ASSESSING THE EMISSION IMPACTS FROM THE INTRODUCTION OF HYDROGEN IN THE ROAD TRANSPORT SECTOR - RESULTS FROM THE HYSCENE PROJECT

Morten WINTHER[a, +], Ole-Kenneth Nielsen[a], Morten T. Jensen[a], Marlene S. Plejdrup[a], Jytte B. Illerup[b], Kaj Jørgensen[c], Kenneth Karlsson[c]

[a]National Environmental Research Institute, University of Aarhus, Frederiksborgvej 399, 4000 Roskilde, Denmark

[2]Technical University of Denmark, Søltofts Plads, Bygn. 229, 2800 Lyngby, Denmark

[c]Risø DTU, Technical University of Denmark, Frederiksborgvej 399, 4000 Roskilde, Denmark

[+]Corresponding author: Fax: +45 4630 1212 - e-mail: mwi@dmu.dk

ABSTRACT

This paper focuses on the emission estimation part of the research project HYSCENE, which is currently being carried out in Denmark. The aims is to improve the understanding of the environmental and health impacts, and related socio-cultural and welfare economic impacts of a renewable energy system where hydrogen is an important element. The fuel shift towards hydrogen brings down the road transport consumption of fossil fuels by 2%, 24% and 79%, respectively, in the scenario years 2015, 2030 and 2050. For greenhouse gases, large national emission reductions are expected, and locally, decreasing vehicle emissions in urban streets are predicted in the case of Copenhagen for NO_x *and* $PM_{2.5}$*. On a country scale, however, the* H_2 *scenario results conversely show higher* $PM_{2.5}$ *emissions compared to the baseline situation, mainly due to the increased use of biomass in residential stoves.*

Keywords: *H_2, CO_2, NO_x, $PM_{2.5}$, road transport, emission forecast, stationary energy sources.*

1. INTRODUCTION

The aim of the HYSCENE project is to improve the understanding of the environmental and health impacts, and related socio-cultural and welfare economic impacts of a renewable energy system where hydrogen is an important element. The core part of HYSCENE consists of a fossil fuel baseline projection, and a hydrogen scenario assuming a certain penetration of hydrogen fuel in the Danish road transport sector, and more widespread use of wind power and biomass for power and heat generation. This presentation focuses on the emission estimation part of the HYSCENE project. The assumptions behind the projection of hydrogen consumption will be explained. The main CO_2-eq., NO_x and $PM_{2.5}$ emission results will be discussed for the scenario years 2015, 2030 and 2050. Finally, GIS distributed emission results will be shown for Denmark (17x17 km) and for the Greater Copenhagen area (1x1 km) in the scenario years. The GIS distributed emission data serve as an input for further dispersion modelling in the HYSCENE project.

2. METHOD

2.1. Fuel consumption data

Data for fuel consumption in the HYSCENE baseline projections and H_2-scenarios have been provided by Risø National Laboratory for Sustainable Energy. The Risø data for the baseline situation is based on historical and forecasted fuel consumption information from the Danish Energy Authority (DEA), and thus includes the forecast years 2015, 2030 and 2050, which were selected for emission calculations in HYSCENE. The sectors covered by Risø data are road transport, other transport (sea transport, railways and domestic aviation), power plants, district heating, households, trade and service, and industry (including agriculture/forestry/aquaculture).

Prior to emission calculations in HYSCENE, certain modifications of the Risø fuel consumption data are made in a few cases in order to match the sector and fuel type categories behind the historical Danish emission estimates reported to the UNFCCC and UNECE conventions (Illerup et al., 2007a, 2007b), and the latest official Danish emission projections carried out by NERI (Illerup et al., 2007c and 2008). Another reason for adjustment is to prevent sudden data jumps between the latest historical year and the first year of the forecast period.

For the H_2 scenario part, the Risø data contains the percentages of fossil fuel consumption being displaced by hydrogen in the forecast years. The penetration of hydrogen fuel is assumed to take place on a longer time scale, recognizing the need for technology research and development, infrastructure development, making transportation means ready for the market, penetration of vehicle sales, and penetration of the total stock, etc. Furthermore, the H_2 scenario is formed to leave space for other alternative fuels such as electricity (Jørgensen, 2008).

The hydrogen is assumed to be produced by means of electrolysis, based on electricity from the Danish public grid, and the hydrogen transmission and distribution is assumed to use the existing nationwide natural gas pipe system. Refuelling and joint storage facilities for hydrogen are envisaged to be established equivalent to the present refuelling infrastructure for fossil fuels. It is furthermore presumed that all hydrogen driven vehicles will be based on fuel cell propulsion systems, and that the hydrogen fuel is supplied in a gaseous state to the vehicles.

The transfer to hydrogen which will lead to the introduction of onboard technologies with a much better energy-efficiency than the current fossil fuel based technologies, and expected technology developments during the scenario period cause the conventional fuels to be replaced by similarly smaller quantities of hydrogen. Technology improvements are likely to result in increased tank pressure ratios, more light-weight tank materials, improved on-board fuel efficiencies and longer vehicle range. For more information regarding the hydrogen production and transmission/distribution, fuel cells and storage tanks, see Jørgensen (2008).

Table 1: Consumption of fossil fuel in the HYSCENE baseline and H_2-scenario

	2015	2030	2050	2015	2030	2050	2015	2030	2050
	Baseline (PJ)			H_2-scenario (PJ)			H_2-scenario (%-H_2)		
Passenger cars	97.7	109.5	120.6	97.7	87.0	16.9	0.0	20.5	86.0
Buses	8.0	7.9	7.9	5.2	0.0	0.0	35.0	100.0	100.0
Vans	29.2	30.4	33.7	29.2	24.3	11.7	0.0	20.0	65.3
Trucks	29.8	32.3	35.9	29.8	25.9	12.5	0.0	20.0	65.3
2-wheelers	1.6	1.8	2.0	1.6	1.8	2.0	0.0	0.0	0.0
Sum	166.3	182.0	200.1	163.5	139.0	43.0	1.7	23.6	78.5

The percentage figures of hydrogen penetration are given in Table 1 for passenger cars, vans/trucks, and buses, respectively, and corresponding figures of fossil fuel consumption in the baseline scenario and the H_2 scenario are also shown.

Subsequently, the amount of hydrogen (PJ) used by hydrogen fuelled vehicles is then estimated by using average Tank to Wheel (TtW) efficiency factors for vehicles using fossil fuels and hydrogen fuel, respectively. For the latter vehicles the factors comprise the efficiency of the drive system and effect of higher vehicle weight. The efficiency factors are shown in Table 2.

Table 2: Efficiency factors for fossil (TtW) and hydrogen fuelled vehicles (drive system, weight, and resulting TtW) used in HYSCENE

	Baseline Mean eff. (TtW)			H_2-scenario Mean eff. drive system			H_2-scenario Extra cons. (weight)			H_2-scenario Mean eff. (TtW)		
	2015	2030	2050	2015	2030	2050	2015	2030	2050	2015	2030	2050
Pass. cars	0.17	0.18	0.19	0.40	0.46	0.53	1.20	1.10	1.05	0.33	0.42	0.50
Buses	0.19	0.20	0.20	0.40	0.46	0.53	1.20	1.10	1.05	0.33	0.42	0.50
Vans	0.20	0.20	0.20	0.40	0.46	0.53	1.20	1.10	1.05	0.33	0.42	0.50
Trucks	0.20	0.20	0.20	0.40	0.46	0.53	1.20	1.10	1.05	0.33	0.42	0.50

The loss of hydrogen from fuel handling at filling stations, and the hydrogen leakage in transmission lines and central storage are quantified by using leakage factors (0.05 in both cases, and the total hydrogen mass is found by dividing with the lower heating value for hydrogen (120 GJ/tons fuel). Table 3 shows the estimated consumption of hydrogen (in the vehicles), and hydrogen losses (in PJ and tonnes) for road transport in 2015, 2030 and 2050. The H_2 leakage is equivalent to about 10% of the consumption.

Table 3: Hydrogen consumption (by vehicles), and losses for road transport used in HYSCENE.

		2015	2030	2050
H_2 consumption (PJ)	Passenger cars	0.0	9.7	39.0
	Buses	1.6	3.8	3.1
	Vans	0.0	2.9	8.7
	Trucks	0.0	3.1	9.3
	Sum	1.6	19.5	60.2
H_2-leakage (PJ)	Sum	0.2	2.1	6.5
H_2-leakage (tonnes)	Sum	1420	17416	53824

2.2. Emission calculations

An internal NERI model with a structure similar to the European COPERT III emission model is used to calculate the Danish road transport emissions. For most vehicle categories, updated fuel use and emission data from the new COPERT IV version (EMEP/CORINAIR, 2007) is incorporated in the NERI model. A thorough description of fleet and mileage data, emission factors, and the emission calculation approach for road transport is given by Winther (2007).

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 (EMEP/-CORINAIR, 2007) for the historical situation (Illerup et al., 2007a and 2007b). Appropriate forecast assumptions for fleet, activities and emission factors are used to predict the future emissions, also taking into account emission legislation already adopted. The calculation methods for the forecast part are further described in Winther (2001), Winther and Nielsen (2006), Illerup et al. (2007c and 2008) and Winther (2008).

For the remaining sectors the methods for calculating historic emissions are found in Illerup et al., 2007a and 2007b, and for the projection in Illerup et al. 2007c and 2007d.

The approach to determine the saved emissions in the H_2 scenario, is to remove the quantity of fossil fuel from the baseline estimations, being displaced by hydrogen fuel consumption. This is done separately for passenger cars, vans/trucks, and buses. In each forecast year, the saved emissions originate from the newest vehicles, being replaced by hydrogen fuelled ones.

3. RESULTS

The HYSCENE emission results are shown in Table 4 for CO_2-eq. (deriving from CO_2, CH_4 and N_2O), NO_x, $PM_{2.5}$ and the hydrogen loss. For CH_4 and N_2O, respectively, IPCC indices of 21 and 310 are used to relate the global warming potential (GWP) of these components to CO_2.

Table 4: CO_2-eq., NO_x, $PM_{2.5}$ and H_2 emission results calculated in HYSCENE

		CO_2-eq. (ktons)			NO_x (tons)			$PM_{2.5}$ (tons)				H_2(tons)
		Road	Other	Sum	Road	Other	Sum	Road exh.	Road non-exh.	Other	Sum	Sum
2004	Baseline	11953	53121	65074	66565	176401	242967	2876	842	25520	26363	0
2015	Baseline	12722	46816	59538	30842	117040	147882	1017	897	17770	18667	0
	H2 scenario	12514	43364	55877	30144	120329	150473	1008	897	23382	24278	1420
	Reduction	209	3452	3661	697	-3289	-2591	9	0	-5611	-5611	-1420
	Red. (%)	2	7	6	2	-3	-2	1	0	-32	-30	
2030	Baseline	13910	45174	59084	14683	90273	104956	301	976	12070	13046	0
	H2 scenario	10636	27653	38289	10250	92454	102704	231	976	16832	17808	17416
	Reduction	3274	17521	20795	4432	-2181	2251	70	0	-4762	-4762	-17416
	Red. (%)	24	39	35	30	-2	2	23	0	-39	-37	
2050	Baseline	15294	47358	62651	15239	93058	108297	301	1074	11121	12195	0
	H2 scenario	3277	25186	28463	4242	95350	99593	103	1074	15753	16827	53824
	Reduction	12017	22172	34189	10997	-2293	8704	198	0	-4632	-4632	-53824
	Red. (%)	79	47	55	72	-2	8	66	0	-42	-38	

The largest emission impacts are noted for road transport. For this source category increasingly significant emission reductions are expected for the years 2015, 2030 and 2050 in terms of CO_2-eq. (2%, 24%, 79%), NO_x (2%, 30%, 72%) and exhaust $PM_{2.5}$ (1%, 23%, 66%) resulting from the gradual shift towards the usage of hydrogen fuelled vehicles. The non exhaust $PM_{2.5}$ emissions arising from tyre and brake wear and road abrasion, remains the same in the baseline and the H_2 scenario. Hence, smaller emission reductions are expected for total road transport $PM_{2.5}$ in 2015, 2030 and 3050 (0%, 5% and 14%, respectively) compared to exhaust alone.

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 H_2-scenario**.** The achieved emission reductions for other sources, however, are more moderate than for road transport alone, and hence the total Danish GHG emissions in 2015, 2030 and 2050 reduce by 6%, 35% and 55% in the H_2-scenario compared to the baseline case.

The higher NO_x emission in the H_2 scenario compared to the baseline situation for other sources is due to an increased use of natural gas and biogas. These fuels have very high NO_x emission factors when combusted in gas engines. Further, the use of biomass does not bring down the NO_x emissions. The higher $PM_{2.5}$ emission for the H_2 scenario compared to the baseline is the large increase in biomass combustion especially in the residential sector associated with high emission factors. For other sources in 2015, 2030 and 2050, negative emission changes are calculated for NO_x (-3%, -2%, -2%) and $PM_{2.5}$ (-32%, -39% and -42%).

For road transport, passenger cars is the largest source of fuel consumption, and Figure 1 shows the emission development (CO_2-eq., NO_x, $PM_{2.5}$) for this vehicle category in the baseline and H_2 scenario. The emissions of CH_4 and N_2O only accounts for a small amount of the total greenhouse gases, and hence the achieved CO_2-eq. emission reductions are more or less the same as the percentage of fossil fuel (in energy units) replaced by hydrogen, (Table 1). The emission picture for NO_x and $PM_{2.5}$ (from exhaust) is very similar to the one for CO_2-eq.

In HYSCENE, the newest vehicles from the baseline case are assumed to be hydrogen fuelled in the H_2 scenario, and in 2030 (and even more pronounced in 2050) the total mileage driven by vehicles not complying with the most stringent EU emission standards is merely small. Hence no significant total emission reductions will be achieved by a direct substitution with the oldest part of the fleet. For 2015 an exception is valid for buses, though.

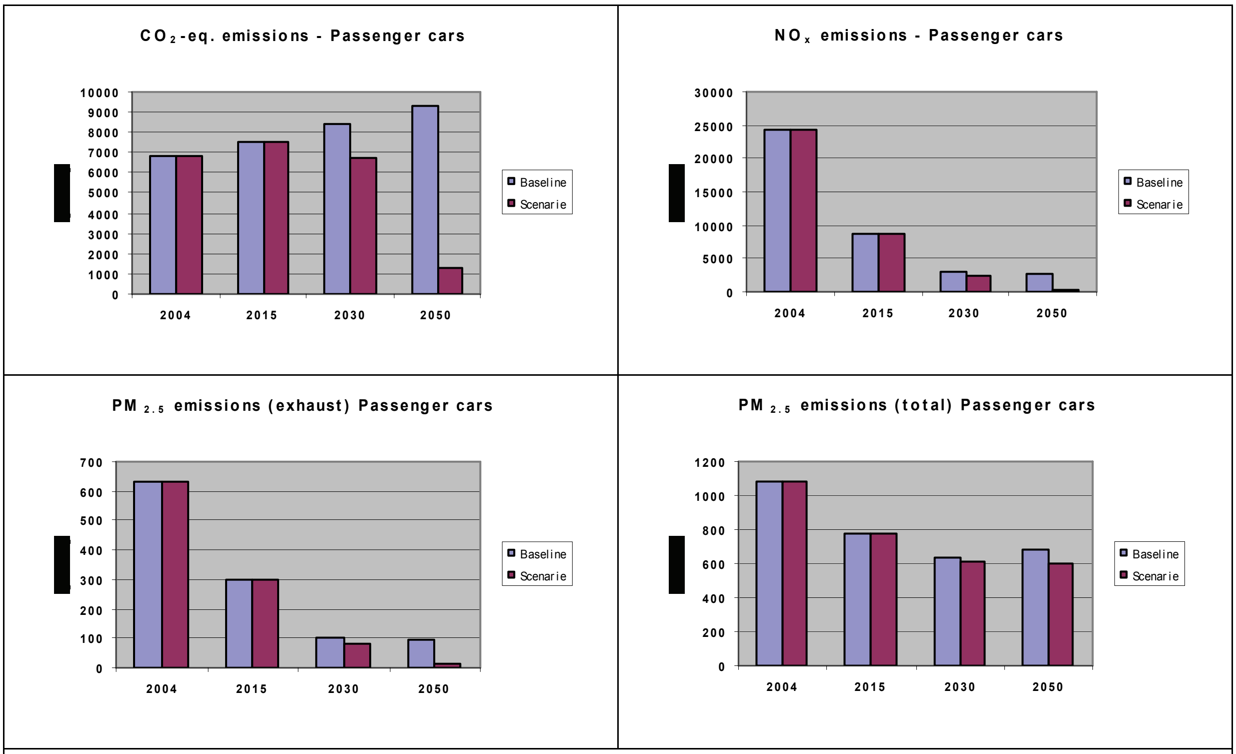

Figure 1: Emission development for passenger cars in the baseline and H2 scenario

Figure 2 shows the 17x17 km GIS distribution of the $PM_{2.5}$ emissions for Denmark based on the HYSCENE results. The expected increase in $PM_{2.5}$ emissions in the H_2 scenario is visible compared to the reference case, due to the increased use of biomass in the residential sector. Due to traffic, the NO_x emissions are relatively dense in urban areas. Figure 3 shows the GIS distribution of the HYSCENE NO_x emissions (1x1 km) for the Greater Copenhagen area, related to road traffic. The emissions in the H_2 scenario clearly become lower compared with the baseline results. For exhaust $PM_{2.5}$, the emission picture (not shown) is more or less the same as for NO_x. If, however, the non-exhaust part of traffic $PM_{2.5}$ was included also, the expected baseline/H_2 scenario emission changes become small, due to the relatively large emission weight of non-exhaust $PM_{2.5}$ of total traffic $PM_{2.5}$.

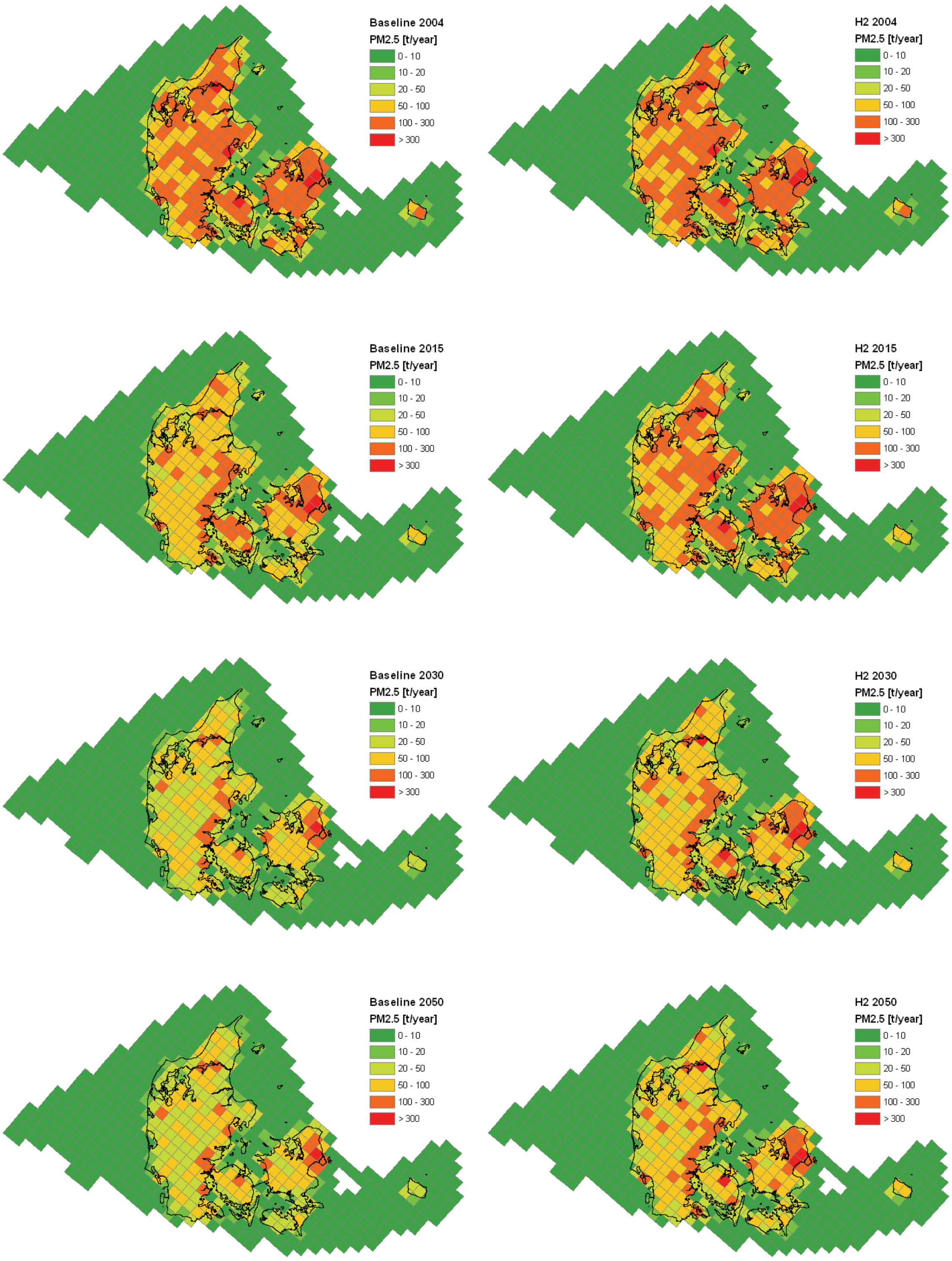

Figure 2: $PM_{2.5}$ emissions (17x17 km) for Denmark for the years 2004, 2015, 2030 and 2050 (baseline and H_2-scenario)

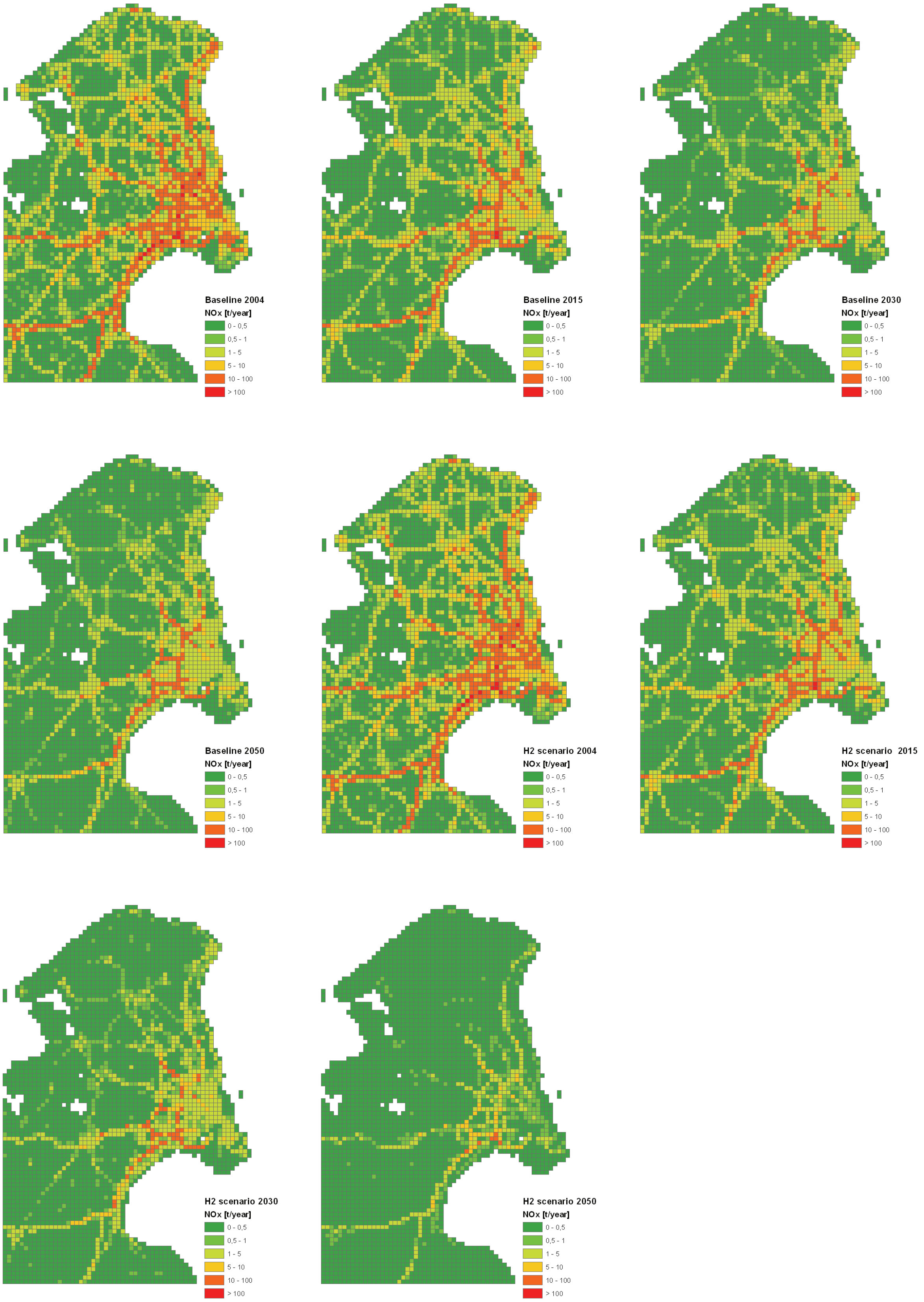

Figure 3: NO_x emissions (1x1 km) for the Greater Copenhagen area for the years 2004, 2015, 2030 and 2050 (baseline and H_2-scenario)

4. CONCLUSION

Significant emission reductions can be achieved from a large scale introduction of hydrogen fuelled vehicles in the road transport sector, as shown in this project for greenhouse gases. Further, decreasing vehicle emissions in urban streets are predicted in the case of Copenhagen for NO_x and $PM_{2.5}$, and this will improve public health. On a country scale, the H_2 scenario results conversely show higher $PM_{2.5}$ emissions compared to the baseline situation, mainly due to the increased use of biomass in residential stoves. If a future national energy system envisages more widespread private use of biomass, the health problems will inevitably become larger, if no additional steps are taken in terms of emission legislation, and technology development related to particle filters and retrofitting of these.

5. ACKNOWLEDGEMENT

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6. REFERENCES

EMEP/CORINAIR (2007): Emission Inventory Guidebook 3rd edition, prepared by the UNECE/EMEP Task Force on Emissions Inventories and Projections, 2007 update. Available at: http://reports.eea.europa.eu/EMEPCORINAIR5/en/page002.html.

Illerup, J.B., Lyck, E., Nielsen, O.K., Mikkelsen, M.H., Hoffmann, L., Gyldenkærne, S., Nielsen, M., Winther, M., Fauser, P., Thomsen, M., Sørensen, P.B. & Vesterdal, L. (2007a): Denmark's National Inventory Report 2007. Emission Inventories - Submitted under the United Nations Framework Convention on Climate Change, 1990-2005. National Environmental Research Institute, University of Aarhus. - NERI Technical Report 632: 642 pp. (electronic).

Illerup, J.B., Nielsen, O.K., Winther, M., Mikkelsen, M.H., Hoffmann, L., Nielsen, M., Gyldenkærne, S., Fauser, P., Jensen, M.T. & Bruun, H.G. (2007b): Annual Danish Emission Inventory Report to UNECE. Inventories from the base year of the protocols to year 2005. National Environmental Research Institute, University of Aarhus. - NERI Technical Report 649: 182 pp. (electronic).

Illerup, J.B., Nielsen, O.K., Winther, M., Mikkelsen, M.H., Lyck, E., Nielsen, M., Hoffmann, L., Gyldenkærne, S. & Thomsen, M. (2007c): Projection of Greenhouse Gas Emissions. 2005 to 2030. National Environmental Research Institute, University of Aarhus. - NERI Technical Report 611: 116 pp. (electronic).

Illerup, J.B., Nielsen, O-K., Winther, M., Mikkelsen, M.H., Nielsen, M., Fauser, P. & Gyldenkærne, S. (2008): Projection of SO_2, NO_X, NMVOC, NH_3 and particle emissions - 2005 to 2030. National Environmental Research Institute, University of Aarhus. 121 pp. – NERI Technical Report no. 655.
Jørgensen, K. (2008): Scenario large-scale introduction of hydrogen in the Danish transport sector, Risø, Technical University of Denmark,documentation note, 9 p.

Winther, M. (2001a): 1998 Fuel Use and Emissions for Danish IFR Flights. The Danish Environmental Protection Agency - Environmental Project no. 628, 2001. 112 p.

Winther, M. & Nielsen, O.K. (2006): Fuel use and emissions from non-road machinery in Denmark from 1985–2004 – and projections from 2005-2030. The Danish Environmental Protection Agency. - Environmental Project 1092: 238 pp.

Winther, M. (2007): Danish emission inventories for road transport and other mobile sources. Inventories until year 2004. National Environmental Research Institute. - Research Notes from NERI 236: 244 pp. (electronic).

Winther, M. (2008): Fuel consumption and emissions from navigation in Denmark from 1990-2005 - and projections from 2006-2030. Technical Report from NERI no. 650. 109 pp.