THE ROLE OF POWER-TO-GAS IN ACHIEVING GERMANY’S CLIMATE POLICY TARGETS WITH A SPECIAL FOCUS ON CONCEPTS FOR ROAD BASED MOBILITY
THE ROLE OF POWER-TO-GAS IN ACHIEVING GERMANY’S CLIMATE POLICY TARGETS WITH A SPECIAL FOCUS ON CONCEPTS FOR ROAD BASED MOBILITY

Prof. Dr. Hans-Martin Henning

Andreas Palzer
Fraunhofer Institute for Solar Energy Systems ISE Freiburg

Study on behalf of ETOGAS GmbH, Stuttgart
Executive Summary

This study was performed by Fraunhofer ISE using the model REMod-D (Renewable Energy Model – Germany) [ISE 2013] with a special focus on the role of road-based mobility concepts in achieving Germany’s 2050 Greenhouse Gas (GHG) reduction targets of at least 80% (compared to 1990).

The REMod-D model base was exploited here for the first time to yield insights on the optimal choice of mobility and drive-train concepts including mobility pathways utilizing renewable hydrogen and methane. The model includes all energy sectors (power, heat, industry, transport) and determines a minimum cost solution, providing the most economic energy system configuration for achieving a CO₂ reduction target in Germany. In this study, we analyzed systems with CO₂ emission reduction between 75% and 85%.

In a nutshell, the results indicate the following:

- Achieving high CO₂ emission reduction targets (above 82%) is not feasible in a system without any Power-to-Gas technology producing either renewable Hydrogen (H₂) or Synthetic Natural Gas (SNG).

- For emission reduction targets lower than 82%, minimal cost solutions without a commercial availability of Power-to-Gas technology would lead to significant higher overall annual cost compared to systems which make use of Power-to-Gas technology: For instance, at 80% CO₂ reduction the cost saving of a system making use of Power-to-Gas technology is ~ 60 billion € per year in comparison to a system without any Power-to-Gas technology.

- In our base case scenario, gas-based vehicles with internal combustion engine represent the cost-optimal solution for private cars up to a CO₂ reduction target of 81%. Very high CO₂ reduction targets above 82% favor an increasing share of battery concepts (gas/battery hybrid systems as well as battery-only systems) in the optimal car concept mix.

- With increasing CO₂ emission reduction, synthetic gas produced from volatile renewable power increasingly replaces import of fossil natural gas.

- Major parts of synthetic gas are used in the mobility sector in combination with either fuel cell based electric engines (hydrogen) or in combination with internal combustion engines using a mix of biogas, fossil natural gas and renewable synthetic natural gas. Depending on the assumed cost development, the one or the other of these concepts may play a more dominant role and due to that uncertainty it is difficult to draw final conclusions on the superiority of the one or the other concept.

It is important to mention that still significant uncertainty exists about cost projections for all involved technologies and in particular for those technologies where almost no commercial market exists today, such as large scale hydrogen and Power-to-Gas technology using renewable electricity. Used cost values are based on various references and all cost and performance values for hydrogen and Power-to-Gas technology are based on values provided from Etogas GmbH.
## Content

1. **Introduction** .............................................................................................................. 6  
   1.1 Methodology ........................................................................................................... 6  
   1.2 Definition of Scenarios ......................................................................................... 9  

2. **Results** ..................................................................................................................... 10  
   2.1 Base case scenario ............................................................................................... 10  
   2.2 Scenario without Power-to-Gas technology ....................................................... 14  
   2.3 Cost-reduction scenario for electric and fuel cell cars ....................................... 14  

3. **Conclusion** ............................................................................................................... 18  

4. **References** ............................................................................................................... 19  

5. **Appendix** ............................................................................................................... 20  

1 Introduction

This study was performed using the model REMod-D (Renewable Energy Model – Germany) [ISE 2013]. It includes a dynamical model of renewable and fossil energy production, of energy conversion technologies and end uses in all energy sectors (power, heat, industry, transport), as well as a balance of all related CO$_2$ emissions. The integrated optimization of all energy sectors yields a minimum total cost solution, i.e. it provides the most economic system configuration for achieving a future CO$_2$ reduction target in Germany.

For this study, the REMod-D model base was extended to include different vehicle concepts (fuel cell, internal combustion engine fuel/gas, battery, hybrid). Detailed assumptions and parameters of the model are listed in the Appendix.

For future scenarios achieving a CO$_2$ reduction of 70-85% (compared to 1990), while supplying the full energy demand of power, heat, industry and transport sector in Germany, the cost-optimal total configuration was determined and analyzed with special respect to road-based mobility concepts, the use of renewable gases Hydrogen (H$_2$) and Synthetic Natural Gas (SNG) in transport as well as the overall use of the Power-to-Gas (PtG) technology.

1.1 Methodology

The simulation and optimization model REMod-D was developed at Fraunhofer ISE. This model comprises a holistic simulation and optimization of a future German energy system. The model includes electricity generation and all end-use sectors. To describe this complex system appropriately the energy flows of all components (generators, converters, storages, and consumers/loads) are modeled on an hourly basis. A generic optimizer identifies optimized system configurations which lead to minimized overall cost (full cost) to operate and maintain the overall system.

The main goal of the study was to investigate the role and importance of PtG technologies (Power-to-H$_2$ and Power-to-SNG) in an energy system with significantly reduced energy-related CO$_2$ emissions. A special focus was put on the analysis of different concepts for road based mobility, i.e. concepts of engines for cars (private, trucks). For this purpose a new version of the REMod model was applied which contains

- detailed descriptions for the conversion of biomass into secondary energy carriers,
- detailed descriptions of different options for the conversion of electricity from renewable resources (solar, wind) in to synthetic gaseous fuels and
- a set of concepts for car engines such as battery/electric engine, fuel cell/electric engine, internal combustion engine using CNG / SNG, internal combustion engine using conventional fuels (gasoline, diesel) and various hybrid concepts, namely internal combustion engines and fuel cell combined with batteries, respectively.
A sketch of the overall energy conversion scheme is shown in Figure 1.

In order to compare different mobility scenarios under similar conditions, the low temperature heat demand of the building sector was fixed to a reduction by 60% compared to today’s final energy value (780 TWh), and the composition of technologies (technology mix) to supply buildings with heat (space heating, domestic hot water) was also fixed (cf. Appendix, Tab. 5.1); this composition turned out reasonable (cost-optimal) under previous optimization runs which focused on the electricity and heat sector.

By this methodology, the degrees of freedom for the optimization were reduced and limited to the following domains: electricity generation, storage, fuel conversion and mobility.

Further parameters that are assumed to have an influence on the mobility sector are the projected gasoline/diesel and gas prices as well as CO₂ certificate cost; these values were provided by the client and are listed together with cost and efficiency assumptions for private cars in the Appendix. The latter values not only contain the cost for the vehicle, but also average cost for the required infrastructure.
The following car concepts were analyzed (ICE = internal combustion engine, gas = CNG and SNG):

<table>
<thead>
<tr>
<th>Concept</th>
<th>Abbreviation</th>
<th>Maximal fraction Cars</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fuel Cell Electrical</td>
<td>Veh_FC</td>
<td>60%</td>
</tr>
<tr>
<td>ICE gas</td>
<td>Veh_ICEGas</td>
<td>100%</td>
</tr>
<tr>
<td>ICE fuel</td>
<td>Veh_ICEFuel</td>
<td>100%</td>
</tr>
<tr>
<td>Battery Electrical</td>
<td>Veh_Bat</td>
<td>60%</td>
</tr>
<tr>
<td>Hybrid Fuel Cell</td>
<td>Veh_FCBat</td>
<td>100%</td>
</tr>
<tr>
<td>Hybrid ICE gas</td>
<td>Veh_ICEGasBat</td>
<td>100%</td>
</tr>
<tr>
<td>Hybrid ICE fuel</td>
<td>Veh_ICEFuelBat</td>
<td>100%</td>
</tr>
</tbody>
</table>

Electrical vehicles were limited to max. 60% since some limitations with respect to infrastructure and range and therefore application likely will remain [11].
1.2 Definition of Scenarios

In order to investigate the influence of different assumptions concerning the cost and a possible limitation in the potential of technologies, several scenarios were defined. All scenarios use the fixed set-up described in chapter 1.1, and each scenario is calculated with different CO₂-emission reduction targets from 75% up to 85% compared to Germany’s energy-related CO₂ emissions in the year 1990.

<table>
<thead>
<tr>
<th>Scenario</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Base case - All assumptions as described before</td>
</tr>
<tr>
<td>2</td>
<td>Base case, but without availability of Power-to-Gas</td>
</tr>
<tr>
<td>3</td>
<td>Reduction of concept-specific cost of fuel-cell and battery-driven vehicles of ~60%, hybrid-vehicles ~40%</td>
</tr>
</tbody>
</table>

Note: Concept-specific cost reduction means cost reduction on vehicle level. The infrastructure cost component is not affected.

Tab. 2: Description of selected scenarios
2 Results

2.1 Base case scenario

For the base case scenario and CO₂ reduction targets of 75% and 80-85%, the cost-optimal composition of private car concepts is shown in Figure 2. Under the assumed conditions, gas-based vehicles with internal combustion engine represent the cost-optimal solution for private cars up to a CO₂ reduction target of 81%. Very high CO₂ reduction targets above 82% favor an increasing share of battery concepts (gas/battery hybrid systems as well as battery-only systems) in the optimal car concept mix. In the highest studied case of 85% CO₂ reduction, all systems are using concepts that include batteries.

The installed capacity of renewable power sources (wind onshore, wind offshore, photovoltaics) for the base case scenario is shown as a function of CO₂ reduction in Figure 3. With increasing CO₂ reduction targets, the required capacity is increasing but hits their potential boundaries already at CO₂ reduction targets at 81% and higher (see Figure 3). The high installed capacity is related to the fact that energy supply for all sectors – power, heat, industry and transport (road, rail, ship, aviation) - is included.
Figure 4 shows the installed Power-to-Gas capacity for the base case scenario, separately for Power-to-Hydrogen (i.e. electrolysis) and Power-to-SNG (electrolysis and methanation). In all studied CO\textsubscript{2} reduction cases, the installed Power-to-Gas capacity is larger than 30 GW\textsubscript{el}, dominated by Power-to-SNG. In the higher CO\textsubscript{2} reduction scenarios, the installed capacity is significantly above 100 GW\textsubscript{el}.

The annual total cost of the entire system is shown in Figure 5. The total system cost is continuously increasing with more ambitious CO\textsubscript{2} reduction targets. In the next section, the cost of systems without Power-to-Gas will be shown for comparison.
Figure 6 shows the composition of gaseous energy carriers in the base case scenario. The results clearly show that fossil natural gas is increasingly replaced mainly by renewable SNG with increasing CO₂ reduction targets.

Fig. 6: Source of gaseous energy carriers. Scenario “base case”
Figure 7 depicts an energy flow chart from production units to the different end-use sectors including all converters and storages for a selected case (80 % CO₂ reduction).

Our interpretation of these results is as follows: With increasing CO₂ emission reduction targets, the overall trend is (i) a replacement of fossil natural gas by synthetic gas (\( \mathrm{H}_2 \) and SNG) produced from renewable energy on the one hand, and (ii) for CO₂ reduction above 82 % a replacement of fuel based vehicle concepts by battery based vehicle concepts on the other hand side. The reason for (i) is simply the need to reduce fossil fuels in order to achieve CO₂ targets. The reason for (ii) is the need to increase overall conversion efficiency with help of electrical vehicles (fuel cell and battery) at the point when further installation of renewable power sources wind and solar get limited by their potentials (81 % of CO₂ reduction and above). However, the trend which leads to a substitution of fuel based concepts by battery based concepts also favors battery-hybrid concepts with hydrogen and SNG at 84% and 85 % CO₂ reduction, at least as long as the amount of purely battery based concepts is limited. The result shown here corresponds to a limitation of purely battery based concepts to a maximum of 60 % of all cars, which seems justified by the fact, that also in future a significant amount of long-distance cars will be needed.
2.2 Scenario without Power-to-Gas technology

The base case scenario assumes the commercial availability of the PtG technology. The results show that above 70% CO₂ reduction, the cost-optimal energy supply system requires Power-to-Hydrogen as well as Power-to-SNG installations on a multi-GW scale.

We now analyze the consequences, if the Power-to-Gas technology is not commercially available but same CO₂ reduction targets are to be met. The results for this scenario 2 show that the system highly depends on PtG facilities: Figure 8 gives the total annual system cost in the case that Power-to-Gas is not available. The striking consequence is that CO₂ reduction targets of >82% are not achievable under the assumptions of this study.

![Fig. 8: Total system cost of Scenario 2 – no Power-to-Gas technologies available]

In addition, the annual cost for achieving CO₂ reduction targets of 75% or more is significantly higher if PtG installations are not available on a large scale. For example, at 80% CO₂ reduction, the cost saving due to PtG is ~ 60 billion € per year compared to the system without PtG.

From an economic point of view, considering specific cost of PtG of 700-1100 €/kWₑ it the cost of a buildup of ~100 GWₑ PtG capacity will be covered by the above mentioned cost savings in less than 5 years.

2.3 Cost-reduction scenario for electric and fuel cell cars

The third analyzed scenario makes rather aggressive assumptions on the cost reduction of battery and fuel cell-based vehicles: It is assumed that the vehicle-related cost for fuel cell- and battery-electrical vehicles will reduce by -60% compared to the base case, and costs for hybrid vehicles by -40%. Infrastructure cost is assumed to be the same as in the base case.

The overall trends are similar to the base case scenario: Fossil natural gas is increasingly replaced by renewable SNG, and battery concepts become dominant for high CO₂ reduction target values above 84%. However, under the cost reduction assumptions made in this scenario, fuel cell based vehicles will play a much more important role.
Results

Figure 9 shows the composition of private car concepts under the cost reduction assumptions. The strong reduction of fuel cell and electric vehicle cost leads to a high share of fuel cell vehicles in the mobility mix already at 75% CO\textsubscript{2} reduction. Part of the mobility is mix is still gas-based – due to the assumption that the fuel cell penetration is limited to 60%. Higher CO\textsubscript{2} reduction targets again favor battery-based vehicles and at 85% CO\textsubscript{2} reduction, the remaining, not fully electric share of the private mobility mix is made up by gas-hybrid vehicles.

![Drive concepts automobile](image)

The installed capacity of wind and photovoltaic converters is shown in Figure 10. The potential limitations are reached above 80% CO\textsubscript{2} reduction as in the base case scenario.

![Installed Power RE](image)

Figure 11 shows the installed capacity of Power-to-Hydrogen (electrolysis) and Power-to-SNG (electrolysis and methanation) installations for Scenario 3. Compared to Scenario 1 (Figure 4), the installed Power-to-Hydrogen capacity is higher and with increasing CO\textsubscript{2} reduction target, it is successively replaced by Power-to-SNG capacity. The total PtG input power is higher than 50 GW\textsub{el} in all cases.
Results

The total annual system cost (Figure 12) increases from around 260 billion € p.a. in the 75% CO₂ reduction case to around 300 billion € p.a. in the 85% CO₂ reduction case and therefore increases less strongly than in the base case scenario (Fig. 5). Note, however, the Power-to-SNG capacity in the high CO₂ reduction scenarios is actually only slightly lower than in the base case.

Fig. 11: Installed capacity of electrolysis and methanation facilities.
Scenario 3 “cost reduction fuel cell & electric concepts”

Fig. 12: Total system cost.
Scenario 3 “cost reduction fuel cell & electric concepts”
The composition of gaseous energy carriers used in the system is shown in Figure 13. Up to 82% CO$_2$ reduction, about 20% of the gas is hydrogen; at higher CO$_2$ reduction targets, the hydrogen is replaced by synthetic natural gas.

Fig. 13: Source of gaseous energy carriers. Scenario 3 “cost reduction fuel cell & electric concepts”
3 Conclusion

Under increasing CO₂ emission reduction targets for the entire German energy system, fossil natural gas is increasingly replaced by synthetic gas (H₂ or SNG) produced from renewable electricity once levels of 75 % CO₂ emission reduction and above are to be achieved. Results indicate that it is not possible to achieve high CO₂ emission reduction targets above 82 % in a cross-sectoral energy system without help of Power-to-Gas technology in which electricity from renewable sources, mainly wind and solar, is flexibly used in other sectors (mainly mobility and industry) in form of hydrogen and/or synthetic natural gas. Under lower reduction targets (we analyzed values down to 75 %) systems without any hydrogen or Power-to-Gas technology would lead to significant higher overall annual cost compared to systems which make use of these technologies.

However, overall it turns out difficult to achieve very high CO₂ reduction targets of 85 % and above for the German energy system under the made assumptions, boundary conditions and technical limits of renewable energy resources.

Major parts of synthetic gas are used in the mobility sector in combination with either fuel cell based electric engines (hydrogen) or in combination with internal combustion engines using a mix of biogas, fossil natural gas and renewable synthetic natural gas. Depending on the assumed cost development, the one or the other of these concepts may play a more dominant role and due to that uncertainty it is difficult to draw final conclusions on the superiority of the one or the other concept. Here further cost analysis and more sensitivity studies will be needed for a better understanding of the different options. In those studies also other boundary conditions which are not part of our modelling have to be taken into account (for instance the amount of purely battery based vehicles will be limited due to the more limited distance per full storage charge in comparison to other concepts).
4 References

5 Appendix

Tab. 5.1: Fixed fractions of heating technologies

<table>
<thead>
<tr>
<th>Decentralized Technologies</th>
<th>Centralized Technologies</th>
</tr>
</thead>
<tbody>
<tr>
<td>Heat pump, el.</td>
<td>42,3%</td>
</tr>
<tr>
<td>Heat pump, gas</td>
<td>8,7%</td>
</tr>
<tr>
<td>Boiler (wood, gas)</td>
<td>16,8%</td>
</tr>
<tr>
<td>CHP (gas)</td>
<td>7,2%</td>
</tr>
<tr>
<td>CHP (gas)</td>
<td>23,75%</td>
</tr>
<tr>
<td>Geothermal</td>
<td>1,25%</td>
</tr>
</tbody>
</table>

Tab. 5.2: Cost assumptions gasoline/diesel, biomass, gas, CO2 certificates

<table>
<thead>
<tr>
<th>Fuels</th>
<th>CO2-certificates</th>
</tr>
</thead>
<tbody>
<tr>
<td>Gasoline/Diesel</td>
<td>120 €/MWh</td>
</tr>
<tr>
<td>CO2-certificates</td>
<td>75 €/tCO2</td>
</tr>
<tr>
<td>Natural gas</td>
<td>59 €/MWh</td>
</tr>
<tr>
<td>Biomass</td>
<td>60 €/MWh</td>
</tr>
</tbody>
</table>

Tab. 5.3: Cost and performance parameter for Power-to-Gas

<table>
<thead>
<tr>
<th>Technology</th>
<th>Cost assumptions</th>
<th>Efficiency assumptions</th>
<th>Source</th>
</tr>
</thead>
<tbody>
<tr>
<td>Power-to-Hydrogen</td>
<td>700 €/kW_{el}</td>
<td>75%</td>
<td>[1,6]</td>
</tr>
<tr>
<td>Power-to-SNG</td>
<td>1100 €/kW_{el}</td>
<td>61%</td>
<td>[6]</td>
</tr>
<tr>
<td>Hydrogen Storage</td>
<td>1500 €/kW_{el}</td>
<td>85%</td>
<td>[6,10]</td>
</tr>
<tr>
<td></td>
<td>0.69 €/kWh</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Tab. 5.4: Cost and performance assumptions for private car concepts; the values not only contain the cost for the vehicle, but also average values for the required infrastructure.

<table>
<thead>
<tr>
<th>Concept</th>
<th>Cost assumptions</th>
<th>Efficiency assumptions</th>
<th>Source</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fuel Cell</td>
<td>32700 €/car</td>
<td>36%</td>
<td>[1–5]</td>
</tr>
<tr>
<td>ICE gas</td>
<td>23400 €/car</td>
<td>25%</td>
<td>[1,3,4,6–8]</td>
</tr>
<tr>
<td>ICE fuel</td>
<td>21100 €/car</td>
<td>25%</td>
<td>[1,3,4,7]</td>
</tr>
</tbody>
</table>
### Conclusion

<table>
<thead>
<tr>
<th>Type</th>
<th>Cost per Car (€)</th>
<th>Efficiency</th>
<th>Battery Efficiency</th>
<th>References</th>
</tr>
</thead>
<tbody>
<tr>
<td>Battery</td>
<td>31500</td>
<td>71%</td>
<td>71% (Battery)</td>
<td>[1,3,9]</td>
</tr>
<tr>
<td>Hybrid Fuel Cell</td>
<td>48000</td>
<td>36%</td>
<td>71% (Battery)</td>
<td>[1-5,9]</td>
</tr>
<tr>
<td>Hybrid ICE gas</td>
<td>31800</td>
<td>25%</td>
<td>71% (Battery)</td>
<td>[1,3,6,7]</td>
</tr>
<tr>
<td>Hybrid ICE fuel</td>
<td>29500</td>
<td>25%</td>
<td>71% (Battery)</td>
<td>[1,3,6,7]</td>
</tr>
</tbody>
</table>