Impacts of large-scale introduction of hydrogen in the road transport sector on urban air pollution and human exposure in Copenhagen

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1. Introduction

The vision of a renewable energy system with hydrogen as an important energy carrier requires a technological transformation of the present pre-dominantly fossil energy system. It involves the production of hydrogen with renewable energy sources, distribution of hydrogen in pipelines and e.g. new filling stations for cars, new technologies for use of hydrogen e.g. fuel cell cars etc. Such a hydrogen economy promises large environmental benefits for air pollution. Fuel cells combine oxygen from the air with hydrogen to produce electricity and only emit harmless water. When traditional combusting of fossil fuels is replaced the related emissions of pollutants are avoided. Reduced CO2 emissions will reduce the green house effects. Furthermore, air quality problems in large cities and related public health problems will be diminished (Jacobsen et al., 2005). Ground level ozone will decrease and reduce related health problems and agricultural production losses. In addition, a reduction of environmental problems related to the deposition of air pollutants e.g. acidification and eutrophication will improve the natural environment for flora and fauna. However, there may also be drawbacks. The production, distribution and use of hydrogen will increase the leakage of hydrogen to the atmosphere. Recent research indicates that hydrogen may be involved in processes leading to increased depletion of the ozone layer and an increase in the green house effect (Tromp et al. 2003).

The aim of the project ‘Environmental and Health Impact Assessment of Scenarios for Renewable Energy Systems with Hydrogen’ (HYSCENE) is to improve modelling of the environmental impacts and related socio-cultural and welfare economic impacts of a proposed hydrogen/renewable energy system with focus on large-scale introduction of hydrogen as energy carrier in the road transport sector (http://hyscene.dmu.dk). This extended abstract will focus on the impacts on urban air pollution and human exposure.

2. Methodology

A busines-as-usual and a hydrogen scenario are defined for 2004, 2015, 2030 and 2050. Hydrogen is gradually introduced and in the hydrogen scenario it is envisaged that 75% of the total domestic transport energy demand in Denmark is covered by hydrogen in 2050.

Data for modelled fuel consumption in the busines-as-usual and H2 scenario has been transformed into emissions. The calculation of emissions for the Danish road transport sector is based on a structure similar to the European COPERT emission model. For other mobile (national sea transport, domestic aviation, railways, military, non road working machinery, recreational craft) and stationary combustion sources, detailed activity based calculations are made following the European EMEP/CORINAIR guidelines for the historical situation. Appropriate forecast assumptions for fleet, activities and emission factors are used to predict the future emissions, also taking into
account emission legislation already adopted. Emissions have been distributed geographically on a 1x1 km² grid for the road transport sector and on a 17x17 km² for other sources for air quality modelling (Winther et al. 2008).

The impacts on air quality on different geographic scales are assessed from regional to local level with the Greater Copenhagen Area as case study area. The Greater Copenhagen Area encompasses about 1.8 million people in a varied environment including the capital of Copenhagen, a number of middle-sized and small cities, and rural areas. On the regional scale, the hemispheric air chemistry transport model (Danish Eulerian Hemispheric Model - DEHM) is used to estimate air quality in Denmark (17x17 km²) (Brandt et al. 2001; Frohn et al. 2002). Urban background concentrations are modelled on a detailed grid (1x1 km²) with the Urban Background Model (UBM) (Berkowicz 2000b) and street concentrations are modelled with the Operational Street Pollution Model (OSPM) (Berkowicz 2000a) for a large selection of streets in the case study area using the AirGIS system (Jensen et al. 2001;2009). Human exposure assessment is also carried out combining air pollution data with population data. Human exposure assessment is conducted on a 1x1 km² grid for the Greater Copenhagen Area. Very detailed population data (age, gender) is available based on the Central Person Registry (CPR) that includes population data for every single address in Denmark. Air quality assessment is also carried out for 138 busy streets in the capital of Copenhagen.

3 Busines-as-usual and H₂ Scenarios

The busines-as-usual and the H₂ scenarios include almost the same assumed total energy consumption in the Danish society over the years. The busines-as-usual scenario is based on the current official projections for the Danish energy sector. The H₂ scenario assumes a change into using H₂ as a primary energy carrier in the road transport sector.

The busines-as-usual scenario is extending from 2004 to 2050. This scenario assumes implementation of the current governmental energy plan (extending to the year 2030). For the years between 2030 and 2050, the development is established from linear extrapolation of the obtained trends between 2004 and 2030. The road transport accounts for 95% of the total domestic transport energy consumption in the busines-as-usual scenario.

The main objective of the H₂-scenario is to investigate the large-scale application of H₂ as an energy carrier in the Danish transport sector. In this scenario, it is assumed that the domestic road transport sector will obtain 75% coverage of H₂ as energy carrier by the year 2050. By 2050 the penetration of H₂ as energy carrier is assumed to be 100% in bus transport, 86% in passenger cars, and 65% in light and heavy duty vehicles. H₂ is projected to be introduced in the bus sector by 2008 and in the passenger cars as well as the light and heavy duty vehicles by 2015. The total H₂ share in the transport sector is assumed to 1% in 2015, increasing to 22% in 2030, and further to 75% by 2050. It is assumed that all H₂ driven vehicles will be based on fuel cell propulsion/electric engine systems, and not on internal combustion engines. The H₂ is assumed to be stored in compressed gas tanks and supplied in gaseous state. It is envisaged that refuelling facilities for vehicles and joint H₂ storages are established in appropriate accordance with the given role in overall power and heating system, and equivalent with the present refuelling infrastructure for conventional fuels. Another assumption is that the transmission and distribution of H₂ will take place by means of the existing nationwide Danish natural gas pipe system. The loss of H₂ from fuel handling at filling stations, and leakage in transmission lines and central storage is quantified by application of leakage factors (0.05 in both cases, and the total H₂ mass is obtained from dividing with the lower heating value for H₂ (120 GJ/tons fuel). The total H₂ leakage is equivalent to about 10% of the consumption. The H₂ generation is established as part of the STREAM modelling of the electricity sector for the selected years. The STREAM model (Sustainable Technology Research and Energy Analysis Model) is a spreadsheet based energy system model covering the whole energy system. H₂ generation is
assumed to take place by means of electrolysis based on electricity from the public grid in Denmark.

On the power supply side, the busines-as-usual scenario is more or less a continuation of the current power system in Denmark (the wind power share is increased from today’s 20% to 30% in 2050). New more efficient power plants will replace old plants, but the combination of fuels used will still be the same. Wind power is increased during the scenario period and the future power production is mainly based on coal, gas and wind.

For the H2-scenario, Denmark is assumed to be heading towards a fossil fuel free energy supply system. The driving factors for this development are here assumed to be high oil, gas and coal prices. For the H2 scenario the Danish renewable resources useful for power production are mainly related to wind energy and biomass production. However, future energy resources may also include wave power and photovoltaic. The H2 scenario stretches these resources to their limit and to keep up with the increasing power demand new coal fired power plants with carbon capture and sequestration (CCS) are build from 2015 as test plants and from 2030 as full scale and normal operating power plants.

4 Results and Discussion

4.1 Emissions and their geographic distribution

Total emissions from the busines-as-usual and the H2 scenario are shown in Table 1 for CO2-eq. (derived from CO2, CH4 and N2O), NOx, PM2.5 and the hydrogen loss.

<table>
<thead>
<tr>
<th></th>
<th>CO2-eq. (kttons)</th>
<th>NOx (tons)</th>
<th>PM2.5 (tons)</th>
<th>H2(tons)</th>
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<tbody>
<tr>
<td></td>
<td>Road</td>
<td>Other</td>
<td>Sum</td>
<td>Road</td>
</tr>
<tr>
<td>2004 Busines-as-usual</td>
<td>11953</td>
<td>53121</td>
<td>65074</td>
<td>66565</td>
</tr>
<tr>
<td>2015 Busines-as-usual</td>
<td>12722</td>
<td>46816</td>
<td>59538</td>
<td>30842</td>
</tr>
<tr>
<td>H2 scenario</td>
<td>12514</td>
<td>43364</td>
<td>55877</td>
<td>30144</td>
</tr>
<tr>
<td>Reduction</td>
<td>209</td>
<td>3452</td>
<td>3661</td>
<td>697</td>
</tr>
<tr>
<td>Red. (%)</td>
<td>2</td>
<td>7</td>
<td>6</td>
<td>2</td>
</tr>
<tr>
<td>2030 Busines-as-usual</td>
<td>13910</td>
<td>45174</td>
<td>59084</td>
<td>14683</td>
</tr>
<tr>
<td>H2 scenario</td>
<td>10636</td>
<td>27653</td>
<td>38289</td>
<td>10250</td>
</tr>
<tr>
<td>Reduction</td>
<td>3274</td>
<td>17521</td>
<td>20795</td>
<td>4432</td>
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<tr>
<td>Red. (%)</td>
<td>24</td>
<td>39</td>
<td>35</td>
<td>30</td>
</tr>
<tr>
<td>2050 Busines-as-usual</td>
<td>15294</td>
<td>47358</td>
<td>62651</td>
<td>15239</td>
</tr>
<tr>
<td>H2 scenario</td>
<td>3277</td>
<td>25186</td>
<td>28463</td>
<td>4242</td>
</tr>
<tr>
<td>Reduction</td>
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<td>22172</td>
<td>34189</td>
<td>10997</td>
</tr>
<tr>
<td>Red. (%)</td>
<td>79</td>
<td>47</td>
<td>55</td>
<td>72</td>
</tr>
</tbody>
</table>

Table 1 CO2-eq., NOx, PM2.5 and H2 emission for busines-as-usual and H2 scenario (Winther et al. 2008)

The largest emission reduction is seen for road transport due to the gradual shift to H2. The non-exhaust PM2.5 emissions arising from tyre, brake and road wear remain the same in the busines-as-usual and the H2 scenario, and hence influences the total reduction in PM2.5 emissions although PM2.5 exhaust emissions are reduced drastically. For other sources than road transport, GHG emissions reductions are also expected, due to the assumed increase in the use of wind power and biomass in the H2 scenario. However, the achieved emission reductions for other sources are more moderate than for road transport alone. The higher NOx emission in the H2 scenario compared to the busines-as-usual situation for other sources is due to an increased use of natural gas and biogas since they have very high NOx emission factors due to combustion in gas engines. Further, the use of biomass does not bring down the NOx emissions. The higher PM2.5 emission for the H2 scenario...
compared to the business-as-usual is the large increase in biomass combustion especially in the residential sector associated with high emission factors. This illustrates the need for better emission control of these technologies if they are going to play important roles in future renewable energy scenarios. It may be considered an artefact that these emissions have not been lowered as emission control should be expected during the scenario period.

Figure 1 shows examples of geographic distribution of emissions for Denmark on a 17x17 km² grid and on a 1x1 km² grid for the road transport sector illustrated for the Greater Copenhagen Area. The increase in PM$_{2.5}$ emissions in the H$_2$ scenario is visible compared to the reference case mainly due to the increased use of biomass in the residential sector.

4.2 Air Quality Assessment

An example of primary PM$_{2.5}$ concentration difference between the business-as-usual and the H$_2$ scenario at the regional level in Denmark based on the DEHM model is shown in Figure 2 (left). At the regional or background level it is seen that the concentration differences are very small between the business-as-usual and the H$_2$ scenario as expected due to dilution and removal processes when pollutants are transported over long distances. Primary emitted PM$_{2.5}$ concentrations are slightly higher in the H$_2$ scenario due to higher PM$_{2.5}$ emissions due to increased use of biomass especially for residential heating in the H$_2$ scenario where no mitigating emission control measures were assumed. An example of PM$_{2.5}$ concentration difference (only from primary emitted PM$_{2.5}$) between the business-as-usual and the H$_2$ scenario at the urban background level in the Greater Copenhagen Area based on the UBM model is shown in Figure 2 (right). It is seen that the concentration differences are higher compared to the differences for the regional levels due to shorter dispersion distances. Primary PM$_{2.5}$ concentrations are slightly higher in the H$_2$ scenario due to the above
reasons. To be able to compare with limit values for PM$_{2.5}$, the contribution from modelled secondary formed PM$_{2.5}$ concentrations (e.g. nitrates, sulphates) also has to be taken into account.

In the H$_2$ scenario the slightly higher PM$_{2.5}$ concentrations in the regional and urban background are not offset by decreasing PM exhaust from road emissions resulting in slightly higher PM$_{2.5}$ street concentrations in 138 streets in Copenhagen. For NO$_2$, regional and urban background concentrations are slightly lower in the H$_2$ scenario and street concentrations are reduced substantially (data not shown for street concentrations).

**Figure 2** Left: Example of concentration difference between the business-as-usual scenario and the H$_2$ scenario in µg/m$^3$. In this case in 2050 for primary emitted PM$_{2.5}$ modelled with the DEHM model on a 17x17 km$^2$ grid. Right: Primary PM$_{2.5}$ concentration difference between the business-as-usual and the H$_2$ scenario at the urban background level in the Greater Copenhagen Area based on the UBM model on a 1x1 km$^2$ grid.

**Acknowledgement**

The HYSCENE project is funded by the Programme Commission on Energy and Environment under the Danish Strategic Research Council ([http://fist.dk/site/english](http://fist.dk/site/english)). The project period was 2006-2008.

**References**


