SUSTAINABLE HYDROGEN FUEL PRODUCTION AT PLANTS OR ON-SITE?
AN ECONOMIC AND ENVIRONMENTAL ANALYSIS

Martin Zsifkovits, Sebastian Zangerl, Kurt Heidenberger
University of Vienna, Faculty of Business, Economics and Statistics
Brünner Straße 72, 1210 Vienna
martin.zsifkovits@univie.ac.at

ABSTRACT
Shortage of oil is imminent in the near future and CO_2-
emissions have to be reduced dramatically in the next
decades to contain global climate warming. A possible
approach to solve these problems is a change in the
mobility sector via the reduction of fossil fueled vehicles.
One of the most promising alternative approaches is
hydrogen technology. Nevertheless, major questions have
to be answered before a hydrogen mobility market can be
established. Here, a major issue is, whether fuel should be
produced in major plants or on-site, directly at filling
stations. In this paper, we try to answer this question
based on a mathematical model that investigates
economic and ecological consequences of both
production modes.

KEY WORDS
Hydrogen; Renewable energy; Plant production; On-Site
Production, Fuel Cell vehicles

1. Introduction
Technical developments and the need for permanent
availability of energy are matters of today's globalized
world. Especially under consideration of the increase of
the global population, the limitation of resources, as well
as problems such as the rising air pollution and
greenhouse gas emissions, long-term strategies regarding
the use of renewable energies are needed [1]. The use of
fossil energy sources leads to emissions of carbon dioxide
(CO_2), and, thereby a too high concentration of CO_2 in
the atmosphere leads to a global climate change [2]. The
atmospheric CO_2-level was rather stable at 280 parts per
million (ppm) for about 10,000 years. This changed after
the year 1750. Currently, the CO_2 level is at 391.07 ppm
as measured on Oktober 1st, 2012 at the Mauna Loa
Observatory, Hawaii [3]. This implies an increase of
about 40% within the last 262 years.

Not only are changes of the global climate, but also
influences on humans health proven consequences of too
high CO_2-emissions [4]. Examples are an increase in
arterial blood pressure and the promotion of insulin
resistance leading to increased risk of future diabetes
mellitus and the metabolic syndrome [5].

Several studies claim that air pollution, and thus the
burning of fossil fuel, have to be decreased dramatically
in the near future. Kemfert claims, that the reduction has
to amount to at least 50% until 2050, to avoid harmful
effects of climate warming [7].

In addition to forecasts for increasing CO_2 concentration
energy supply shortage is a prevailing topic. The world
economy will face shortage of oil in the near future.
According to the International Energy Agency, peak oil
for conventional oil was already reached in 2006 and will
be reached for unconventional oil between 2020 and
2030. Although several studies differ in their detailed
results, all of them show that the supply-side will not be
able to satisfy the global demand for oil in the future.
Particularly emerging economies such as China and India
are facing dramatically growing demands for energy [6].

The transportation and mobility market occupies a rather
big share in the consumption of fossil fuels and also in
growing air pollution. About 60 to 70% of the low level
ozone is a result of fossil fueled traffic [8]. The high
demand for conventional vehicles also brings a high
demand for energy, respectively fossil fuels, with it. To
reduce greenhouse gas emissions a modification in the use
of different energy sources is needed. One promising
technology for the reduction of greenhouse gas emissions
is the use of hydrogen power from sustainable, renewable
energy sources [2].

Due to the high share of the mobility market in overall air
pollution, a change in this segment might be a promising
solution. The only emission hydrogen fueled cars directly
produce is pure water. Nevertheless, hydrogen technology
faces several difficulties in the market entry process. One
of the challenges is the need for efficient production
processes. In this paper we want to investigate, whether
production in central production plants and a subsequent
transportation to refueling stations, or production directly
at hydrogen filling stations should be favored from both,
an economic and ecological perspective. Therefore, we develop a mathematical model to compare both alternatives. The next chapter will give insight into the theoretical model, and in Section 3 we present a numerical example.

2. Mathematical Model

To compare the hydrogen production at a central plant with the on-site production at a hydrogen filling station, a mathematical model was designed. The model is connected to that of Granovskii et al. [9], where the environmental and economic analysis of the hydrogen production was compared based on the energy sources used. The model compares the production of hydrogen via natural gas reforming with the use of two renewable technologies, wind and solar electricity generation, to produce hydrogen via water electrolysis. To compare these different technologies the authors introduced sustainability indexes that are partly used in our model as well. The most important element of this model is that indirect costs and emissions regarding the construction and operation of the manufacturing plants were taken into account [9].

We have integrated this basic idea of comparing different means of production and introduced it into our model to investigate economic and ecological effects of different production methods.

2.1 Model Structure

Our model deals with the question of the optimal location for hydrogen production [10]. The production at a central plant is compared to the on-site production at a hydrogen filling station. Both plants use the electrolysis of water for hydrogen production. The required energy is generated by renewable technologies (wind turbines and photovoltaic panels). Missing capacities for on-site production are compensated for by a local energy provider. The model uses the CO₂-equivalent emission in kilograms per produced kilogram of hydrogen fuel. The production costs are measured in Euro per kilogram of hydrogen fuel (€/kg) as a benchmark. The structure of the used model is illustrated in Figure 1.

Figure 1: Central vs. on-site production
The left side of Figure 1 illustrates the process of central production, while the right side shows the on-site production process of hydrogen. The main difference is the transportation of the produced hydrogen with trucks from the central plant to the fueling station. For the on-site production no transportation is needed.

The model considers economic and environmental parameters. The comparison of these parameters can produce support for the decision of whether hydrogen should be produced at a central plant or on-site at a filling station.

2.1.1 Economic Parameters

For the economic comparison the unit Euro per kilogram of hydrogen fuel (€/kg) is used as a reference size, which shows the relation of one produced kilogram of hydrogen to the overall production costs in Euros. Investments into the production plant are made in \( n=0 \), but are of course split over the overall lifetime of the production plant. For reasons of complexity, probabilistic capacity load is not considered in this context. Thus, the partial annual amount of the onset investments is set into relation with the amount of produced hydrogen together with the annual operating cost and their annual increase.

\[
P_{C_{n,t}} = \frac{l_{LT}}{H2C_t} + \left( OC_n \cdot r^{n-1} \right) \quad (1)
\]

2.1.2 Environmental Parameters

For the environmental analysis two parameters can be compared. The first one is the emission of CO\(_2\) in kilogram per produced kilogram of hydrogen fuel (EHP), which is captured by Formula 2.

\[
E_{H\Pi P} = \frac{\Sigma CO_2}{H2C_t} \quad (2)
\]

Here the sum of CO\(_2\) is the indirect emission related to the production of hydrogen. At the central production plant it also includes the emission of CO\(_2\) that results from the required transportation via trucks. For the on-site production it includes the emissions related to the additional consumed energy from the local provider for the given energy mix.

The second indicator is related to the model of Granovskii et al. \[9\]. The parameter \( \Delta E_{ind} \), which denotes the indirectly used fossil fuel energy is explained by formula 3.

\[
\Delta E_{ind} = \frac{\Sigma EEO + EOP}{LFT} \quad (3)
\]

This indirectly used fossil fuel energy is the fossil fuel energy used in the whole construction process and used materials of an energy production plant. Hence, the energy equivalents of all construction materials and devices together with the fossil energy needed for the installation and operating of a plant are set in relation to the plants’ lifetime \[9\].
2.2 Constraints

The ensuing calculations rely on different side conditions, which are denoted in the upcoming part. Firstly, the demanded quantity of hydrogen fuel at one fueling station per day can be calculated with the product of the average number of refueled vehicles per hour, the daily operating hours of the station and the average hydrogen quantity demanded by every vehicle [11].

\[ HDD = VTH \times OHD \times HQV \quad (4) \]

For the dimensioning of the filling station, we assume out of service security; i.e. that the volume of the stations’ tank (VT) to store the produced or delivered hydrogen should be at least three times the daily demanded quantity \( (VT = HDD \times 3) \).

The amount of energy needed daily for the production of hydrogen fuel is based on the required amount of hydrogen fuel and the total energy needed for production. In the calculations that follow later, we assume the need of 50 kWh for one kilogram of hydrogen fuel, whereby technological developments should be considered in further calculations [12].

\[ EDD = HDD \times E \quad (5) \]

As the production of hydrogen via electrolysis also needs water, the overall required amount of water has to be estimated. Currently, 9.5 liters of water are needed for the production of one kilogram of hydrogen [1].

\[ WDD = HDD \times 9.5 \quad (6) \]

For the central production plant it is also necessary to consider the transportation of the produced hydrogen. Hence, a variable for the distance between the plant and the station (DPS) must be introduced. The distance a truck needs to drive for one delivery (DDT) equals two times DPS. The costs for the transportation per day are the costs for one delivered kilometer times the sum of the delivered distance, including approach and departure.

\[ TCD = DDT \times PDU \quad (7) \]

In the model all annual values are the product of the daily value and 365 days a year.

To get deeper insight into how the model works, we applied a numerical example to find out which production type should be implemented in our sample region. Therefore we calculate the price of one kilogram of hydrogen fuel and the emissions caused in the production and delivery process.

3. Numerical Example

For our numerical example we assume a hydrogen fueling station located near Vienna, Austria. For the given example the following setup parameters where chosen:

- OHD: 16
- VTH: 4
- HQV: 5
- r: 0.02
- E: 50
- LT: 25

According to our assumptions HDD equals to 320 kilograms of hydrogen fuel per day. Therefore the demand per year, HDY, is equal to 116,800 kilograms. Resulting from the daily demand, the capacity of the tank needed at the fueling station is \( VT=960 \) kilograms.

In the next steps, we will analyze the economic and ecological effects of the difference of hydrogen fuel production directly on-site at the station, and at a central plant with subsequent delivery to the fueling station.

3.1 Central Hydrogen Plant

For the central hydrogen production plant we decided to choose an already existing one, so that the used measures and parameters are as realistic as possible. The plant is called “Tauernwindpark” and is located in the Austrian region Oberzeiring, Styria. In the plant there are 11 wind turbines of the type Vestas V 66 (1,750kW each) in operation, as well as a 5 hectare photovoltaic plant (2 MW peak). The capacity of the whole plant equals to 39.5 million kWh per year [13], [14], [15].

According to the assumed need of 50 kWh of electricity per produced kilogram of hydrogen fuel, the central plant is able to produce 790,000 kilograms of hydrogen per year (H2C\textsubscript{r}). Hence, about 6 fueling stations (6.76) comparable to the one used in the model could be supplied. The distance for delivery to the chosen fueling station, DPS, accounts for 227 kilometers. Due to the possible volume of hydrogen transported by a truck, the station would have to be supplied daily by one truck.

3.1.1 Investments

The investments for the “Tauernwindpark” wind farm amounted to 20 million Euros. The annual operating costs for the wind power plant are about € 880,000. The investment costs for the photovoltaic plant amounted to about € 9 million Euros. The operating costs for the photovoltaic plant are about € 400,000 per year [15]. The needed electrolyzer equipment has a price of about 5 million Euros and the operating costs are about € 200,000 per year [16], [17]. The production of hydrogen fuel through electrolysis would require about 7.5 million liters.
of water at the given quantity of produced fuel per year. The costs of the used water therefore amount to € 10,507 per year, at a given price of € 1.4/m³ [18]. This means total investments of € 34 million and operation costs of about € 1.5 million per year.

3.1.2 Transportation

To deliver the produced hydrogen from the production site to the fueling station and to go back to the plant a truck has to drive 454 kilometers (DDT=454). For our calculations we assume, that PDU equals €0.77 per kilometer. Therefore, the costs of transportation per year, TCY, account for €862,555.7 per production plant. The value for PDU was inflation-adjusted by 2% per year from 2004 [19].

3.1.3 Environmental Indicators

The production of hydrogen via electrolysis itself does not produce additional greenhouse gas emissions. Nevertheless, there are indirect emissions due to the installation and operation of the plant. Using the model of Granovskii et al. (2006) the CO₂-equivalent emissions of the central production plant is equal to 2,918 tons per year [9]. The required CO₂ emission of the transport annually equals to 929.8 tons per production plant [20].

3.1.4 Estimated Values

The following table summarizes all calculated results for the central production plant in detail.

<table>
<thead>
<tr>
<th>Investments (I)</th>
<th>€ 33,909,672.0</th>
</tr>
</thead>
<tbody>
<tr>
<td>Operation costs per year (OC)</td>
<td>€ 1,487,377.0</td>
</tr>
<tr>
<td>Costs of transportation (TCY)</td>
<td>€ 862,555.7</td>
</tr>
<tr>
<td>Amount of hydrogen produced per year (H₂C₂)</td>
<td>790,000.0 kg</td>
</tr>
<tr>
<td>Δ𝐸ₗₑ₆₆ per year</td>
<td>GJ 127,481.0</td>
</tr>
<tr>
<td>CO₂-equivalent emission per year</td>
<td>t 2,918.0</td>
</tr>
<tr>
<td>CO₂-emission of transport per year</td>
<td>t 929.8</td>
</tr>
</tbody>
</table>

3.2 On-Site Production

The station for the on-site production is located outside of a populated area in Vienna. Thus, it is legally possible to install wind turbines. The needed area for the whole fueling station and combined hydrogen production plant amounts to about 4,000 m². The production operates with one wind turbine (Vestas V66) and 2,000 m² of photovoltaic cells. Figure 2 illustrates how the on-site production could be arranged.

The used wind turbine is of the same type as those in the "Windpark Oberzeiring". The capacity of electricity for the hydrogen production at the fueling station results from the possible energy capacity of the wind turbine and the photovoltaic cells. Further demand has to be satisfied with energy from an energy provider.

The wind turbine produces on average 3.36 million kWh per year, which equals to 9,200 kWh per day. The photovoltaic panels produce on average 466 kWh per day. In total the on-site production plant is able to produce on average 9,666 kWh per day. Referring again to 50 kWh of electricity needed for the production of one kilogram of hydrogen fuel, the station requires about 16,000 kWh for the production of the demanded 320 kg of hydrogen fuel per day [14]. This leads to the additional demand of 6,334 kWh of energy, satisfied by a domestic energy carrier.

3.2.1 Investments

The needed investments for the on-site production plant amount to about 4.3 million Euros, while the operating costs per year amount to about € 130,000. The costs for the required water (9.5 liters per kg hydrogen) are about € 1,500. The costs for the additional energy supplied by the domestic energy carrier are € 145,650 (with a price of € 0.063/kWh [21]). In total the operation costs are round € 277,204.

3.2.2 Environmental Indicators

Using again the model of Granovskii et al. (2006), the CO₂-equivalent emissions per year equal 258.7 tons for the on-site production plant. Additionally, one has to take into account that there are indirect emissions related to the consumption of energy from the domestic energy carrier. These emissions amount to 451.8 tons of CO₂ per year for the given energy-mix in the sample area [9].
3.2.3 Estimated Values

The following table provides a summary of the calculated results for the on-site production.

<table>
<thead>
<tr>
<th>Table 3: Calculated numbers for on-site production station</th>
</tr>
</thead>
<tbody>
<tr>
<td>Investments (I)</td>
</tr>
<tr>
<td>Operation costs per year (OC)</td>
</tr>
<tr>
<td>Costs of transportation</td>
</tr>
<tr>
<td>Amount of hydrogen produced per year (H2C0)</td>
</tr>
<tr>
<td>ΔE_ind per year</td>
</tr>
<tr>
<td>CO2-equivalent emission per year</td>
</tr>
<tr>
<td>CO2-emission per year (energy mix)</td>
</tr>
</tbody>
</table>

3.3 Economic Analysis

For the economic analysis of both production and distribution possibilities we consider the price of one produced kilogram of hydrogen fuel (€/kg) as the output value and reference size. Therefore, we consider again the costs of both means of production.

Central plant production:

| Investments:                                | € 33,909,672.00 |
| Operating costs:                           | € 2,349,932.70  |
| Total:                                     | € 36,259,604.70 |

On-site production:

| Investments:                                | € 4,301,174.00 |
| Operating costs:                           | € 277,203.77   |
| Total:                                     | € 4,578,377.77 |

In the following analysis we assume the same lifetime for both production plants, as the same technologies are used. Thus, we decided to set the lifetime at 25 years for each plant. Due to prior findings we assume, that the operating costs increase by 2% every year. At the central plant we therefore compare the annual part of total investments and annual operating costs including transportation costs with the produced and delivered amount of hydrogen fuel:

\[
PC_{1,0} = \frac{\left(\frac{33,909,672}{25} + 2,349,932.7\right)}{790,000} = 3.85 \text{ €/kg} \quad (9)
\]

Thus, the economic analysis shows that the total costs are lower for on-site production. The difference amounts to 21.82% per produced kilogram of hydrogen fuel.

3.4 Ecological Analysis

For the ecological analysis of both production types, we compare the results calculated on the basis of Granovskii et al.'s model [9]. As a reference size, the emissions per produced kilogram of hydrogen fuel are compared.

Central plant production:

| CO2-equivalent emission:          | t 2,918.0 |
| CO2-emission of transport:       | t 929.8  |
| Total:                           | t 3,847.8 |

For the annual production of 790,000 kg of hydrogen fuel, CO2-emissions of 4.87 kilograms per kilogram of hydrogen fuel occur. The indirect fossil fuel energy \(\Delta E_{ind}\) is 127,481 GJ per year in total and 0.16 GJ per kilogram of hydrogen.

On-site production:

| CO2-equivalent emission:          | t 258.7  |
| CO2-emission of energy-mix:      | t 451.8  |
| Total:                           | t 710.5  |

For the annual production of 116,800 kilograms of hydrogen fuel, emission of 6.08 kg CO2 occur per kilogram of hydrogen. The indirect fossil fuel energy \(\Delta E_{ind}\) is 20,760.15 GJ per year in total and 0.178 GJ per kilogram of hydrogen.

As a result of the environmental analysis, one can see that the plant production is more environmentally friendly than the on-site production at the fueling station.

4. Conclusion and Further Research

The first conclusion and finding of our survey is that hydrogen mobility would be much more environmentally friendly than fossil fueled mobility. In general it can be said, that the fuel value of 1 kg of hydrogen fuel equals the fuel value of 2.33 liters of conventional fuel, or 2.7 liters of Diesel. The corresponding CO2-emissions amount to 2.33 kg CO2 per liter of conventional fuel and 2.64 kg per liter of Diesel. These emissions do not include the emissions produced at the refining process or the transport to the stations, where the emissions of hydrogen fuel in our survey do so. Nevertheless, CO2-emissions are far lower for hydrogen fuel than for conventional fuel.
Additionally, it can be concluded that hydrogen fuel can be produced economically more competitively, than estimated in several prior studies. While one kilogram of hydrogen fuel could be produced at a price of 3.85 Euros in an on-site plant, the same energetic value of conventional fuel is currently traded at a price above 4 Euros in Central Europe (including all taxes).

The comparison of the two possible production modes of hydrogen fuel, at a central plant and on-site at fuel stations, shows that there is an economic advantage for the production directly on-site at stations. The main reason for this is that the production at central plants demands additional transport to stations. Nevertheless, the ecological performance of the on-site production is not really satisfactory. The reason for this is, that energy has to be used by the local energy provider and this energy is in general not as ecologically friendly as the on-site production. However, the high rate of additional traffic in the case of a central plant production additionally favors the on-site production.

There is a lot of further research that could be done based on our model. The ecological performance of the on-site production should be improved through innovative ideas, what we are actually doing in another paper. Additionally we assume that a tank capacity at stations of triple the daily demand would be enough for demand fluctuations as well as production fluctuations based on non-optimal weather conditions. This aspect could be investigated in a simulation model for several geographical areas. Furthermore, the fueling station and thus the on-site production is located outside a populated area, so that wind turbines can be legally installed. This is again an assumption that is not true for all stations in reality. The same holds for the assumption of 4000 m² of area for fueling stations. Especially in this context, more research could be done on further possibilities for energy production for the conversion into hydrogen fuel. One approach we are thinking about is the connection to residents in the vicinity of a station that provide space for such energy production plants.

References