HYDROGEN AS A GREEN SECONDARY ENERGY SOURCE FOR FUEL CELL SYSTEMS

- AN ENVIRONMENTAL AND BUSINESS VIEW –

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Abstract

Hydrogen as a green secondary of energy is one of the most promising solutions for our future energy supply. Hydrogen can be ideally used as a link between the energy sectors of electricity, heat and mobility and reduces the use of fossil energy sources in present. Green hydrogen production will fundamentally change our energy economy.

Fuel cells as an energy conversion system with Hydrogen increase the overall efficiency, reducing greenhouse gas emissions and the dependencies of fossil energy sources.

This article shows the context between the primary energy sources and fuel cell applications. The efficiency chain and the environment dependencies are explained unequivocally. The aim of the scientific paper is to show the possible consequences of environmental impacts using hydrogen as an energy source in hydrogen business applications.

Methodologically the proposed model is used on two case studies, to determine greenhouse gas emissions to reveal the different dependency of fuel and application. The latest data´s of hydrogen production and fuel cell applications are implemented in the model.

The results of the research show the crucial aspects to use hydrogen as a secondary energy carrier in two case studies. The results can help all groups and institutions that want to deal with hydrogen and their energy conversion processes to get a better understanding from an environmental and technical view.

Keywords: Green Hydrogen, Fuel Cells, Fuel Cell Vehicles, Fuel Cell heating Systems, Environmental Impact.

Introduction

Today's energy conversion processes with fossil fuels substantially contribute to global warming and climate changes. [IPCC 2018, IPCC 2014, Le Quere 2014, Schönwiese 2019, Hutter 2018]. The daily flow of crude oil is over 92 million barrels [ENI 2018, IEA 2018]. Reducing man-made anthropogenic greenhouse gases by burning fossil fuels requires new ideas and concepts for energy conversion systems.

In order to achieve the global climate targets, which were agreed in Paris [UN 2015], rapid action is required to reach the 2°C scenario [Hansen 2015, Crastan 2015, Peterson 2015] keeping the warming process in human hands [Nerem 2018, Lüdtke 2018, Ibisch 2018]

On solution is using H2 as a secondary energy source produced out of a renewable energy source (green H2) for the energy supply [Emonts 2018, Machhammer 2015, Tetzlaff 2011, Quaschning 2016, Quaschning 2013, Stern 2018, Töpler 2012]. Sustainable green hydrogen production could be a future strategy for a new hydrogen economy. Decentralized highly efficient and smart grid compatible energy conversion systems driven with locally produced hydrogen can be one key energy strategy in the future. Producing energy where is it needed in small and very highly efficient energy conversion systems [Staiger 2016a, 2016b, 2017]
There are different definitions and views how hydrogen economic could work. The indicator of a true hydrogen economy is to supply the end user with hydrogen. The latest energy conversion to power and heat takes place with the end user.

This has the following advantages:

- Cogeneration in each building (CHP) with highly efficient fuel cell systems,
- Excess electricity in every building (enabling cheap electric heater),
- Mobility with Hydrogen cars (fuel cell driven) or electrical vehicle's,
- Cost distribution of electricity and heat through a pipe network.

Stationary and mobile application with fuel cells as an energy conversion system, driven with H2 fuel produced out of renewable sources will help moving in a sustainable energy future [Emonts 2018, Fang 2015, Staiger 2018]

Scientific aspects

Transforming Process for producing green H2

To analyze and understanding how energy is converted the different energy sources like primary, secondary, final and usable energy terms must be defined [Baehr 2006, Fritsche 2015, Quaschning 2016]. The naturally occurring energy sources defined as primary energy sources. This is divided into renewable (inexhaustible) and non-renewable (exhaustible) energy sources.

The dilemma with nearly all energy sources is conversion loses from one energy type in another [Baehr 2006, Kramer 2014, Allelein 2013, Quaschning 2016,]. Table 1 shows the efficiency of different energy conversion systems.

Table 1. Efficiency of energy conversion systems [Baehr 2006, Kramer 2014,Quaschning 2016]

Energy conversion systems	**Efficiency**
Geothermal power plant	10%
Parabolic trough power plant	15%
Solar cell	15%
Fuel cells (electricity + heat)	80-95%
Wind generators	45%
Nuclear power	30-40%
Coal generators	30-40%
Solar panels	70%
Combined cycle power generator	60%
Wood gas power plant	80%
Hydro generators	80%
CHP Combined heat and power	90%

Table 1 shows different power plant types and their current efficiencies.

Table 2. Efficiency of different hydrogen processes [Baehr 2006, Kramer 2014, Quaschning 2016]

Processes	**Efficiency %**	**Trend %**
Primary energy oil, petrol	82 %	equal
Primary energy oil, diesel	90 %	equal
Generation electricity from coal generator	30 - 40 %	
Generation electricity from a gas generator	50 %	*higher*
Distribution losses over powerlines and	96 %	higher

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transformer		
H_2-Production		
Electrolysis Alkaline	70 – 80%	80 -90 %
Electrolysis High temperature	80 %	90%
Reformer (CH_4)	80 %	90 %
Steam Reformer	80 %	90 %
Biogas Steam Reformer	80 %	90 %
compressed Hydrogen	90 %	90 %
Liquid Hydrogen	70 %	80 %
Applications		
FCEV (Input to Wheel)	50 %	55 %
BEV (Input to Wheel)	70 – 75%	80 %
Petrol/Diesel car (Input to Wheel)	16- 24 %	same
Hybrid vehicles (ICE internal combustion engine)	20 – 25%	25 %
Fuel Cell (55 % electrical/45 % thermal)	80- 90 %	95 %
Micro CHP	80 – 95%	95 %

Table 2 shows the different necessary processes and their efficiencies for the production of hydrogen. Furthermore, a column of the table it is illustrated the trend of the possible efficiencies in an optimistic scenario.

Different ways for producing hydrogen today are presented in table 3 [Machhammer 2015, Fang 2017, Dincer 2016]. Today's hydrogen production is mostly done through fossil energy sources in the chemical industry so called grey hydrogen [Godula 2015, Tezlaff 2011, Ayers 2017].

Table 3. Today's H_2 production with fossil energy sources

Process	**Fuel type**	**efficiency**	**CO_2 impact**

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Thermal reformer	CH_4	< 80 %	Huge impact
Patrial oxidation	Fossil	< 80 %	Huge impact
Kvaerner process	Fossil	< 95 %	Little impact
Electrolysis fossil	Fossil	< 80 %	Huge impact
Steam reformer	Biomasse	< 80 %	Carbon neutral
Electrolysis	PV/Wind/Wasserkr aft	< 80 %	No impact

Fuel Cell applications, efficiency and environmental impact

Fuel cell is a device for converting chemical energy in electricity and heat (cold burning process) with an efficiency of over 80 to 90% [Vielstich 2003, Niederhausen 2014, Blomen 1993, Kurzweil 2013, Barbir 2011].

Chemical Principle of a polymer Electrolytic FC (PEM)

The entire chemical reaction in PEM fuel cells can be described by the equation:

$$\rightarrow \quad 2H_{2\,(gas)} + O_{2\,(gas)} \rightarrow 2H_2O_{\,(liquid)} \quad [1]$$

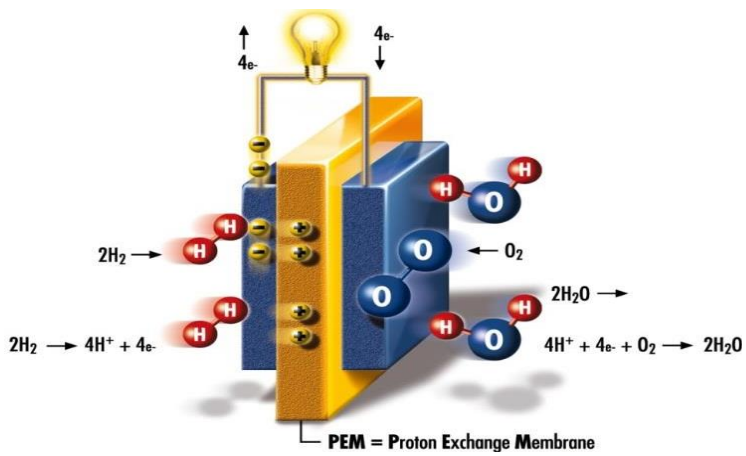

Figure 1. PEM Fuel Cell chemical reaction [H-Tec 2016]

Fuel Cell Types

Depending of the different applications, different fuel cell types are available today on the market.

***Table 4**. FC types, specification and applications [Kurzweil 2013, Barbir 2011, Töpler 2014, Staiger 2016]*

Type	***Fuel Type***	***Operation Temp °C***	***Elect. Efficiency %***	***Energy density W/cm²***	***Applications***
AFC Alkaline FC	H_2	60-80°C	60%		Space program, Military (submarines)
PEFC Proton Exchange	CH_3OH Methanol	80°C	40-50%		Power supplies, Car/Bus, Home heating, CHP, USV up to 250kW
DMFC Direct Methanol	H_2	80-100°C	40-50%	0,6 W/m²	Development phase
PAFC Phosphoric Acid	H_2	200°C	40-45%	0,2 W/m²	CHP´s, Power generators > MW
MCFC Molten Carbonate FC	H_2 (CH_4) Biogas	650°C	55-60%	0,1 W/m²	CHP´s, Power generators > MW
SOFC Solid FC	H_2 (CH_4)	800-1000°C	60%	0,4 W/m²	Home heating, power generators

The common fuel cell will be the PEM Type. For lager CHP the PAFC and MCFC types. For mobile and stationary application, the PEM type is in common.

The environmental impact using H_2 with fuel cell systems

Hydrogen is the first element of the periodic table of the elements. Hydrogen usually occurs under ambient conditions to a molecule consisting of two hydrogen atoms (H_2). The most common element in the universe, represents about 90% of all atoms, approximately ¾ of the total mass. Atomic hydrogen reacts with organic compounds (Carbone element C) to form complex

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mixtures of different products. As an example: Methane CH_4, Petrol C_6 H_{12}. In nearly all organic compounds, H_2 is integrated (decarburization) [Riedel 2015].

Chemical basics and CO_2 emissions

The stoichiometry is based on the conservation of mass: The mass of the starting materials is equal to the mass of the reaction products. This may be determined as the amount of CO2, which is produced during the combustion of various fuels [Riedel 2015, Schwarzbach 2010]

Table 5. *Chemical equations*

	Chemical Elements		***Chemical Elements***		***Reaction Product***	***ΔHR***
Hydrogen combustion (chemical reaction of a Fuel Cell)						
Elements	2 H_2	+	O_2	→	2 H_2O	-572 kJ/mol
Molecular Mass	2* (2*1)	+	1* (2*16)	→	2* (2*1+16)	
Mass equation	4	+	32	→	36	
Mass per g	1	+	8	→	9	
chemical equation for reforming process (fuel cell heating systems)						
Elements	CH_4	+	$2H_2O$	→	$4H_2$ +CO_2	165 KJ/mol
Molecular Mass g/Mol	12+(4*1)		2(2*1+16)		4(2*1)+12+2* 16)	
Mass equation	16		36		8+44	
Mass per g	1		2,25		0,5 + 2,75	
carbon combustion						
Elements	C	+	O_2		CO_2	-393 kJ/mol
Molecular mass	12		16*2		12 + 2*16	
Mass Equitation	12		32		44	
Mass per g	1g		2,66		3,66	

In the table 5 are presented different chemical reactions of hydrogen conversion with individual masses and energy quantities are shown [Riedel 2015, Schwarzbach 2010, own contribution].

Methodology

For the environmental energy conversion model with hydrogen (Figure 2), following parameters for calculation purpose and comparisons are essential for the process: Efficiency of the primary energy conversion, Type of primary energy sources and Type of fuel cell application with efficiency parameter.

The input data´s are from official studies, research and latest scientific publication. An identical reference model for fossil energy sources compares (mirrored) the data with the hydrogen model. An assessment is made with the data and shown in an evaluation table.

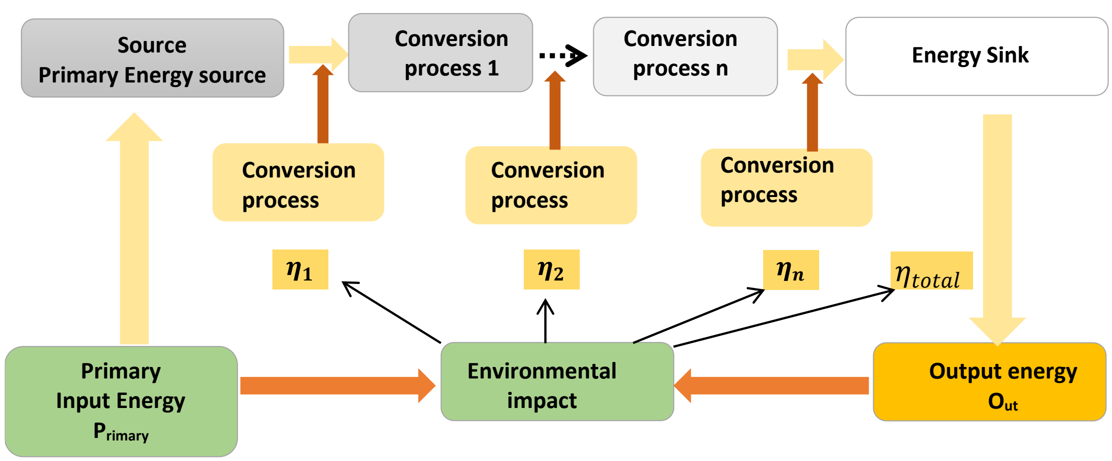

Figure 2. Environmental Energy Conversion Model (EECM)

Efficiency

$$\eta_{h2} = \frac{\Sigma Q_{out}}{\Sigma Q_{input}} \qquad \eta = \frac{\dot{Q}_{out}}{\dot{Q}_{input}} \qquad [2]$$

Total efficiency

$$\eta_{total} = (\eta_1) * (\eta_2) * (\eta_3) * (\eta_4) * \eta_{sink} \qquad [3]$$

$$\eta_{total} = \frac{Q_{out}}{Q_{primary}} \qquad [4]$$

Total Environmental Impact (TEI)

$$TEI = Q_{primary} * CO2cf \qquad [5]$$

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PEF = *Primary Energy Factor*

$CO2cf$ = *CO2 conversion factor [KEA 2015, IINAS 2015]*

TEI = *Total Environmental Impact*

Research Analysis and Results

The research results are compared for a mobile and for a stationary system.

Stationary Systems: Fuel Cell Heating Systems (FCH)

Alternative heating appliances with an integrated chemical energy converter" (Fuel Cell, Cold burning process) which operates with H_2 is far more efficient as a fossil driven Carnot cycle system [Staiger 2016a]. The FCH System produces thermal and electrical energy like in a conventional CHP System. Today's FCH Systems are using fossil gas for operation. To operate the FC, H_2 is necessary. For this reason, a reformer is used to generate the H_2 part out of a fossil fuel like CH_4. Today's FCH systems are not powerful enough to cover the thermal energy demand in standard buildings. For these reasons on top of the FCH System a condensing gas boiler is integrated [Staiger 2017]. The exhaust of Fuel Cells is pure water but over the reformer and condensing gas boiler it will pollute similar emission like on condensing gas boiler.

Reforming Process and Environmental impact today

The amount of CO_2 of the reforming process (see above) can be calculated with the chemical stoichiometry. *Molecular mass is*: Methane = 16g, Carbon Dioxide = 44g, Water 18g, Hydrogen =1g [periodic] Molecular mass equation:

$$16g + 36g = 8g + 44g \rightarrow 1kg\ H_2 \rightarrow 5.5kg\ CO_2$$

With the energy contents of 33.33 kWh/kg H_2 → ***CO_2 equivalent*** → ***166 g CO_2 /kWh***

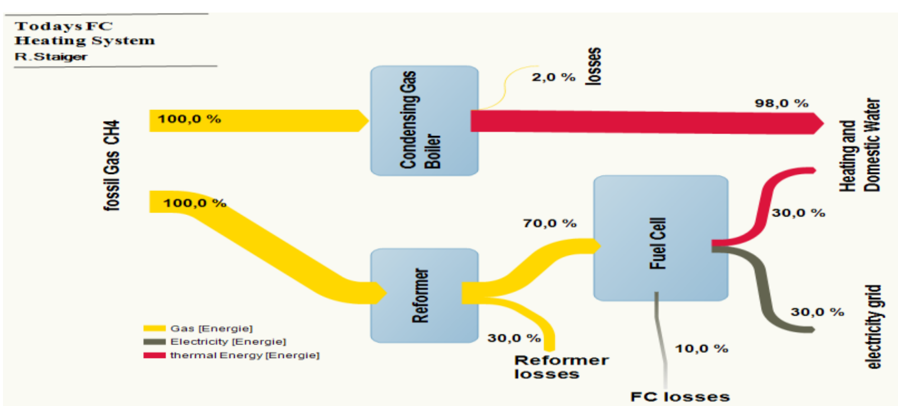

Figure 3. *Efficiency of fuel cell heating systems today (Staiger 2016a)*

Mobile Systems

Batterie electrical Vehicles

Electrical cars in compare to conventional cars with a combustion engine having huge advantages. A normal combustion engine car has efficiency (tank to wheel) of less than 25 %. [Schreiner 2015, Cornel 2015, Tschöke 2015]. Electrical cars in compare have an efficiency of ca. 70-80 %. The amount of fuel with an electrical car is less the 70 % of a combustion engine car. The problem in present is the battery system and the maximum driving distance as well the investment cost and the possible payback time [Grube 2018]. Figure 4 shows the flow of efficiency of a present electrical vehicle.

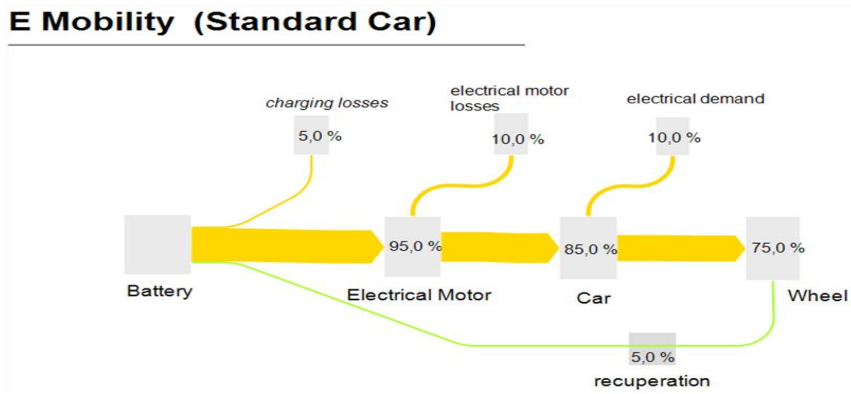

***Figure 4**. Efficiency of an e mobility car with batteries (own contribution)*

Fuel Cell cars

The principal of a fuel cell car is similar like an electrical vehicle. Instead of a battery a tank with hydrogen provide the energy for the car. The efficiency (tank to wheel) is less than an electrical car because of the energy losses of the fuel cell. In compare to an electrical vehicle the efficiency is ca. 45-50 % [Cornel 2015, Tschöke 2015]. Depending of the hydrogen fuel more or less emissions will be generated. Figure 5 shows the principal of a fuel cell car.

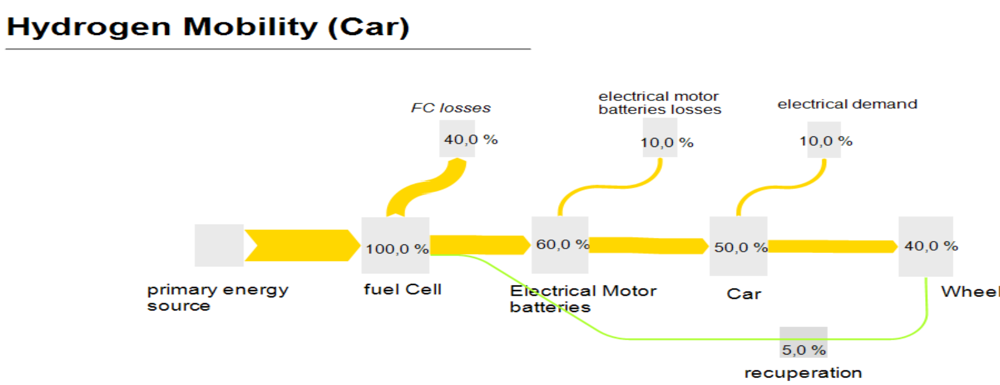

***Figure 5.** Efficiency of fuel cell hydrogen car (own contribution)*

For this research work, two case studies are taken that will make an important contribution to the energy transition in the future. An example in the mobility sector is fuel cell vehicles and electric vehicles. In the stationary area micro combined heat and power plants or fuel cell heating systems in compare a conventional gasification oiler with standard electricity from the grid.

Environmental chain for fuel cell heating systems and for mobility application

Table 6. *Energy Chain from Well to Wheel as an example for different fuel types*

Type	Fuel type	Chain 1 Car %	Chain 2 %	Chain 3 %	Chain 4 %	Chain 5 %	Total %
Car petrol	Petrol	20 %				80 %	16 %
Car with batteries	Fossil Coal	75 %			35 %	80 %	21 %
Car with batteries	PV	75 %			15 %		11 %
Car with fuel cell	Fossil	50 %	90 % compression	80 % electrolysis	35 %	80 %	10 %
Car with fuel cell	PV	50 %	90 % Compression.	80 % electrolysis	15 %		5,5 %

Table 6 shows the different efficiency chains for the following calculations. These are the basics for case studies calculations.

Chain 1 is the efficiency of the technical appliance for example car or fuel cell heating system. Chain 2 and 3 are special processes for compressing hydrogen on high pressure and producing hydrogen with electrolysis from water. Chain 4 is the efficiency of the power generator (for example coal, gas or renewable energy source). Chain 5 are the distribution losses over high power lines and transformers in the energy infrastructure. Chain Well to Wheel: the total chain from production to the energy output on the wheels

Short form:

Chain 1 = Efficiency appliances (car), Chain 2 = H_2 compression 700 bar, Chain 3 = electrolysis, Chain 4 = energy conversion electricity (generators, distribution loses), Chain 5= primary energy factor 1,2

Case Study 1: Mobility application petrol car with 50 kW power as a reference

For this example, the car needs 15 kWh energy for 100 km (ca. 8 l/100km). This would be a normal middle-class Car.

Chain Well to Tank → Taking into account losses in production, refining, exploration, drilling and transportation / delivery of fossil fuels (well-to-tank) here factor 1,2.

Table 7. *Energy Chain from Well to Wheel as an example for different fuel types range 100 km*

Application	CO_2 impact kg/kWh	Energy amount on the wheel	Total efficiency	Total primary energy	CO_2 kg Primary Energy	CO_2 gr per km
Reference system						
Car with Petrol	0,287	15 kWh	16 %	93 kWh	26 kg	260 gr
Alternatives						
Car with batteries Coal	0,7	15 kWh	21 %	71 kWh	49 kg	490 gr
Car with batteries PV	0,01	15 kWh	11 %	125 kWh	1,25 kg	12 gr
Car with fuel cell fossil	0,57	15 kWh	10 %	150 kWh	85 kg	850 gr
Car with fuel cell PV	0,01	15 kWh	5,5 %	272 kWh	2,7 kg	27 gr

The result of the analysis in table 7 shows, electrical cars with batteries charging with a renewable energy source (PV) have the best environmental impact. Fuel cell driven cars with H_2 produced out of a fossil energy source (electrolysis with standard electricity) has the worst environmental impact. If H_2 would be produced out of a renewable source like PV, Wind, or Hydro the environmental impact would be 30 times less then produced out of a fossil energy source.

Case Study 2: Fuel cell heating system with 12kW power reference condensing gas boiler

For this case study following parameter are used for the Fuel Cell heating applications.

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Table 9. *Parameter for Fuel Cell Heating application*

Parameters	Data
Output Power of the Heat appliances P (a×b)	12 kW
Thermal energy demand/a Qout (c×d)	20.000 kWh/a
Electricity demand (3-4 people)	4.000 kWh
Location	Germany

Table 10. *CO_2 Impact Primary Energy usage*

Type	Efficiency unit	Efficiency chain 2-5	Total unit energy kW	Total Primary energy kW/a	CO2 equiv. $kgCO_2/kW$	CO_2 kg/a
Reference System						
gas	0,98	80 %	20.400	25.500	0,24	6.120
electricity		35 %	4.000	11.428	0,56	6.400
Total CO_2 emission /a						***12.520***
Fuel Cell Heating System with fossil gas						
FCH with fossil gas 1 kw el. 0.8 kw thermal	0,70	80 %	28.570	35.700	0,24	8.568
	45% el.	100 %	4.000			
	35% th.		3.200 Rest gas 19.022			
Total CO2 emission /a						***8.568***
Fuel Cell Heating System with H_2 produced from fossil gas						
FCH with fossil H_2 1 kw el. 0.8 kw thermal	0,9	50 %	22.222	44.000	0,24	10.580
	45% el.		4.000			
	35% th.		3.200 Rest gas 19.022			

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Total CO2 emission /a						***10.580***
Fuel Cell Heating System with H_2 produced from renewable source PV						
FCH with PV H_2 1 kw el. 0.8 kw thermal	0,90	10 %	22.222	222.222	0,01	2.222
	45% el.		4.000			
	35% th.		3.200 Rest gas 19.022			
Total CO2 emission /a						***2.222***

The result of the analysis which are presented in table 10 shows, that conventional condensing gas boiler and electricity from the grid has the worst environmental impact. The reason is the bad efficiency of the production of electricity. The generated electricity with the Fuel Cell heating system should be compared with the standard electrical generation CO_2 equivalent factor and subtracted from the energy amount on Gas. In the Micro CHP´s the efficiency chain is far better for producing electricity. Ideal situation would be a H_2 driven FCH System where H_2 is produced out of a renewable energy source like PV, Wind or Hydro.

Conclusion

The research shows that hydrogen as a secondary energy fuel has a huge impact, under which conditions hydrogen will be produced and processed.

Hydrogen as a secondary energy carrier can be an ideal energy source and a substitution for conventional fossil energy sources.

It will reduce the environmental impact and will decarbonize the present energy structure. Another important point is the storability of hydrogen gas and using this in decentralized highly sophisticated energy systems like in the mobility or stationary product area. Through this energy generating the cost will be less and less transmission losses will occur.

The research shows that hydrogen must be produced out of a renewable primary energy source. Fuel cells will be a key technology in the transformation of hydrogen to other forms of energy. In compare to existing conversion processes (Carnot Cycle) fuel cells are far more efficient.

Energy conversion should be designed in decentralized intelligent units. The energy transformation should take place directly at the consumer where the energy is needed. The efficiency of the energy “value chain” plays an important role (renewable energy availability example photovoltaic systems).

In the mobility sector (Cars) the energy source for charging up batteries or producing hydrogen must come from a renewable energy source. Fossil driven sources would make the environmental impact even worse. If you count the number of cars which are available, the environmental impact in a long term is huge.

For stationary system like in our example a Fuel Cell heating System, it would improve also with a fossil energy source the environmental impact. Ideally the fuel should be produced as well out of a renewable energy source.

Outlook

Hydrogen as a green energy source could have a potential for saving greenhouse gases and have more independency from conventional fossil fuel. Hydrogen as a green energy source can change the energy economy in the future.

Future studies could more accurately analyse the levelized cost of energy (LCOE) with the help of renewable energy sources, the investment cost, the total operating cost (TOC) of the appliances, and efficiency of hydrogen-based systems.

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He is a CEO in an engineering office for energy efficiency in Germany. In the last decade, he published several patents in the field of heat pumps/fuel cells. His latest patent submission with in his working company published Dec. 2015, described a special refrigeration control unit, using a fuel cell device. He helps in audit processes for ISO 50001 Energy Management Systems and doing technical plausibility checks for NSAI in Dublin. He works as an assessor, auditor and expert for energy efficiency in small medium size Companies (SME), doing energy calculations for existing and low energy buildings for public and private customer for improving efficiencies, reducing greenhouse gases, saving energy and money.