed, for the technical analysis the indicators of self-consumption and autarky were calculated. Four cases were assessed. The first case assessed an ICEV with the household, second case assessed an FCEV with the household. The third case and fourth case with two subcases each were considered. The two subcases are, one where the FCEV has a power output of 3 kW and the other where the power output is 1 kW. The boundaries and scope of these 4 cases were discussed in chapter 3.

It was found that for the 3 kW power output scenario, case 4 (V2G) is more economically feasible compared to case 1 which is the reference case and represents a traditional energy supply for households based on electricity from the grid and gas for heating. The NPV for case 4 is lower by 4.94% compared to case 1. The NPV for case 3 (V2H) and 2 on the other hand are higher by 2.66% and 7.26% respectively compared to case 1. We find that for case 4 the deciding factor in making it more economically feasible was the revenue being generated as a prosumer and no heating gas costs since the heat converted from the FCV plus the heat pump was more than enough to cover the heating costs. One important observation is that, the operational costs for the FCV including travelling and docking are extremely high due to the high $H_2$ fuel costs at 9.5 EUR/kg. Lowering prices of $H_2$ by even 1 EUR makes case 3 economically competitive with case 1. Vehicle investment costs also play a key role in the LCC results, the investment cost for the FCV are more than double compared to that of the ICEV. The sensitivity analysis performed in chapter 5 also proves this point since the NPV is impacted significantly while varying the vehicle investment cost for cases 2,3 and 4. For the 1 kW power output scenario, case 3 (V2H) is more economically feasible compared to case 1 because the NPV for case 3 is lower by 3.37% compared to case 1. The NPV for case 4 (V2G) and 2 are higher by 12.96% and 7.26% respectively compared to case 1. We find that for case 3 the deciding factor is the usage of the heat pump, which decreases the heating costs significantly. Due to the lower power output of the FCV, it is not feasible to have a V2G scenario together with a heat pump in operation. Thus, no heat pump is considered for case 4 for the 1 kW power output scenario and this severely increases the heating costs due to heating gas being required to cover the thermal load of the household. A lower power output of 1 kW also means lower revenue compared to the 3 kW power output, as less electricity is being converted and getting fed to the grid. An important observation that also justifies having the 1 kW power output scenario is that the operational costs for the FCV are almost halved compared to the 3 kW power output scenario. The lower power output also essentially means that the $H_2$ rate of consumption while docking is significantly less compared to the higher power output. Observations about the vehicle investment costs and $H_2$ fuel costs for the 3 kW power output also hold the same for the 1 kW power output scenario and are again proven with the sensitivity analysis results in chapter 5. Reducing power output of FCEV, self-consumption remains same for V2H scenario but reduces for V2G. Reducing power output of FCEV, autarky decreases for both V2H and V2G. Since less electricity is fed to the heat pump at 1 kW power compared to 3 kW. Self-consumption and autarky decrease from case 3 to 4 irrespective of the power output, since electricity is being fed to the grid instead of being consumed in the household.

The technical indicator of self-consumption is the highest for case 3a and 3b. Autarky is the highest for case 3a and 4a since these two cases have higher power output of the FCEV.

The results of this study prove that for some cases the V2G and V2H concepts integrated with an FCV are feasible economically and technically according to the indicators chosen. There are of course limitations to this study and the next section discusses those along with some avenues for future research related to this topic.

# 7. Outlook

The following points give an overview about some limitations to this study and possible future improvements and additions for research related to this topic:

- Due to the limited time for the thesis, this study focuses on economic and technical analysis. For a multidimensional analysis a life cycle assessment that compares the ecological impacts of the FCVs and ICEVs could be subject for future work.

- The weather conditions simulated by the LPG 5.1 are for the duration of one year. No future weather simulations or assumptions are made. This can be a further addition for future work since weather conditions do impact the electricity and thermal profiles of a household.

- The lifetime of the LCC performed was considered to be 30 years. It was assumed that with the maintenance costs of the vehicles their respective lifetimes will match 30 years. This is a limitation of the study and can be improved upon with more accurate data.

- Fuel cell stack degrades with usage over the years, no stack degradation is considered in this study. Considering stack degradation can improve the accuracy of the results and provide a better outlook on the results and FCV performance.

- The LCC was calculated using Microsoft Excel®. Future work related to this topic could model the entire energy system, for example using a python package like FINE [71]. Using such a framework can make the modelling easier and faster, it would also be possible in theory to accurately model the system with all the inputs and outputs, optimize the results and assess the energy system. Modelling on python also means other packages can be used together, for example Gurobi optimizer can be used along with FINE to optimize results or in our case optimize the costs.

# 8. References

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