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Life Cycle Costing Analysis: Tools and Applications for Determining Hydrogen Production Cost for Fuel Cell Vehicle Technology

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Abstract: This work investigates life cycle costing analysis as a tool to estimate the cost of hydrogen to be used as fuel for Hydrogen Fuel Cell vehicles (HFCVs). The method of life cycle costing and economic data are considered to estimate the cost of hydrogen for centralised and decentralised production processes. In the current study, two major hydrogen production methods are considered, methane reforming and water electrolysis. The costing frameworks are defined for hydrogen production, transportation and final application. The results show that hydrogen production via centralised methane reforming is financially viable for future transport applications. The ownership cost of HFCVs shows the highest cost among other costs of life cycle analysis.

Keywords: hydrogen economy; cost analysis; life cycle costing; methane reforming; water electrolysis; centralised hydrogen production

1. Introduction

The phrase 'Hydrogen Economy' is not a recent concept. John Bockris first introduced it in 1976, where hydrogen was identified as clean energy carrier. In a Hydrogen Economy, the lightest of all gases must be processed as any other market commodity. Hydrogen is to be produced, packaged, transported, stored and transferred to the end-user [1], where it can be converted to electricity by the usage of fuel cells or other conversion devices [2].

Hydrogen can be produced from conventional fossil fuels, but also from more environmentally friendly and renewable resources. The total annual world production of hydrogen was around 368 trillion m^3 [3]; 48% of hydrogen was produced from natural gas, about 30% from oil, 18% from coal and 4% via water electrolysis [4]. Eighty percent of the produced amount was mainly consumed by the chemical industry and by petrochemical refineries [5]. The remaining amount was utilised in various processes including situations that hydrogen used as energy carrier.

In addition, the global demand for hydrogen in 2010 was 43 Mtons and the forecast is to reach around 50 (or more) Mtons by 2025, majorly affected from the demand for ammonia production, methanol and petroleum refinery operations [6,7]. The hydrogen consumption (in million Tons) is shown in Figure 1. Asia and Pacific are the world's leaders in consuming hydrogen (almost 1/3 of the global consumption), followed by North America and Western Europe [6,7]. The hydrogen as an alternative fuel can be used as potential energy carrier at the transportation sector for Fuel Cell Electric Vehicles (FCEVs) [8].

Figure 1. Hydrogen consumption (in millions of Tons) for the year 2010 (below) and the forecast for the year 2025 (up).

The hydrogen production via methane steam reforming and water electrolysis can take place in centralised or decentralised facilities [9]. For the case of centralised hydrogen production, hydrogen is distributed to the area of application via tank trailers in liquefied or gaseous form [10]. For the case of decentralised production, hydrogen is produced and stored in the location of usage, by normally utilising hydrogen fuelling stations [11].

The viability of the hydrogen technology as alternative fuel for transportation applications depends on several factors; the current and future cost of hydrogen, the technological advantages that employs hydrogen as fuel when utilising fuel cells, the long-term restrictions on greenhouse gases emission and the cost of competitive technologies, such as batteries and super capacitors [12]. Therefore, the cost analysis for hydrogen production is a very important an crucial aspect to identify the economic feasibility of using hydrogen in the transportation sector, regardless the technological obstacles at the current time, such as the hydrogen storage capacity and the specifications to meet the future high demand for transportation [13,14]. The introduction and implementation of using the life cycle cost analysis is one method that can be deployed in order to identify and decide the feasibility of using hydrogen as alternative fuel [15].

Accurate evaluation techniques for decision-making are required for economic, social, and environmental aspects. Various models have been developed such as [16]; the E3-database model in Germany and France, the H2A model developed by U.S Department of Energy Hydrogen, G4-ECONS methodology to estimate the levelled unit energy cost, and, finally, the HEEP model, which applies analysis and feasibility studies related to hydrogen production using nuclear energy [16–18]. The models mentioned above can be classified according to the tools and methods deployed for the cost estimation. The classification can be performed based on the following criteria; life cycle energy analysis models including energy flows and environmental assessment criteria [19,20], infrastructure development models and future benefit [21,22], social life cycle infrastructure and vehicle market models [23–25], and finally, energy economy models including hydrogen production and environmental assessment [26]. Table 1 summarises the most recent studies and techniques for hydrogen economy evaluation for hydrogen mobility applications. The current article focuses on the study of the cost analysis for hydrogen production for fuel cell vehicles applications. The costing analysis is applied for four hydrogen production routes. The analysis includes a framework and sensitivity analysis to compare costing results.

Table 1. Recent studies of hydrogen economy for mobility applications.

Scope of Study	Framework of Study	Area of Investigation	Ref
Social cost-benefit analysis framework for fuel cell vehicle versus internal combustion engine vehicle.	Cost benefit analysis framework was introduced; considering economic comparison, external costs estimation and social–economic comparison.	Cost Benefit Analysis of German Market based on previous published study for fuel cell electric vehicle, including externality costs in Europe for society benefits analysis.	[27]
Techno-economical characterization for Alkaline water electrolysis.	Alkaline water electrolysis life cycle was studied focusing on the metrics' approach and the approaches to specify realistic projections of sensitive technical and economic parameters, such as investment cost or future electricity cost.	The weighted average cost of capital for alkaline water electrolysis was used for analysis for cost estimation and financial analysis on three different production sites.	[28]
Techno-economic modelling of future hydrogen supply chains with spatial resolution.	Study evaluates all parts of the supply chain, from hydrogen production to refilling, the case of Germany for the target year 2050, considering a spatial resolution regarding costs, primary energy demand and CO_2 emissions. It also optimizes potential for hydrogen distribution.	Simulation approach of each step of the supply chain using optimization method.	[29]
Techno-economic model of future hydrogen supply chains.	Investigates the application area of different hydrogen supply chain architectures through a point-to-point analysis based on the methodology of the lowest-cost hydrogen delivery mode investigated by [30], full supply chain from hydrogen production by electrolysis, large-scale storage, transportation and fuelling.	Well-to-tank analysis to estimate greenhouse gas emissions for conditioning a transportation fuel	[31]
Cost of hydrogen applications are compared with conventional energy supply.	Five scenarios have been developed to compare the cost of using hydrogen with conventional energy sources, taking into account the cost of CO_2 emissions.	Methodology of life cycle cost is employed to conduct the cost of hydrogen production and application for islands and specific applications.	[32]
Economic model is developed to evaluate the investment and operational cost.	Build an economic evaluation model that describes the investment cost and operational cost, making the mathematical optimization to reach a minimum total annual cost of Hybrid Battery/Hydrogen Storage.	Optimizing the life cycle capital was formulated to determine the optimal configuration of a hybrid renewable energy.	[33]
Techno-economic analyses and life cycle assessments of four hydrogen production technologies using natural gas as a feedstock.	Understanding of the techno-economic and life cycle environmental performance of a set of emerging hydrogen production technologies.	Technical and financial conditions under which each technology is expected to be attractive are explored for carbon price.	[34]
Well-To-Wheel (WTW) analysis for hydrogen.	Global emission model for integrated systems (GEMIS) interacted with greenhouse gases, regulated emissions, and energy use in transportation (GREET) for Portugal.	Greenhouse gases emissions (GHGs) compared with the gasoline vehicle from different hydrogen production routes.	[35]
Integrate multi-objective optimization with principal component analysis to address the environmentally conscious design of hydrogen networks.	A Framework has been proposed for optimizing hydrogen supply chains in accordance with several environmental indicators.	Multi-objective mixed-integer linear program (MILP) is formulated that takes into account the simultaneous minimization of the most significant impacts of life cycle assessment (LCA) for Spain.	[36]
Life cycle including the effect on environment.	Demonstrate the costs of every step and to discuss their relationship for coal hydrogen production.	The minimum cost of each production step was analysed and focused on strategic selection for China.	[37]

Table 1. *Cont.*

Scope of Study	Framework of Study	Area of Investigation	Ref
Techno-economic analyses and life cycle assessment (LCA).	Two main gasification processes for producing hydrogen from biomass showing minimum hydrogen selling price.	Evaluate and compare the impact of gasification technology on the techno-economic and life cycle environmental performance of hydrogen production from biomass.	[38]
Life cycle costing analysis framework for hydrogen production and utilization.	Apply the method of life cycle cost for hydrogen production and utilization via analysis the feasible economic tools for forecasting hydrogen cost by developing an economic model framework including sensitivity analysis criteria.	Engineering economic tools that can be applied in general/universal form for estimating feasible hydrogen production systems, considering major cost breakdown structure to simplified life cycle model using Microsoft Excel as the tool.	Current study

Analytical tools must be standardised in order to develop a decision-making tool for hydrogen end-users and policy makers. In the current study, the life cycle costing model is proposed and introduced specifically to investigate an in-depth analysis in the Hydrogen Economy. It is a systematic analytical process for the evaluation of various alternatives with the objective of choosing the most suitable alternative. The main objective of this work is to apply the concept of life cycle cost analysis and explore the feasibility of various hydrogen production systems and techniques utilising this methodology. A life cycle costing concept in the energy field by defining a possible system boundary for various hydrogen sources is investigated and implemented. The proper life cycle costing framework for hydrogen production is proposed and used to determine the most cost effective and economically feasible hydrogen source as alternative fuel. The analysis focuses in small to medium-scale hydrogen production for FCVs. The proposed life cycle model also investigates the impact of changing several technological parameters on the hydrogen cost through a sensitivity analysis.

In the present work, essential economic evaluations have been identified in order to estimate the hydrogen cost based on life cycle methodology. Using the life cycle analysis principles, where the feasible and simplified costing framework structure is developed, a simple procedure and a general way to estimate the hydrogen cost production, transportation and utilization is introduced. The costing breakdown structure has been identified according to the boundaries of the hydrogen system and it is linked to the developed engineering economic model to simulate the feasible hydrogen cost using Microsoft Excel as a simulation tool. The estimated cost is then applied, using sensitivity analysis for a fair and feasible alternative selection in a simplified manner. This estimation is conducted without influence of the environmental assessment aspects or advanced energy selection modelling software. In such a way, the current approach can offer a more general and universal form to estimate the hydrogen production cost and it is not limited by the regional factor.

2. Methodology

2.1. The Life Cycle Costing Model

The concept of life cycle cost includes the total cost of the product from the early stages (development and manufacturing), mid stages (storage and transport) to the final stage where the product reaches the end-user. The life cycle costing is a management cost method which can be used for all sorts of products. However, the nature and objective of the analysis depends on the product itself.

For the needs of the current analysis, the Life Cycle Costing (LCC) model studies the cost-effective activities during hydrogen production and distribution. The feasible system of hydrogen technology is used to develop the LCC model, which defines a common hydrogen cost breakdown structure. The life cycle model is defined to estimate the hydrogen cost based on several hydrogen resources. The model defines various cost categories involved in hydrogen technology. Figure 2 presents the proposed life cycle costing model structure and strategy for hydrogen fuel costing analysis. The framework includes sensitivity analysis of feedstock price, vehicle cost, change on demand and capacity of hydrogen production. Both technical and economical parameters are included during the life cycle costs analysis.

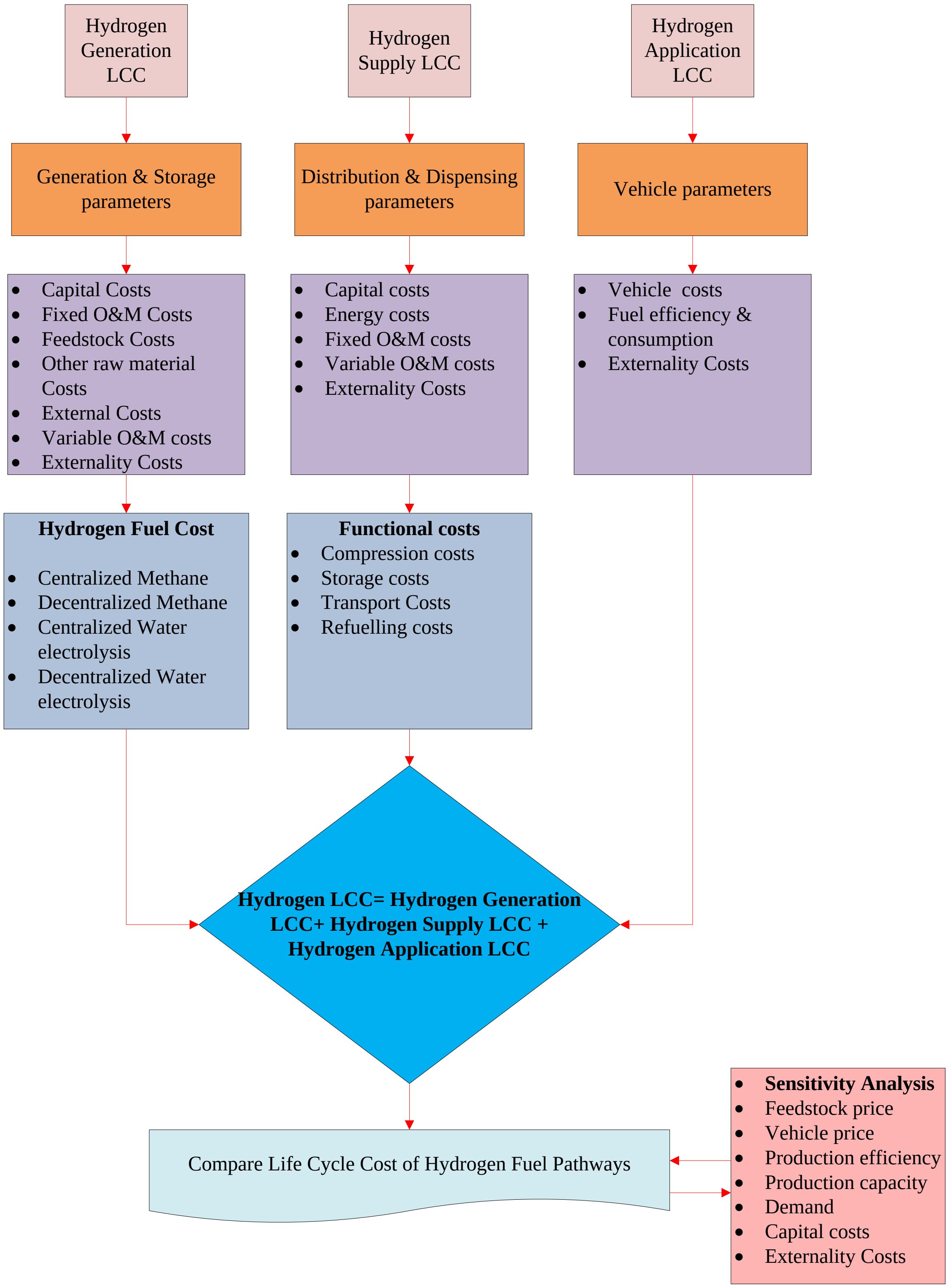

Figure 2. Proposed life cycle costing model structure and strategy for hydrogen fuel costing analysis.

Figure 3 presents the cost categories taken into account in the current work, in terms of hydrogen production, hydrogen distribution and usage. The capital costs consist of construction, preparation and cost for equipment. The running costs include: raw and other materials, primary energy usage, utilities, labour and other variable operating costs. The disposal costs consist of wastewater and CO_2 treatment. Finally, other costs take into account any costs not included in the previously mentioned cost categories that can have potential effects on the analysis. The technical data that are used to perform the life cycle analysis are presented in Table 2. The basic requirements to estimate the life cycle costing is to generate accurate cost data. Hydrogen production depends on: process efficiency, capacity and availability factor and hydrogen storage methods onsite. Hydrogen supply includes mode of transportation, dispensing components and supply capacity. The hydrogen utilization cost depends on the vehicle type and system. Several cost estimations techniques are used, such as the bench marking technique, the parametric approach, and estimating costs from first principles [39–41].

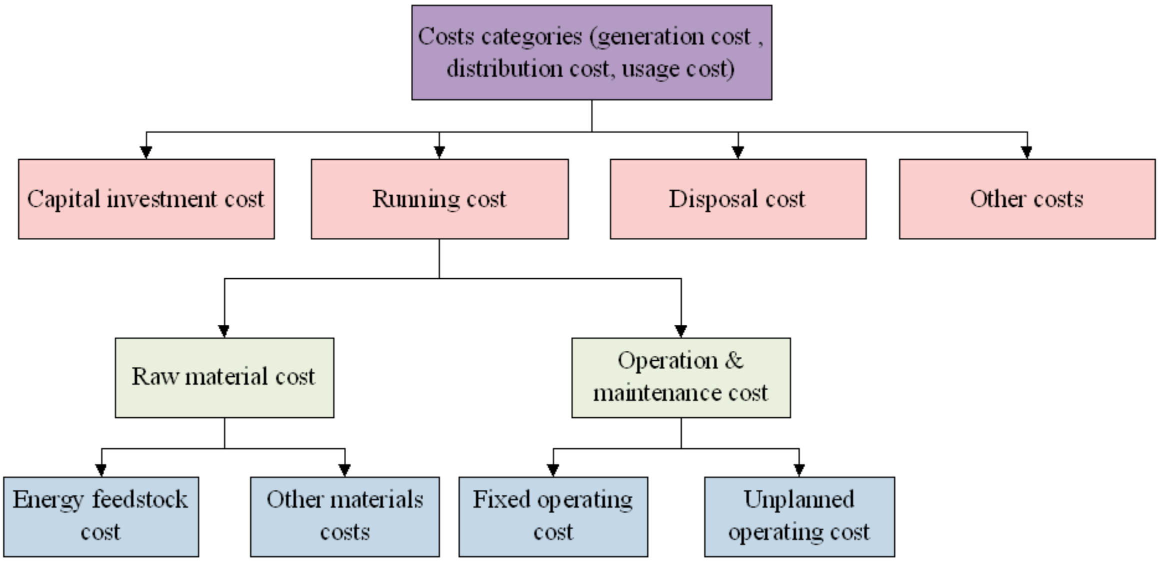

Figure 3. The major cost categories for life cycle costing analysis.

Table 2. Technical data and parameters for life cycle analysis for economic data identifications.

Hydrogen Production	Hydrogen Supply	Hydrogen Use
• Hydrogen production plant • Process efficiency • Capacity and availability factor • Annual hydrogen production rate • Number of generation units • Maximum amount of utilities (raw material) required for process • Other non-direct raw material amounts required • Hydrogen storage methods	• Mode of transportation • Transportation distance • Type of transportation vehicles • Transportation capacity • Vehicle driving distance • Dispensing components (storage and compression)	• Vehicle capacity • Vehicle type· Vehicle driving distance • Average speed of vehicle

2.2. Economic Analysis

For the needs of the current study, the economic comparison between alternatives is the main objective of the life cycle cost analysis. The equations applied in this study are listed in Table 3. The operation period (lifetime) is considered as 40 years for the centralised hydrogen production and as

20 years for the decentralised production. The data can be validated regarding analytical model outputs using the cause-effect relationship, data treatment and comparison with similar production process.

Table 3. Economic analysis equations used for life cycle analysis.

Equation Number	Equation	Abbreviation
(1)	$NPV = \sum_{t=0}^{t=N} \frac{PV}{(1+i^*)^t}$	NPV : Net Present Value PV : Present Value N : Study period i^* : After Tax Nominal IRR
(2)	$\% C_j = \frac{NPV\ C_j}{Total\ \ NPV}$	C_j: is j cost value
(3	$Hydrogen\ cost\ contribution = Hydrogen\ LCC \times \%\ C_j$	C_j: is j cost value
(4)	$i^* = ((1+i) \times (1+f)) - 1$	i^* : After Tax Nominal IRR i : After tax Real IRR f : Inflation Rate
(5)	$IIF = (1+f)^{(AY-SY)}$ $IF = (1+f)^{(SY-RY)}$	AY : Actual Year SY : Start up Year RY : Refernce Year IIF : Inflation Increase Factor IF : Inflation Factor f : Inflation Rate
(6)	$DCC = DDCC + IDCC$ $CI = DCC + NDCC$ $Inflated\ DCC = -DCC \times IF\ \times IIF \times \%\ CI\ at\ start\ up$ $Inflated\ NDCC = -NDCC \times IF\ \times IIF$	DCC : Depreciable Capital Cost $DDCC$: Direct Deprciable Capital Costs $IDCC$: Indirect Deprciable Capital Costs CI : Capital Investment $NDCC$: Non Depreciable Capital Costs IIF : Inflation Increase Factor IF : Inflation Factor
(7)	$Inflated\ other\ NDCC = -NDCC \times IF \times IIF$	$NDCC$: Non Depreciable Capital Costs IIF : Inflation Increase Factor IF : Inflation Factor
(8)	$Inflated\ Replacement\ Costs =$ $-Replacement\ Costs \times IF \times IFF$ $Inflated\ FC = -FC \times IF \times IIF$	FC : Fixed Cost IIF : Inflation Increase Factor IF : Inflation Factor
(9)	$Feed\ Cost =$ $-Inflated\ Feedstock\ Cost \times Annual\ H_2\ Produced \times IIF$ $MC = -inflated\ MC \times IF \times IIF$	MC : Material Costs IIF : Inflation Increase Factor IF : Inflation Factor
(10)	$Other\ VOC =$ $-IF \times Other\ \ Feedstock\ \times Actual\ H_2\ Produced \times IIF$	VOC : Variable Operating Costs IF : Inflation Factor IIF : Inflation Increase Factor
(11)	$WC = \%\ WC \times (FC + Feed\ Costs + MC + VOC)_t -$ $WC(FC + Feed\ Costs + MC + VOC)_{t-1}$	WC : Working Capital VOC : Variable Operating Costs FC : Fixed Cost
(12)	$SV = \%TCI \times IIF$	SV : Salvage Value TCI : Inflated Total Capital Investment at start up year IIF : Inflation Increase Factor
(13)	$DC = Infalted\ DCC \times IIF$	DC : Decommissioning Costs DCC : Depreciable Capital Cost IIF : Inflation Increase Factor
(14)	$R = H_2\ Nominal\ LCC \times IIF \times Annual\ H_2\ Produced$	R : Revenue IIF : Inflation Increase Factor
(15)	$D_t = \frac{DCC-SV}{n}$ $B_t = DCC - t\left(\frac{DCC-SV}{n}\right)$	DCC : Depreciable Capital Cost SV : Salave Value B_t : Book value at the year t D_t : Depreciation charge during year t n : estimated life of the asset
(16)	$TI = Pre\ Depreciation\ Income + D_t$	TI : Taxable Income

Table 3. *Cont.*

Equation Number	Equation	Abbreviation
(17)	$Total\ Taxes = Tax\ Credit - (TI \times Tax\ Rate)$ $Pre\ Depreciation\ Income =$ $R + SV + FC + DC + Feed\ Costs + MC + Other\ VOC$	R : $Revenue$ SV : $Salave\ Value$ FC : $Fixed\ Cost$ DC : $Decommissioning\ Costs$ MC : $Material\ Costs$ VOC : $Variable\ Operating\ Costs$
(18)	$After\ Tax\ Income =$ $Pre\ depreciation\ Income + Total\ Taxes$	
(19)	$CFBT = DCC + Replacement\ Cost + WC + NDCC +$ $Pre\ Depreciation\ Income$ $CFAT = DCC + Replacement\ Cost + WC + NDCC +$ $Pre\ Depreciation\ Income + Total\ Taxes$	$CFBT$: $Cash\ Flow\ Before\ Tax$ $CFAT$: $Cash\ Flow\ After\ Tax$ DCC : $Depreciable\ Capital\ Cost$ WC : $Working\ Capital$ $NDCC$: $Non\ Depreciable\ Capital\ Costs$
(20)	$Actual\ H2\ Produced =$ $Plant\ Design\ Capacity \times Capacity\ Factor$	
(21)	$Annual\ H2\ Produced = Actual\ H2\ Produced \times 365$	

3. Case Study

Hydrogen is currently produced from various resources via steam reforming process and water electrolysis [42,43]. The proposed model will be based on hydrogen that is produced from natural gas steam reforming and water electrolysis (Tables A1–A6) Hydrogen can be produced by following two paths: large-scale centralised production plants (centralised generation) or small-scale distributed production plants (decentralised generation). The analysis for the produced hydrogen at centralised form includes the stage of the production pathway, starting from the preparation of feedstock (raw materials). The central production equipment, distribution preparation equipment and the necessary storage equipment have to be considered. The stage of the distribution pathway starts from the gate of the centralised plant and ends at the gate of hydrogen refuelling station, including the hydrogen transmission equipment. The dispensing pathway stage includes all the processes and equipment within the refuelling station, such as hydrogen compression and hydrogen storage processes. The analysis for hydrogen produced at decentralised form includes the production pathway stage, including the preparation of raw materials and onsite raw material conversion to hydrogen. The dispensing pathway stage includes the processes within the refuelling station, such as hydrogen compressing and hydrogen storage.

3.1. Natural Gas Steam Reforming

Hydrogen production via methane steam reforming can be achieved in both centralised and decentralised facilities as illustrated in Figure 4. In the case of centralised production, hydrogen should be distributed to the area of the application via tank trailers in liquefied or gaseous form. During the decentralised production, hydrogen is produced and stored in the location of usage.

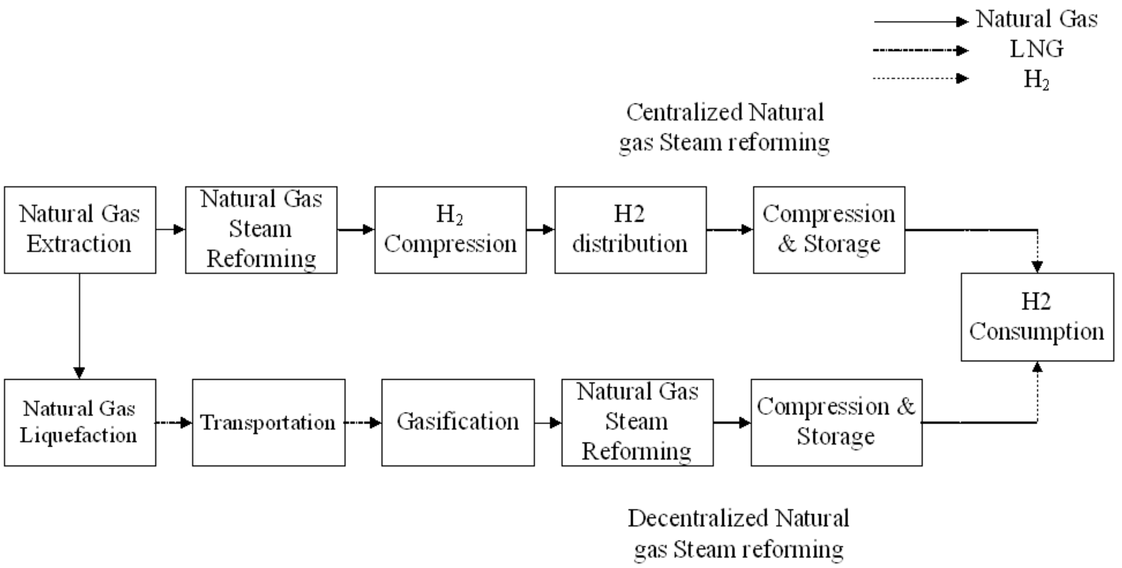

Figure 4. Hydrogen production process via natural gas steam reforming, centralized and decentralized forms.

3.2. Water Electrolysis

The conversion of pre-treated water to hydrogen and oxygen is known as water electrolysis. For the needs of the current study, decentralised hydrogen production through electrolysis is considered as small-medium scale hydrogen refuelling stations are available on the market representing the decentralised form of hydrogen production for fuel cell vehicles. This process is represented in Figure 5. The centralised process is a large-scale hydrogen production operation that produces hydrogen on-site and requires hydrogen transportation and distribution.

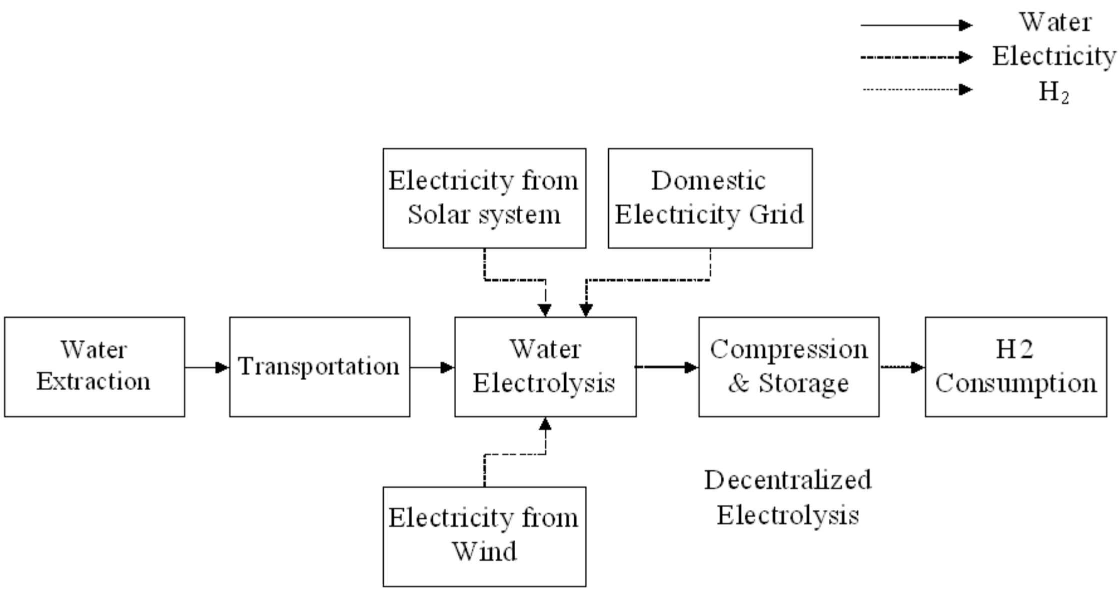

Figure 5. Hydrogen production process via water electrolysis, representing decentralized form of hydrogen refuelling station.

4. Results and Discussion

4.1. Hydrogen Production and Storage Life Cycle Costs

The outcome of the life cycle model presents a minimum rate of return of investment. Table 4 shows that centralized methane reforming achieved the lowest hydrogen costs through the life cycle span (0.90 USD/kg). The most expensive process on the life cycle analysis for hydrogen production and storage was found to be the decentralized electrolysis with a value of 4.30 USD/kg. The major cost parameters contributing to the life cycle results are: the feed cost, the cost for raw materials and the capital costs. Figure 6 presents the contribution of the cost parameters individually to the hydrogen cost for each production method analysed. It can be extracted that the feed cost for the centralised methane reforming, the centralised electrolysis and the decentralised electrolysis has the lions share in the total cost of hydrogen production. For the case of decentralised methane hydrogen production, the capital costs, the fixed operating costs, the feed cost and the raw material cost are almost equally contributing to the final cost of hydrogen. Finally, for the decentralised electrolysis, besides the contribution of the feed cost, the capital cost and the raw material cost also affect the hydrogen cost.

Table 4. Life cycle costs of hydrogen production and storage, minimum rate of return of investment.

Hydrogen Alternative	Life Cycle Cost of Generation and Storage (USD/kg)
Centralized methane reforming	0.90
Decentralized methane reforming	3.83
Centralized electrolysis	2.92
Decentralized electrolysis	4.30

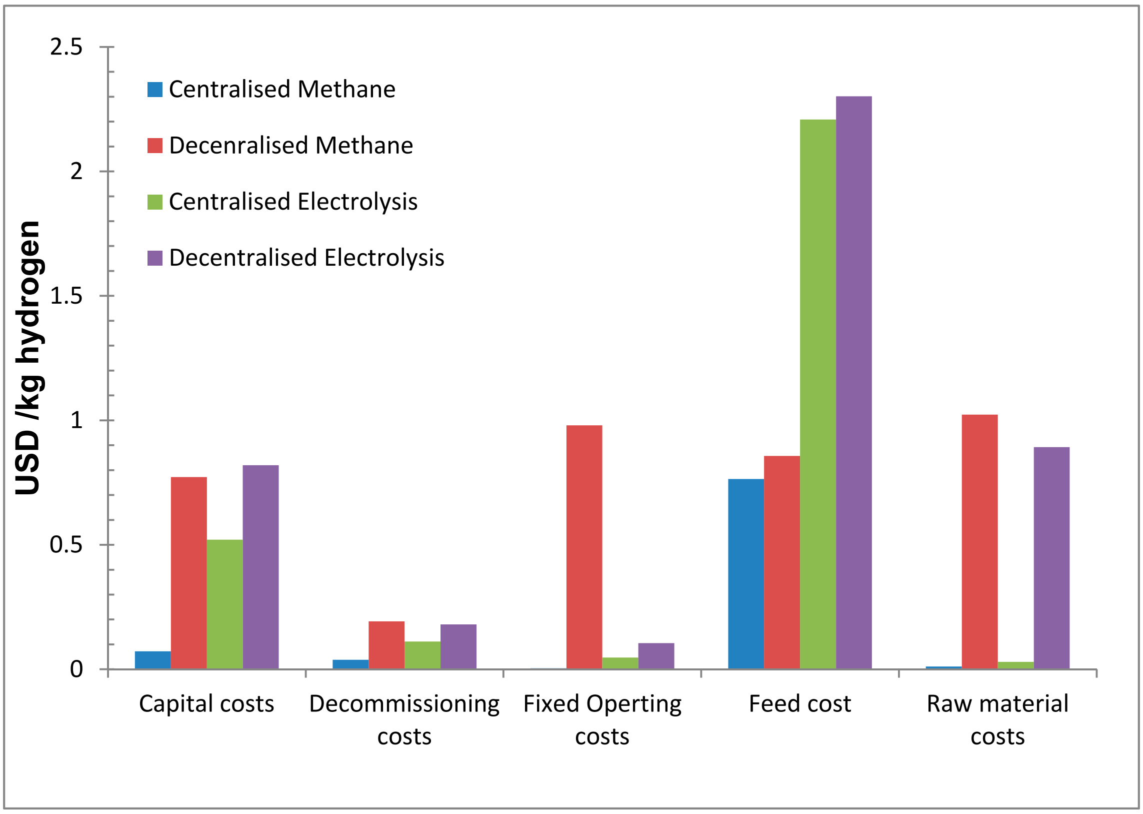

Figure 6. Hydrogen cost contribution for each hydrogen production life cycle.

4.2. Life Cycle Cost for Hydrogen Transportation and Dispensing

Hydrogen is produced in centralised forms and usually transported to the application area immediately. The life cycle model for the hydrogen transportation and dispensing applied for both the cases of centralised methane reforming and centralised electrolysis showed that the case of centralised methane reforming had lower minimum rate of return of investment compared to the case of centralised electrolysis production as presented in Table 5. The cost for the hydrogen transportation and dispensing depends on the capacity and demand of the produced hydrogen. The hydrogen cost contribution for the transportation and dispensing for the centralised methane and centralised electrolysis production is presented in Figure 7. The major cost contributor in the hydrogen transportation model is the cost of the fuel required for the transportation, where for both the examined cases the contribution is equivalent. For the case of the centralised electrolysis, the capital costs and the raw material cost are also contributing towards the final cost. The life cycle cost resulted from electrolysis resulted in the highest cost as the transportation of hydrogen produced from the electrolysis method depends on the size and capacity of the centralized electrolysis plant, which is normally smaller in production capacity compared to the centralised methane steam reforming. In addition, the dispensing cost of high-pressure hydrogen gas for the methane reforming production contributed towards lowering the cost of energy required for dispensing process compared to the case of hydrogen production via centralised electrolysis. Thus, the compression and dispensing cost for high pressure and large hydrogen production capacity is economically more viable compared to a low pressure/or low hydrogen production capacity.

Table 5. Life Cycle Costs of Hydrogen Transportation.

Hydrogen Alternative	Life Cycle Cost of Transportation and (USD/kg)
Centralized methane reforming	0.41
Centralized electrolysis	0.92

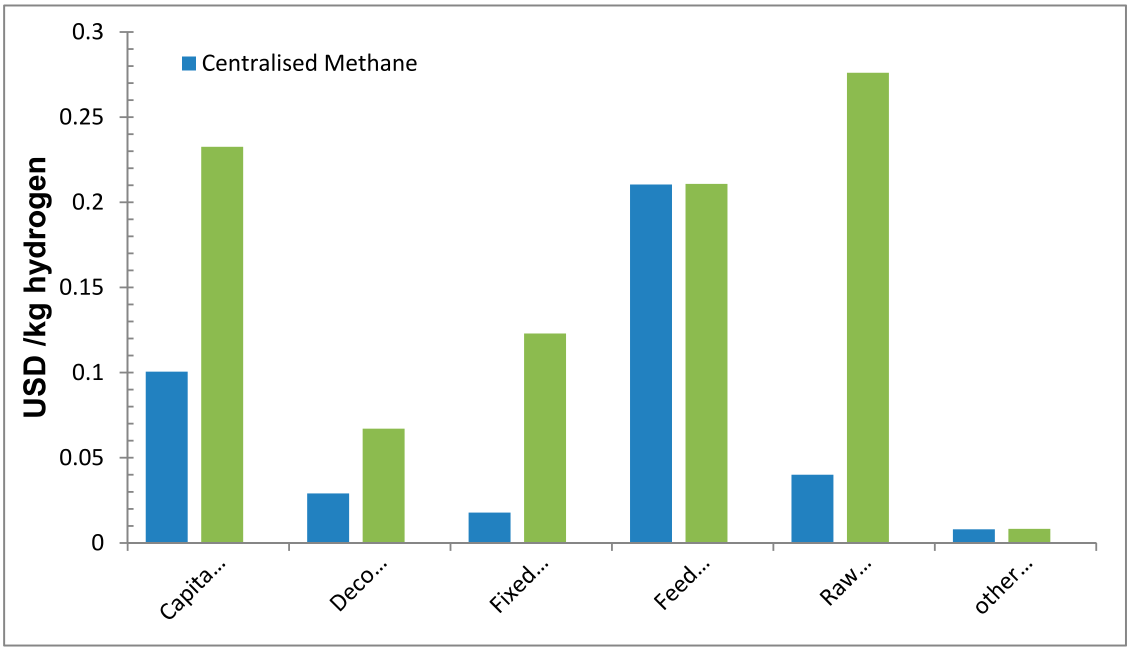

Figure 7. Hydrogen cost contribution for hydrogen transportation and dispensing life cycle.

4.3. Hydrogen Application Life Cycle Costs

The produced hydrogen can be used as fuel to feed Fuel Cell Vehicles (FCVs). The cost of hydrogen from the previous life cycle analysis is used to identify and evaluate the total entire usage cost of hydrogen in FCVs during the life span. The investment cost of FCVs is the main cost contributor for hydrogen life cycle applications. The capital investment showed 77% of the total life cycle cost of the applications, 19% was for hydrogen as fuel cost and 4% for fuel cell vehicle maintenance.

4.4. Sensitivity Analysis

The uncertainty of data cannot be eliminated. Uncertainty refers to the costs at which the probability of occurrence is unknown. Sensitivity analysis is the most used technique to deal with uncertainty. The approach is to find and identify the critical assumptions that can affect the cash flow analysis. The purpose of this analysis is to study high costs data items that may affect the future cost. The 10–20% of changing the cost will identify 60–80% of the total cost. A sensitivity analysis was applied for the hydrogen production process and it was majorly focused on the capacity factor of production, the feedstock cost and the capital cost changes. For hydrogen mobility applications, the contribution of the capital cost was compared. For the analysis of the hydrogen transportation and dispensing, there was a drawback regarding the availability of data for the simple case introduced; thus, further investigation is required for future forecasting analysis.

In general, hydrogen production cost was found to be affected from the capacity factor as shown in Figure 8a. For the case of centralised methane reforming was the effect of the capacity factor is almost negligible, as the designed production plant is compatible for high demand requirements. For the cases of centralised/decentralised electrolysis and the decentralised methane reforming, the shape of the hydrogen nominal cost when the capacity factor increases is almost hyperbolic and tends to reach the minimum cost at the maximum capacity factor.

The effect of increasing the feedstock costs showed that hydrogen production via electrolysis was very sensitive compared to the methane source, as the slope for both the centralised and decentralised cases was found to be larger compared the methane steam reforming cases, as presented in Figure 8b. The cost of electricity used for electrolysis is dependent on the grid supply, which is directly connected to the fossil fuel cost. It was difficult to predict the electricity generation cost from renewable sources, and the present model assumed the contribution of fossil fuel-based electricity sources only. In addition, the water price is increasing, which adds further higher cost into the vehicle cost price electrolysis hydrogen production route.

For the case of hydrogen fuel cell vehicle usage, the cost of the vehicle is the main issue for the current technology. Figure 8c presents the effect of the vehicle cost reduction on the present value of hydrogen application. The fuel cell vehicle cost should be reduced. In the current study, the cost of the vehicle is reduced up to 60%. The reflection of this into total life cycle cost was 57% for capital cost and 35% for hydrogen fuel cost. This indicates that even with a high reduction in the cost of FCVs, the total cost of using such technology today will remain relatively high. For the entire life span, the fuel cost is a good option if it is compared with internal combustion engine cars.

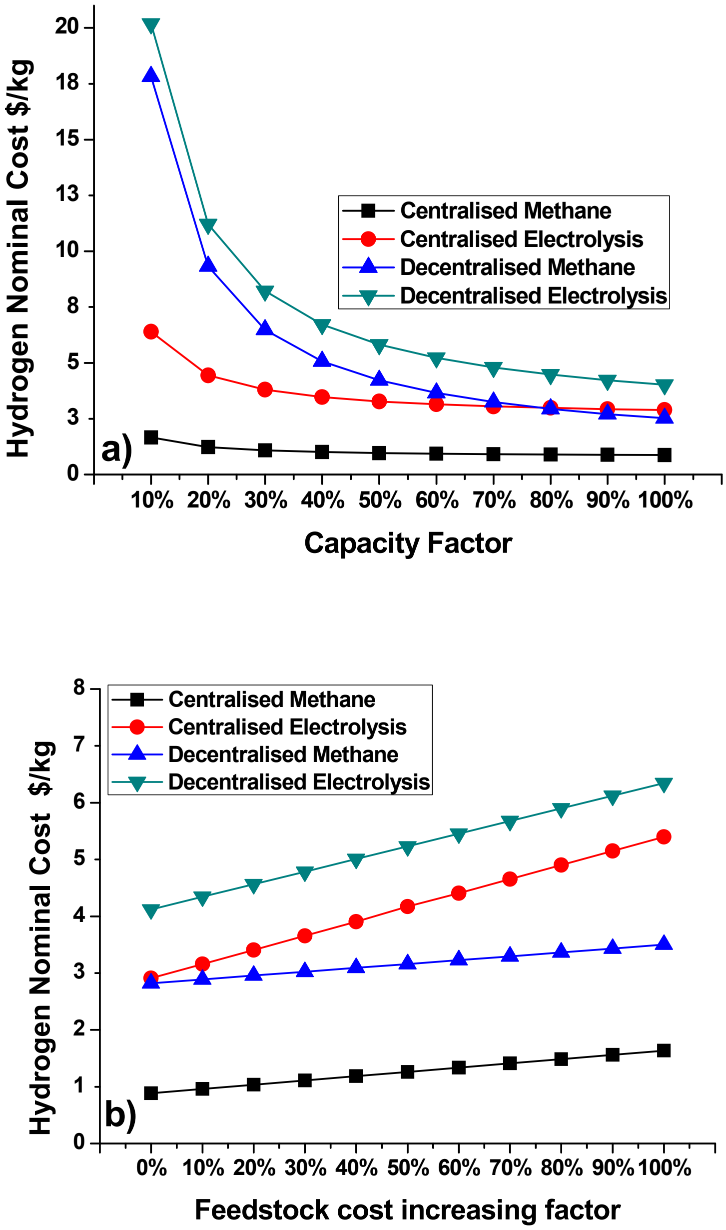

Figure 8. *Cont.*

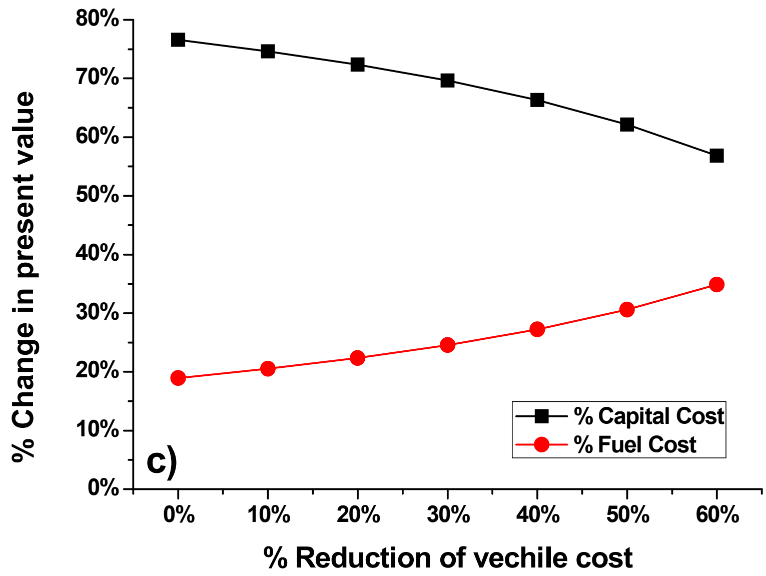

Figure 8. Effect of increasing the capacity factor for hydrogen production to the hydrogen production life cycle cost (**a**), effect of increasing the feedstock cost to the hydrogen production life cycle cost (**b**) and effect of the vehicle cost reduction on the present value of hydrogen application (**c**).

5. Conclusions

The cost estimation of hydrogen technology is essential for the acceptance of a future Hydrogen Economy, especially in the transportation sector. The main objective of this study was the definition and adoption of the life cycle costing method regarding hydrogen production for hydrogen utilization in fuel cell vehicles. The simulation results of the hydrogen production and storage showed that the hydrogen production via centralised methane steam reforming is the most economically feasible alternative amongst the rest production routes at current study. Further investigation on the hydrogen transportation and dispensing model has been performed and the outcomes showed that the centralised production via methane reforming is still the most prominent alternative compared to the other decentralized production methods. The FCV cost is a drawback for adapting this technology in the near future, due to the high cost of vehicle. Sensitivity analysis investigated the effect of changes of capacity factor and feedstock cost in hydrogen price where the effect of changes was obvious for hydrogen production via electrolysis. The challenges for hydrogen costing analysis—such as changes in technology, changes in renewable energy acceptance, and changes in material costs—can be added into the costing framework to increase the forecasting reliability of hydrogen. The framework costing structure for hydrogen production and data analysis suggested at current work can be used for stationary applications.

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Conflicts of Interest: The authors declare no conflict of interest.

Appendix A

Table A1. Hydrogen production and storage input data.

Data	Centralised Methane Reforming	Decentralised Methane Reforming	Centralised Electrolysis	Decentralised Electrolysis	Units
Number of Hydrogen Units (Assumed)	1	2	1	1	
Plant Design Capacity (Typical available plant)	380,000	1500	52,300	1500	kg/day
Capacity Factor (assumed)	90%	85%	95%	95%	
Efficiency of the Process [44]	80%	75%	75%	70%	
Hydrogen Storage Pressure (Typical available storage system)	70	35	70	35	MPa
Hydrogen Storage Capacity [45]	98,589	49,294	49,294	49,294	kg
Hydrogen Compressor Power [45]	74,472	64,223	74,472	64223	kWe
Plant Capital Cost, corrected to year 2018 based on reference [44]	52,673,000	640,000	29,234,000	840,000	USD
Indirect Depreciable Costs (calculated)	7,374,220	70,400	2,923,400	92,400	USD
Non Depreciable Costs (calculated)	50,000	25,000	50,000	25,000	USD
Installation Costs [46], (Forecasted to 2018)	21,069,200	64,000	5,846,800	84,000	USD
Feedstock Usage Calculated (Lower Heating Value of Hydrogen % Lower Heating Value of Feedstock) % Conversion Efficiency Price of electricity (0.05370 USD/kWh)	4.1 ($Nm^3/kg\ H_2$)	4.4 ($Nm^3/kg\ H_2$)	44.5 ($kWh/kg\ H_2$)	47.7 ($kWh/kg\ H_2$)	
Raw materials Usage Water consumed for process production,	12.5	16.3	11.0	11.0	$l/kg\ H_2$
Labour Costs (assumed for typical industry)	25,000	10,000	25,000	10,000	USD

Table A2. Cash flow input data and duration period.

Timeline of Alternative	Centralized	Decentralized
Cash flow year	2018	2018
Start of Construction	2025	2025
Start of Operation	2027	2026
End of Operation	2066	2045
Study Period	40	20
Planned Replacement Period	10	10
Construction Period	2	1
Plant Operation	40	20

Table A3. Economic data for performing cash flow study.

Economic Data	Centralized Methane	Centralized Electrolysis	Decentralized Methane	Decentralized Electrolysis
After-Tax Real IRR	10.0%	10.0%	10.0%	10.0%
Inflation Rate	3.9%	3.9%	3.9%	3.9%
Depreciation Length	40	40	20	20
Tax Rate	15%	15%	15%	15%
Working Capital (% Operating Cost)	15%	15%	15%	15%
Salvage Value (% Total Capital Investment)	10%	10%	10%	10%
% of Capital Investment During Construction year 1	40%	25%	100%	100%
% of Capital Investment During Construction year 2	60%	75%	0%	0%
% Fixed Operating Costs at Start up	100%	100%	100%	100%
% Revenue at Start up	50%	50%	100%	100%
% Variable operating Costs at start up	75%	75%	50%	50%
Decommissioning Costs	10%	10%	10%	10%

Table A4. Hydrogen Transportation Main Data *.

Data	Value	Unit
Capacity of vehicle	920	kg
Transport distance	300	km
Average speed of vehicle	80	km/h
Vehicle average consumption	0.094	L/km
Loading time	4	h

Based on available compressed hydrogen transport.

Table A5. Hydrogen Dispensing Main Data [45].

Hydrogen Dispensing	Value	Unit
Hydrogen Dispensing Pressure	40	Mpa
Hydrogen Dispensing Capacity	73,941	kg
Hydrogen Dispensing Compressor Power	66,145	kWe

Table A6. Fuel Cell Vehicle Data *.

FCV Data	Value
Fuel Tank	USD 975
Electric Motor	USD 1560
Inverter	USD 250
Battery	USD 3000
Fuel cell system	USD 15,985
Vehicle body	USD 2600
Other BOP materials Costs	USD 14,700
Average distance travelled	25,000 km/year
Mileage of FCV	300 km
Consumption for distance travelled	3 kg H_2

Based on available technical data and forecasted data for FCV.

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