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The potential role of hydrogen energy in India and Western Europe

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Abstract

We used the TIMER energy model to explore the potential role of hydrogen in the energy systems of India and Western Europe, looking at the impacts on its main incentives: climate policy, energy security and urban air pollution. We found that hydrogen will not play a major role in both regions without considerable cost reductions, mainly in fuel cell technology. Also, energy taxation policy is essential for hydrogen penetration and India's lower energy taxes limit India's capacity to favour hydrogen. Once available to the (European) energy system, hydrogen can decrease the cost of CO_2 emission reduction by increasing the potential for carbon capture technology. However, climate policy alone is insufficient to speed up the transition. Hydrogen diversifies energy imports; especially for Europe it decreases oil imports, while increasing imports of coal and natural gas. For India, it provides an opportunity to decrease oil imports and use indigenous coal resources in the transport sector. Hydrogen improves urban air quality by shifting emissions from urban transport to hydrogen production facilities. However, for total net emissions we found a sensitive trade-off between lower emissions at end-use (in transport) and higher emissions from hydrogen production, depending on local policy for hydrogen production facilities.
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Keywords: Hydrogen energy; India/Europe; Scenario analysis

1. Introduction

Hydrogen energy is often mentioned as a potential solution for several challenges that the global energy system is facing. The first advantage is the fact that hydrogen use results in nearly zero emissions at end-use, thus improving air quality. Secondly, hydrogen opens up the possibility of (decentralised) production on the basis of a variety of fuels, diversifying energy supply. The latter may contribute to reduce the dependence on imported oil (Dunn, 2001; Lovins, 2003). Hydrogen energy can also play an important role in the mitigation of greenhouse gas emissions (Barreto et al., 2003; Edmonds et al., 2004; van Ruijven et al., 2007). However, the required technology is currently only emerging, hydrogen is still more expensive than other options and the infrastructure for widespread use still needs to be developed.

The future of hydrogen therefore depends critically on whether the above-mentioned barriers are reduced. This is partly determined by the context of the system in which hydrogen is introduced; we here focus on the difference between energy systems in developed and developing countries. This difference is, for instance, important for the reasons for making a transition. For developed regions, issues like competitiveness (being the first), greenhouse gas emission mitigation and energy security play a major role (McDowall and Eames, 2006). For developing regions, the potential to reduce air pollution emissions and improve energy security may be more important. Barriers are also likely to be different. While the affordability of hydrogen energy technology may be a more limiting factor in developing countries than in developed countries, the rapid growth of infrastructure in some developing countries (China and India) may create important opportunities.

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The evolution of the world energy system is complex, which is an argument to use models in the exploration of alternative pathways. However, at the global scale, such models are aggregated and might not deal effectively with regional differences. Hence, one should investigate the regional outcomes in more detail. In this article, we explore the potential role of hydrogen energy in two selected regions: India and Western Europe.[3] The focus on only two regions implies that we are able to account for available information on the local situation. These two specific regions were chosen because earlier research showed that Western Europe might become an early adopter of hydrogen energy (van Ruijven et al., 2007), while India is one of the first (high-growth) developing countries that is seriously looking at hydrogen energy (Bist, 2006). We analyse the impact of hydrogen on the main arguments in its favour: climate policy, energy security and urban air pollution, using scenario results for demand, production and system structure as modelled in the TIMER global energy model (de Vries et al., 2001; van Vuuren et al., 2006). The aim of this analysis is to further specify and differentiate the potential role of hydrogen in the context of different energy systems.

In this paper, Section 2 provides a brief overview of existing energy scenarios for India and Western Europe. Section 3 describes the main drivers and barriers for hydrogen energy and their relevance for both regions. Section 4 discusses the current research and planning on hydrogen energy in both regions. Section 5 focuses on the modelling of hydrogen energy systems and Sections 6 and 7 discuss the results of the model simulations and the impact of hydrogen on its main driving arguments. Section 8 finalises the paper with a discussion and conclusion.

2. Energy scenario literature for India and Western Europe

2.1. Energy scenarios

By comparing available regional energy scenarios for India and Western Europe it is possible to obtain a better insight in the energy system context of these specific regions. A recently published study by the Indian Planning Commission on Integrated Energy Policy (Planning Commission, 2006) explores the future development of the Indian energy system using two economic growth scenarios. A broader set of four scenarios was published in 2003, implementing the IPCC-SRES scenarios for India, using two axes of possible future developments: high and low market integration and centralised and decentralised governance (Shukla et al., 2003). The IEA World Energy Outlook (WEO) 2006 provides two energy scenarios on the basis of a single socio-economic projection: a reference and a policy scenario (IEA, 2006).

For Europe[4] several scenario studies have been published as well, describing a broad range of possible energy futures. We here limit the comparison to the IEA World Energy Outlook (IEA, 2006) and a set of European baseline scenarios from the PRIMES model (Mantzos et al., 2004). The latter explores the impact of different levels of economic growth, energy prices and policy options on energy technologies and transport modes.

The baseline scenario for the this study is the second OECD Environmental Outlook baseline scenario: TIMER OECD-EO (Kram and Bakkes, 2006). This scenario assumes no new explicit policies; it involves continuation of current policies and implicitly assumes the existence of an environmental Kuznets curve on emission factors of developing countries. With respect to energy, it is based on the IEA WEO scenario (IEA, 2004), which is regarded a medium scenario on energy supply and demand. Below, we compare the energy scenarios for India and Europe with the TIMER OECD-EO scenario. We limit this comparison to the period until 2030, because this is the time horizon of most discussed scenario studies. However, in the rest of this article, we use a time horizon up to the year 2050.

2.2. Economy and population

Economic projections for India are characterised by high GDP growth rates, varying between 4% per year in the *IB2 Self-reliance* scenario (Shukla et al., 2003) and the IEA-WEO and up to 9% per year in *IA1 High Growth* (Shukla et al., 2003) and the Planning Commission scenarios. In absolute terms, this corresponds to an increase in GDP from 467 billion USD_{1995}/yr in 2000 to a range of 1750–5600 billion USD_{1995}/yr in 2030. In the same period, the Indian population is expected to grow by about 1.1% per year, to a total of 1.4 billion people in 2030 (IEA, 2006; Planning Commission, 2006). This means that growth rates for GDP per capita are lower than for total GDP: between 3% and 7% per year, or an increase from 460 to 1240–3800 USD_{1995} per capita per year. The TIMER OECD-EO scenario is in the middle of this range, projecting a GDP per capita of 2400 USD_{1995}/yr in 2030.

For Western Europe, economic growth projections decrease from 2.3% (2004–2015) to 1.8% (2015–2030) per year in the IEA-WEO and vary between 1.9% and 2.6% per year in the PRIMES study. In absolute terms, the Western European GDP is projected to increase from 9000 billion USD_{1995}/yr in the year 2000 to 18,000–23,000 billion USD_{1995}/yr in 2030. Population growth estimates for Europe are in the range of 0.1–0.2% per year,

[3]For the geographical definition of this region, see: www.mnp.nl/image.

[4]One particular issue with studies on Europe is the variation in geographical definitions. Official European Union studies often use the definitions of EU15 and EU25 countries, the IEA uses OECD Europe as it is at this moment (including several Eastern European countries and Turkey) and the TIMER/IMAGE model includes the region of OECD Europe as it was around the year 2000 (comparable to EU15 plus Norway and Switzerland) and the region of Eastern Europe (together these regions are comparable to the EU25).

increasing from currently 380 million people to 390–415 million people in 2030. This implies per capita GDP growth projections of 1.7–2.7% per year, or in absolute terms from 27,000 USD_{1995}/yr per capita in 2000 to 45,000–56,000 USD_{1995}/yr in 2030. The TIMER OECD-EO scenario is on the lower bound of this range.

2.3. Energy

For India, the comparison of energy use projections is somewhat complicated by the fact that some studies include non-commercial energy, while others do not. The Planning Commission projects a 5–7-fold increase of primary energy use between 2000 and 2030, excluding non-commercial energy. The other studies are more moderate, projecting TPES to increase 2–3 fold between 2000 and 2030. The TIMER OECD-EO scenario is in line with the average of the other studies (excluding the Planning Commission), projecting a factor 2.3 increase of the total Indian energy use between 2000 and 2030 (Fig. 1, left graph).

In the Indian primary energy mix of the TIMER OECD-EO scenario, coal is projected to remain dominant, followed by oil and biomass. Nuclear and renewable energy sources show a rapid increase in India, but are not projected to reach the European 2003 level by 2050 (see Tables 1 and 2). Biomass energy, which is mainly used for cooking in rural households, made up almost 40% of the total energy use of India in the year 2000; although its share is generally expected to decline, its evolution is one of the main uncertainties in energy use projections. Currently, India already depends strongly on imports of oil and for the future it is expected that imports will increase to almost the total oil consumption in the country (Table 1). Also natural gas, which is increasingly applied in India's transport sector, is expected to be imported up to almost 90% by 2050.

The energy scenarios for India do hardly involve any role of hydrogen. The Planning Commissions recommends the government to develop a research programme for hydrogen, as they regard it a promising energy carrier for the long-term future. The IEA-WEO 2006 expects fuel cells (running on hydrogen) to count for 1% of global electricity production by 2030, but it does not explicitly mention the involved regions. Hydrogen application in the transport sector is indicated 'promising after 2030' (IEA, 2006). The TIMER OECD-EO scenario does not involve any hydrogen energy applications in India before 2050.

For Europe, the projections considered here provide a range of 8–27% increase in TPES in 2030 compared to 2000. The TIMER OECD-EO scenario is on bottom of this range, as it projects an increase of 10% between 2000 and

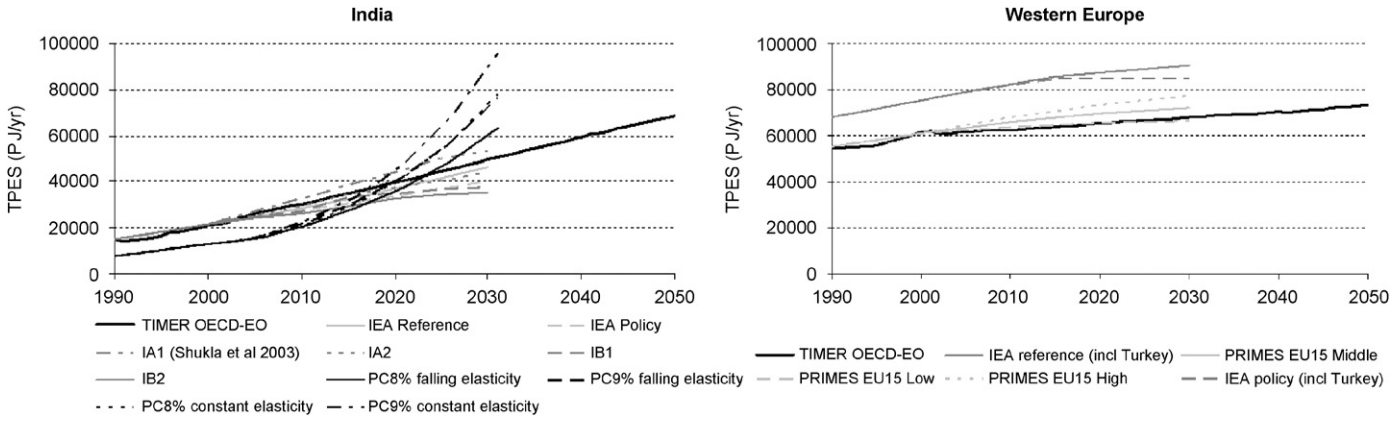

Fig. 1. Total primary energy supply in several scenarios for India and Western Europe. The different levels for Europe in 1990 are due to different regional definitions. The different levels for India are due to the exclusion of non-commercial fuels by the Planning Commission.

Table 1
Total primary energy supply in India (EJ/yr) coal oil natural gas biomass nuclear solar/wind

India	Coal	Oil	Natural gas	Biomass	Nuclear	Solar/wind	Hydro	Total
2000	7.1	4.8	0.9	8.5	0.2	0.0	0.3	21.6
Import	8%	67%						18%
2030	22.0	12.2	2.8	13.6	1.4	0.1	0.7	51.8
Import	8%	91%	50%	7%				29%
2050	29.7	20.7	7.0	12.8	1.7	0.5	0.8	72.1
Import	10%	99%	88%	4%				41%

Historic data: IEA energy balances, *future data*: TIMER OECD Environmental Outlook scenario. Nuclear energy is converted to primary energy using 33% efficiency; numbers for solar, wind and hydro are the energy content of electricity produced.

Table 2
Total primary energy supply in OECD Europe (EJ/yr)

Western Europe	Coal	Oil	Natural gas	Biomass	Nuclear	Solar/wind	Hydro	Total
2000	10.0	25.2	11.8	2.0	9.1	0.0	1.6	59.9
Import	46%	55%	41%	1%				39%
2030	12.5	18.4	23.8	10.4	8.4	2.0	2.0	71.8
Import	72%	57%	59%	48%				50%
2050	17.7	22.9	24.5	5.8	7.4	3.9	2.3	79.6
Import	66%	61%	65%	23%				51%

Historic data: IEA energy balances, *future data*: TIMER OECD Environmental Outlook scenario. Nuclear energy is converted to primary energy using 33% efficiency; numbers for solar, wind and hydro are the energy content of electricity produced.

2030 (Fig. 1). Europe's main primary energy carriers are oil and natural gas, followed by coal and nuclear (Table 2). The high and increasing share of imported energy, especially coal and oil, indicates that indigenous resources in Europe become more expensive while being depleted. The production of renewable energy sources such as biomass, solar/wind, geothermal and hydro is projected to increase steadily.

Although the PRIMES scenario study does not foresee any role for hydrogen in the baseline scenario, the scenarios '*mainstream policy lines: energy efficiency and renewables*' and '*combined policy*', project a total installed capacity of about 56–58 GW of hydrogen-based fuel cells for the EU25 in 2030 (Mantzos et al., 2004). The TIMER OECD-EO scenario does not show any hydrogen in Western Europe before 2050.

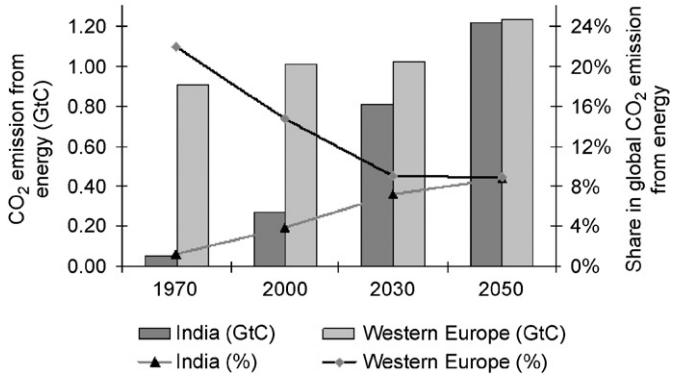

Fig. 2. CO_2 emission from energy use for India and Western Europe for the TIMER OECD Environmental Outlook scenario; absolute (bars, left axis) and relative to the total global energy-based carbon emission (lines, right axis).

3. Drivers and barriers for hydrogen energy in India and Western Europe

3.1. Drivers

In a recent literature overview of hydrogen studies, four main drivers towards a hydrogen energy system were identified: (1) climate change, (2) energy security, (3) air pollution and (4) competitiveness (McDowall and Eames, 2006).

3.1.1. Climate change

India and Western Europe play different roles in the climate policy debate. The Western European energy system emits currently about 1 Gt C/yr, which is about 15% of the global carbon emissions from energy use. The TIMER OECD-EO scenario projects a slow increase, up to 1.2 Gt C/yr in 2050 (9% of the projected global carbon emissions, see Fig. 2). The European Union countries have carbon emission reduction targets under the Kyoto Protocol and the European Council accepted proposals for stringent reductions of greenhouse gas emissions (Council of the European Union, 2007).

India's emissions are currently 0.3 Gt C/yr from energy use, which is 4% of the global emissions. However, future projections foresee a large increase in Indian carbon emissions, leading to 1.2 Gt C/yr in 2050 (similar to Western Europe and 9% of the projected global emissions, see Fig. 2). For India, no official climate policy has been adopted. Some authors (e.g. den Elzen and Meinshausen, 2005) argue that on the longer term participation of India in climate policy is needed in order to reach global stabilisation targets. However, there has been no statement by the Indian government in this direction.

In an earlier study, we found that the role of hydrogen with respect to CO_2 emissions is ambiguous (van Ruijven et al., 2007). On the one hand, hydrogen can make energy systems more flexible in responding to climate policy, because it makes the option of carbon capture and sequestration available to the transport sector. On the other hand, hydrogen production from coal is the cheapest option, causing an increase in CO_2 emissions on the long-term, without climate policy.

3.1.2. Energy security

Energy security is a relevant issue for both India and Western Europe. Fig. 3 shows the absolute trade flows and the share of imported fuels in total domestic use. India, which is currently importing over 60% of its oil, faces the potential situation that it imports all its fuels for the transport sector by 2050. By 2030, India is projected to

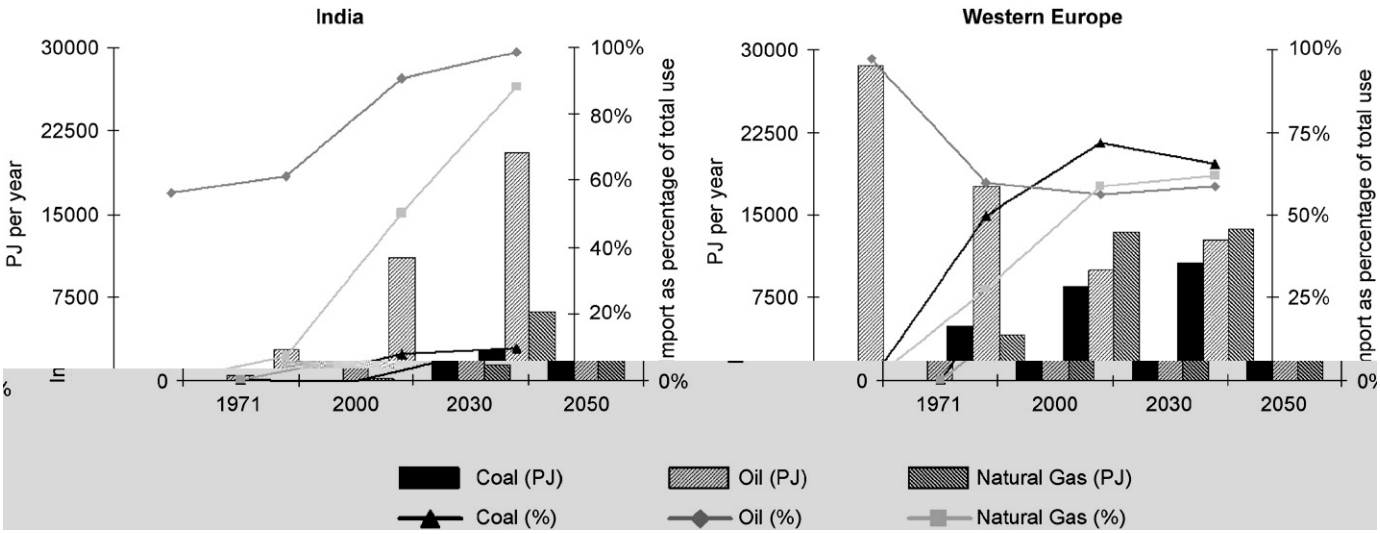

Fig. 3. Energy import for India and Western Europe, in absolute numbers (bars, left axis) and as percentage of the total inland consumption (lines, right axis) for the TIMER OECD environmental outlook scenario.

Table 3
Urban air quality in the 10 largest cities of India (left, for 2004) and Western Europe (right, for 2005), annual average concentration of NO_2, SO_2 and PM10 in mg/m^3

City	Population (million)	NO_2	SO_2	PM10	City	Population (million)	NO_2	SO_2	PM10
Greater Bombay	12.59	19	7	77	Paris	9.32	43	8	21
Calcutta	11.02	53	9	237	London	7.65	44	4	25
Delhi	8.42	57	9	432	Berlin	3.45	22	4	27
Madras	5.42	6	5	96	Milano	3.29	55	8	54
Hyderabad	4.34	29	6	178	Athens	3.07	32	11	41
Bangalore	4.13	61	7	173	Madrid	3.01	43	11	29
Ahmedabad	3.31	23	15	231	Naples	2.95			
Pune	2.49	53	31	340	Rome	2.70	41	2	
Kanpur	2.03	20	9	413	West Midlands (UK)	2.30	30	3	23
Lucknow	1.67	33	16	391	Greater Manchester	2.28	43	2	23

Data for India is from Central Pollution Control Board (2004) and the Western European data are based on European Topic Centre on Air and Climate Change (2005).

import more barrels of oil per year than Western Europe; in 2050 Indian oil import is expected to be almost twice the European inflow of oil. Western Europe is already a major importer of energy, and is expected to keep importing 50–70% of its fossil energy. Natural gas imports are increasing rapidly in both regions in the TIMER OECD-EO scenario. Also imports of coal are expected to keep increasing.

In an overview of hydrogen scenario studies, McDowall and Eames (2006) state that hydrogen is expected to be adopted in regions without significant indigenous oil or gas reserves, like India and Western Europe. Especially in scenarios with limited trade, the more expensive indigenous energy resources of these regions are expected to drive the use of hydrogen. We use long-term supply-costs curves of oil (and other fossil energy sources) in the TIMER model, based on Rogner (1997), but the ultimate resource size and cost estimates are still highly uncertain (e.g. Campbell, 2002). This has consequently a large influence on the future energy mix and carbon emissions (van Vuuren, 2007).

Application of hydrogen in the transport sector can potentially decrease imports of oil and increase the use of indigenous coal or gas reserves, which is relevant for both Europe and India. However, without hydrogen, Europe is already expected to import a major share of its coal and gas in the future and India's gas imports may reach 90% by 2050 as well. Production of hydrogen from these sources might cause additional imports.

3.1.3. *Urban air quality*

Urban air pollution may be a third driver for the introduction of hydrogen in the energy system, because it is a major concern in both India and Western Europe. Recent data on the concentration of air pollutants (NO_2, SO_2 and PM10) show that urban air pollution is generally higher in India than in Europe (Table 3). Annual average