Hydrogen production scenarios in Italy

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Abstract

Hydrogen, an energy vector, displays remarkable versatility with regards to the ways it can be produced. State-of-the-art technologies allow almost every energy source to be converted into hydrogen. What is more challenging, however, is the feasibility of building a new infrastructure to overlap with and, possibly, substitute existing one. This investigation aims to assess what it would entail to add 5% of hydrogen fuel to road transport energy consumption through 2050. The comparison spans five technologies: steam methane reforming, coal gasification, and water electrolysis where power is generated from wind, solar, and nuclear sources. The simulation provides two sets of estimates: calculations on physical infrastructure requirements and its related variable and fixed costs. With regards to facility requirements, the considered technologies show different degrees of feasibility. Coal and nuclear power are not as land-intensive as solar and wind power, but bear problems with pollution and waste disposal, respectively. Economically, coal is least expensive, followed by wind. Natural gas loses competitiveness because of high hydrocarbon prices. The sheer economic rank of preferable energy sources for generating hydrogen should be put into question when internalizing environmental impact of the considered options.

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[1] The usual disclaimer applies.

Abbreviations: RES, Renewable Energy Sources; kwh, kilowatt-hour; SMR, steam methane reforming; Mtep, million tons of equivalent petroleum, GHGs, green-house gases.

1. Introduction

Hydrogen has received a great deal of attention from both scientists and policy makers over the last decade. The energy revolution carries the promise of tackling some old energy industry issues: reliable supplies, independence from foreign oil, global and local emission reductions. Hydrogen's versatility displays manifold solutions: a sizeable amount of feedstock can indeed be converted into it, just as it is the case with electricity. Home production and reliable trade partners can help secure energy supply for the domestic economy.

Of course, this view abstracts a number of challenges that still exist. New technologies ought to be better than old ones in several aspects. First of all, in terms of energy efficiency, higher well-to-wheel performances must be achieved. Similarly, global and local emissions along the whole energy chain must be lowered. From a financial perspective, hydrogen has to make business sense for both suppliers and end users. Finally, new technologies must be easy to use and safe. The bulk of these questions have been faced, and partly addressed, by the scientific community. Feasibility, though, still has a long way to go.

The viability of hydrogen is, indeed, the question. This work is a top-down scenario analysis aiming at investigating what would be the additional infrastructure requirement if 5% of the energy in road transport were to be substituted by hydrogen. Data refer to Italy spanning up to 2050, and the focus is on fuel production. In particular, the study consists of two sections. One deals with the physical and technological issues: how many square kilometers of solar panels would be needed to produce the foreseen amount of hydrogen, for example. The other deals with the economics of infrastructure development. Each feedstock gives rise to fixed and variable costs. The ultimate goal is to collect evidence about how the adoption of hydrogen on a broad scale could possibly be buffered by the whole energy system. Can hydrogen be absorbed smoothly or does it require major infrastructure work?

Such evaluations are useful for policy-makers to estimate the investment’s magnitude of hydrogen-related technologies. It is vital to not just develop knowledge on single technologies but also on how the whole energy system can be shaped.

2. Literature review

The growing body of research that surrounds hydrogen economy-related issues can be divided into two strands. Scientists have focused on applying technological data on actual countries, states, or continents. This kind of exercise becomes instrumental in seeing how feasible it would be to employ hydrogen on an extensive scale. One can also find state-of-the-art technology descriptions and analyses on how scientific progress could make seminal solutions marketable. This group of contributions is location-free, that is facilities are not often meant to be built in a specific geographical area.

When considering location-based contributions, analogies with the current work are strong. For example, Wietschel et al. (2006) study the construction of an hypothetical hydrogen infrastructure in Europe, up to 2030. Though they analyze the whole hydrogen chain, great emphasis is placed on production. Interestingly, they choose the same technologies considered in this paper, except that they also consider also nuclear power. In an attempt to reconcile business sense and the environment, they find that natural gas reforming would be preferable to coal gasification and RES at an early stage of development. On a narrower scope, Ramesohl and Merten (2006) discuss only Germany. They stress that no matter which simulation model is used, great care should be taken to account for how hydrogen penetration would affect the remaining share of the energy system. In particular, they point out that every kwh used to produce hydrogen would be inevitably subtracted from the electric stationary application. This ultimately raises a policy issue on how to best use the limited RES potential. Ramesohl and Merten (2006) conclude that RES for fueling hydrogen would be preferable at a later stage, after 2030, and before that car efficiency should be improved. Still keeping the focus on Germany, Fischedick et al. (2004) underline once again the importance of pondering how to allocate RES potential among its alternative uses. Moreover, they step back and stress the paramount importance of reducing the demand of energy to make a RES-based system viable. Kruger et al. (2003) make the case of hydrogen fuel introduction in New Zealand from 2010 to 2050. With data on demographics, technology, and economics, they analyze what it would mean to produce hydrogen in centralized plants which would then fuel on-board devices. With respect to feedstock, they take nuclear power into great consideration. Similar issues regarding were raised by Ramesohl and Merten (2006). Finally comes California, a state that has taken building a cleaner automotive fleet into great consideration. In Lipman et al. (2004), a team of well-renowned scientists provides suggestions on how California should continue supporting hydrogen-related technologies. Since sustainability is key in their view, RES and biomasses must have a pivotal role in the production of hydrogen.

Since the issue of how to best allocate RES potential between electricity and hydrogen is mentioned with regularity, Winter (2005) becomes an essential reading. When considering production feedstock, both electricity and hydrogen share the same versatility. With regards to storage issues, instead, the two energy vectors face similar limits. In both cases, technological solutions to store energy are still quite demanding in both financial and energetic terms. Transport and distribution are not issues for electricity, while they still are for hydrogen. Along these lines, the overall efficiency from production until the final use of the two energy vectors happens to be a key factor in determining which system would be preferable. Needless to say, gaseous emission considerations closely track energy efficiency ones.

3. The model

This section is organized as follows. First comes a description of the considered technologies. Then the reader gets introduced to how energy demand in transport is generated. Next follows a depiction on how hydrogen share penetration is modeled. Finally, and conveying the previous results, the model's outcomes are wrapped up.

3.1 Technological framework

Hydrogen can be derived from a variety of feedstock. These include fossil resources, such as natural gas and coal, as well as RES, such as biomass, sunlight, and water. Local availability of feedstock, technology maturity, market applications and demand, policy issues, and costs will all affect the choice and timing of these various options.

Along the lines of Wietschel et al. (2006), five technologies are considered within Italy: steam methane reforming, coal gasification, and water electrolysis where power is generated by wind, solar, and nuclear power.

Steam methane reforming

Steam reforming involves the endothermic conversion of methane and water vapor into hydrogen and carbon monoxide. The heat is often supplied from the combustion of some of the methane feed-gas. The process typically occurs at temperatures of 700 to 850 °C and pressures of 3 to 25 bar. The gaseous product contains approximately 12% CO, which can be further converted to CO_2 and H_2 through the water-gas shift reaction.

$$CH_4 + H_2O + heat \rightarrow CO + 3H_2 \qquad (1)$$

$$CO + H_2O \rightarrow CO_2 + H_2 + heat \qquad (2)$$

Partial oxidation of natural gas is the process whereby hydrogen is produced through the partial combustion of methane with oxygen gas to yield carbon monoxide and hydrogen. In this process, heat is produced in an exothermic reaction, and hence a more compact design is possible as there is no need for any external heating of the reactor.

Coal Gasification

Hydrogen can be produced from coal through a variety of gasification processes (e.g. fixed bed, fluidized bed, or entrained flow). In reality, high-temperature entrained flow processes are preferred, so as to maximize carbon conversion to gas. This avoids the formation of significant amounts of char, tars, and phenols. A typical reaction for the process is given in equation number (3), in which carbon is converted to carbon monoxide and hydrogen.

$$C_{(s)} + H_2O + heat \rightarrow CO + H_2 \qquad (3)$$

Since this reaction is endothermic, additional heat is required, as with methane reforming. The CO is further converted to CO_2 and H_2 through the water-gas shift reaction, as described in equation (2).

Hydrogen production from coal is commercially mature, but it is more complex than the production of hydrogen from natural gas. Since coal is abundant in many parts of the world and it will likely be used as an energy source, regardless, it is worthwhile exploring the development of clean technologies for its use.

Water electrolysis

Water electrolysis is the process where water is split into hydrogen and oxygen through the application of electrical energy.

$$H_2O + electricity \rightarrow H_2 + 1/2O_2 \qquad (4)$$

The total energy that is needed for water electrolysis is a slight increase in temperature, while the required electrical energy decreases.

A high-temperature electrolysis process might, therefore, be preferable when high-temperature heat is available as waste heat from other processes. This is especially important globally, as most of the electricity produced is based on fossil energy sources with relatively low efficiencies.

Inevitably, the model makes some assumptions on the more complex issues that pertain to future technological development. In particular, how technical progress will change the chain efficiencies of the five considered technologies is not modeled. Moreover, the future evolution of energy prices will impact their competitiveness, and, therefore, the amount of investment each technology will receive. Provided the difficulty in predicting energy prices, the model is oblivious to these market dynamics.

3.2 Primary energy in road transport forecast

The analysis takes into account the aggregated road transport sub-sectors. It includes the following groups, according to the PRIMES model in European Commission (2003)[2], which is the data source:

- Private (cars, motorcycles)
- Public (buses, taxis)
- Commercial (trucks)

The data have been manipulated, combining them with the percentage of each source on the total energy demand in the transport industry. These last shares have been extrapolated from Bianchi and Bianchi and Di Giulio 2005 CEPRIG model, another data source. Bianchi and Di Giulio (2005) consider the following energy sources for transportation: oil, natural gas, electricity, and renewable. The trend of total energy demand forecasted by Bianchi and Di Giulio (2005) is as follows:

Year	Tot Energy	Oil	Natural gas	Renewable	Electric
2005	40.46Mtep	98.05%	1.19%	0.57%	0.20%
2010	41.70Mtep	97.62%	1.40%	0.62%	0.39%
2015	42.10Mtep	96.16%	1.87%	0.67%	0.69%
2020	43.20Mtep	95.48%	2.80%	0.75%	0.96%
2025	43.64Mtep	94.54%	3.14%	0.82%	1.50%

Figure (1). Bianchi and Di Giulio (2005) energy demand forecast in the transport sector.

Since the energy consumption estimates of the two mentioned models do not stretch until 2050, three scenarios with different functional specifications were regressed[3].

With regard to this section, the assumptions are:

- Hydrogen share equal to 5% in 2050;

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[2] "Italy: baseline scenario".

[3] See annex 2.

- Hydrogen substitutes only oil-derived products;
- $Mtep_H$=2.5 $Mtep_{oil}$: equivalence for efficiency between hydrogen and oil;

Adopting Bianchi and Di Giulio (2005) findings, macroeconomic variables such as GDP and population dynamics are those considered in that model. Similarly, variables related to the motor fleet such as average mileage, energy efficiency, and number of vehicles are not modeled. How congestion could affect energy use is also not modeled.

Data sources adopted, both technical and economical, can be found in annex 1.

3.3 Hydrogen share forecast

Consistent with the forecast on energy employed in the transport sector, three scenarios are drawn. Each scenario consists of a different pattern according to which hydrogen share is supposed to evolve. The functional form of the pattern determines the speed of hydrogen's adoption.

Low scenario

This optimistic scenario shows a relevant decrease in energy demand starting from 2030. The decrease could be due not only to substantial technical improvements, with a subsequent reduction in energy intensity, but also to real changes in peoples' behavior with respect to energy consumption. This scenario embraces a quadratic functional form, so that hydrogen's share is very small in the first decades and then increases swiftly with the introduction of new hydrogen technologies.

$$\%MtepH=a\cdot t^2+b\cdot t+c \qquad (5)$$

Medium scenario

In this case, the assumption is a linear growth of hydrogen's share, considering also a linear growth of all other sources.

$$\%MtepH=d\cdot t+e \qquad (6)$$

High scenario

Due to the fact that this scenario foresees a continuous growth in the total energy demand for transport, a logarithmic function serves the purpose best. In this way, hydrogen's growth is stronger in the first decades and then its growth rate drops. Such a profile could be explained, for example, by a strong public incentive-based energy policy, stimulated by a greater care taken by citizens on transport-related environmental issues.

$$\%MtepH=f\cdot Log(t)+g \tag{7}$$

An important point to model is the gain in energy efficiency when hydrogen substitutes oil-derived products. Since hydrogen is more efficiently produced than traditional oil-derived products, its energy demand in transport gets proportionally reduced. The actual energy needed after the when hydrogen gets employed is:

$$Mtep_{H2}=\frac{\%Mtep_{H2}\cdot Mtep_{Tot}^{Old}}{(1+1.5\cdot\%Mtep_{H2})} \tag{8}$$

There is therefore a savings in total energy consumed due to the introduction of a new and more efficient process.

3.4 Model's outcomes

As previously mentioned, the model provides two outcomes: one relates to physical, infrastructural requirements and the other extrapolates the cost estimates of building and running such plants. All the estimates refer to the three scenarios: low, medium, and high. Each scenario embeds different patterns of both energy demand in transport and hydrogen penetration shares. The low scenario is the most conservative of the simulations. The high scenario provides the most disruptive case for the energy system.

Costs

With regard to costs, each energy source has both fixed and variable costs. Fixed costs refer to the initial investment required to set up a plant. Their magnitude depends mainly on the size of the plant which, in turn, depends on the amount of energy required. Combining standard plant installed power with energy demand forecasts determines the number of plants to build. This, in turn gives fixed investment costs.

The amount of energy to deliver each year as hydrogen determines the size of the variable costs. Each of the five energy sources has specific outlays, such as maintenance, fuel, and decommissioning, which add up to the global variable cost.

Total costs are computed as follows. Variables costs clearly belong to the year in which they arise. Fixed costs are charged only to the year in which the plants are built. This may be seen as a naïve choice, but clearness benefits from consistency across energy sources in such a decision. This is the reason why some of the following graphs, figures (2)-(4), experience bumps.

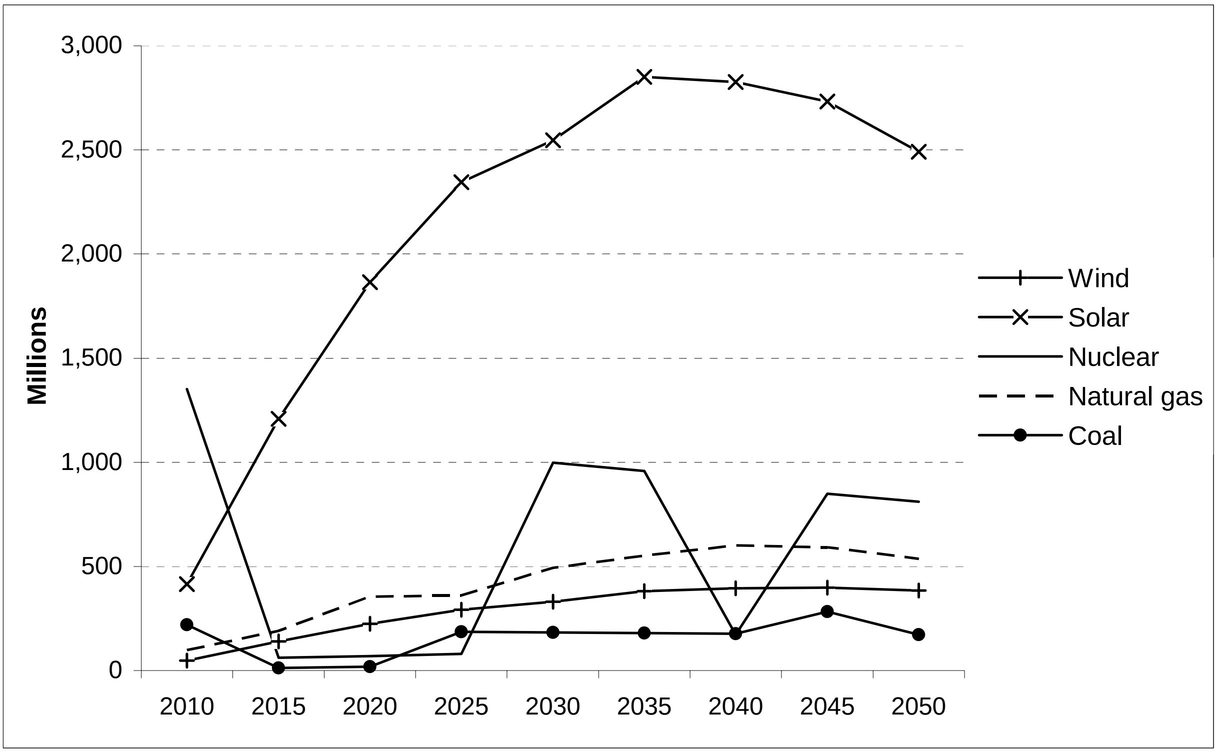

Figure (2). Total costs in the low scenario.

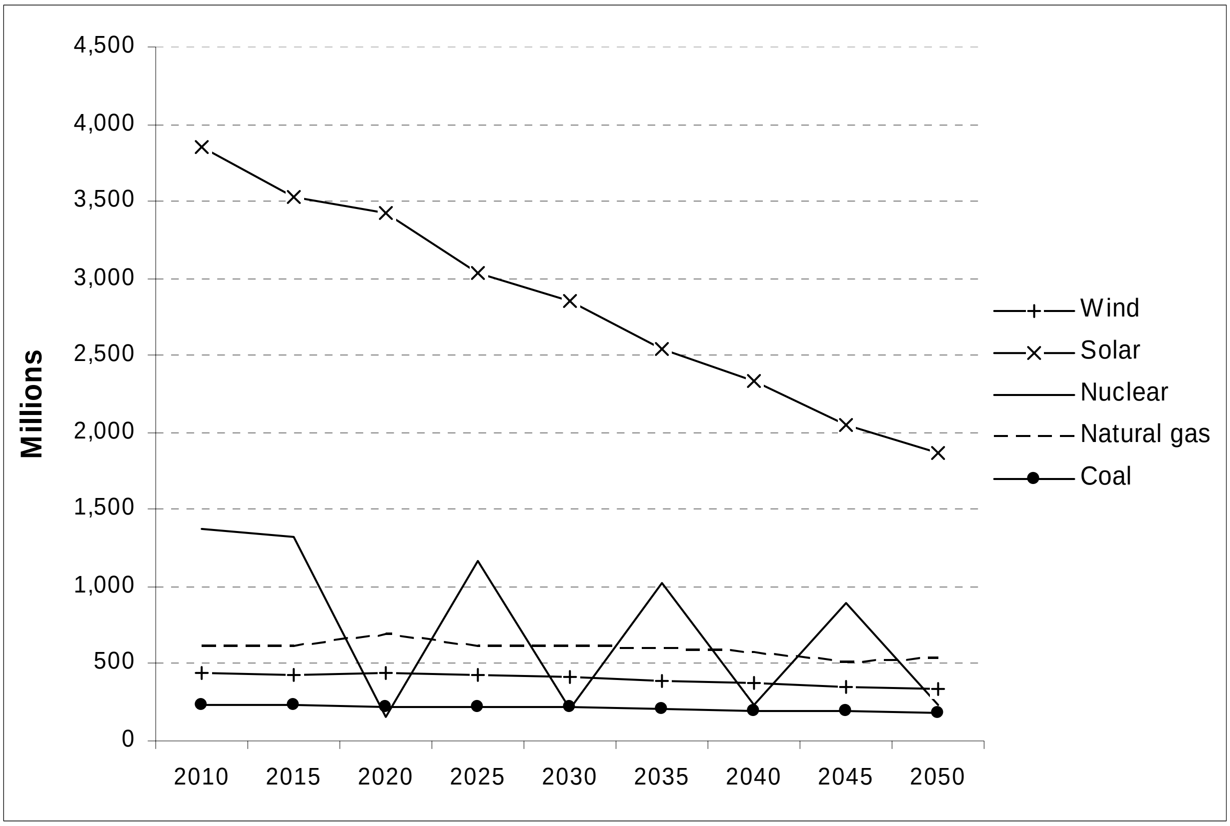

Figure (3). Total costs in the medium scenario.

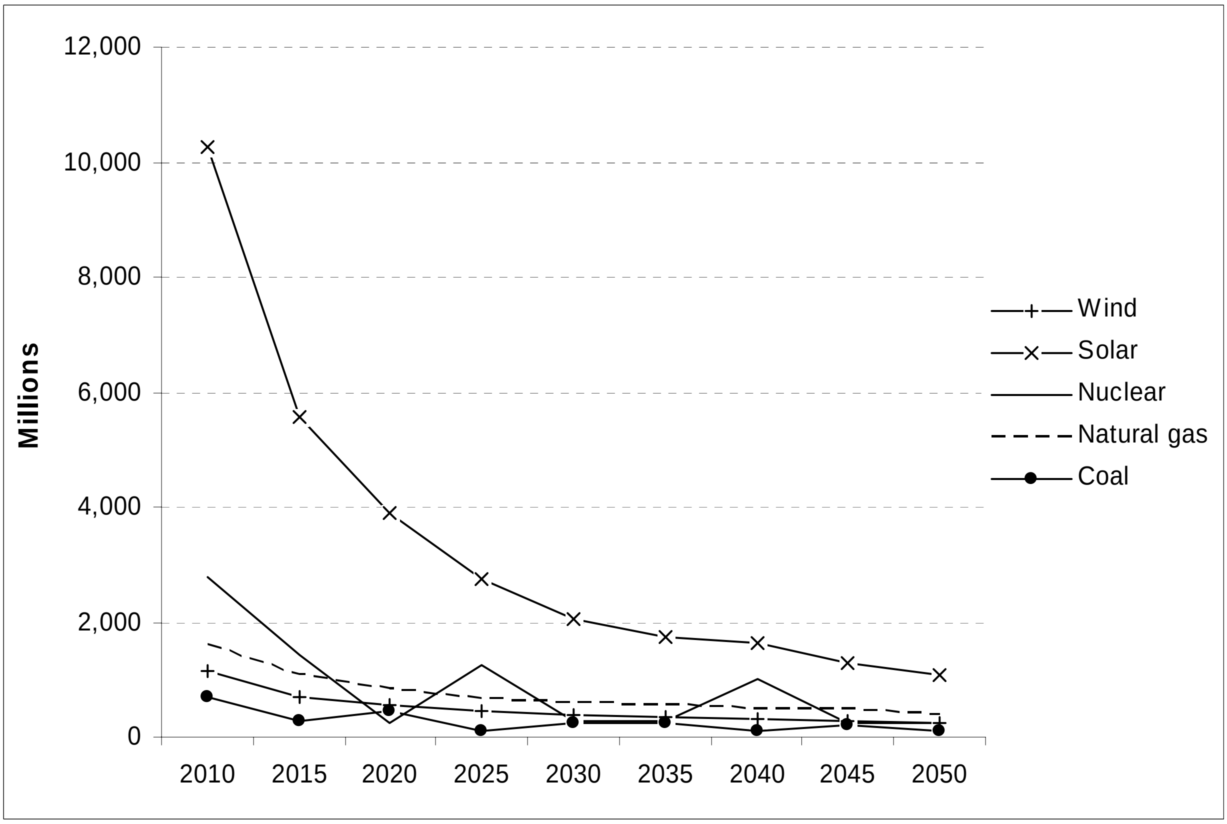

Figure (4). Total costs in the high scenario.

Solar power under-performs all of the other energy sources almost every year. Sunlight-related technologies still have some way to go before becoming competitive. Wind, another RES, shows itself to be even more cost-effective than natural gas. This finding may be partly explained by the high prices of natural gas experienced in the 2000s. The other hydrocarbon fuel, coal, benefits from low feedstock costs and contained installation costs. This results in the lowest costs the same amount of hydrogen over almost all the considered years. Finally, nuclear power, as anticipated, fluctuates heavily depending on the occurrence of set-up costs. If it was only about variable costs, nuclear power would challenge coal's position as the most cost-effective measure for producing hydrogen.

This simulation does not include any modeling effort that takes emissions into account. In particular, it seems clear that coal's ranking, for example, would come into question whenever one would monetize the GHGs emissions compared to, say, nuclear or solar power.

Infrastructure

The estimates of infrastructure requirements follow along the same lines.

	Wind	**Solar**	**Nuclear**	**Natural gas**		**Coal**	
	number of windmills (cumulative)	square kilometers (cumulative)	number of 1,000 MW plants (cumulative)	number of plants (cumulative)	billion m^3 (in 2050)	number of plants (cumulative)	million hard coal ton (in 2050)
Low	5,832	67	5	5	2.0	8	6.1
Medium	6,646	77	5	5	3.3	9	6.9
High	6,829	79	5	5	3.4	9	7.1

Figure (5). Infrastructural requirement.

Even considering the scenarios at the two ends of the spectrum, low and high, estimates do not differ much. If the goal were only to reach 5% of energy demand in transport, however, some of the energy sources become demanding in terms of infrastructural requirement. For example, five hypothetical nuclear plants would pose serious troubles in a country, Italy, that dismissed nuclear power as an energy source with a referendum in 1987. Solar, as well as wind power, would call for a sizable land surface. Natural gas, in turn, would be less troublesome. The Italian natural gas consumption in 2004 was 78.74[4] billions m^3, which would make 3 billions m^3 of natural gas easily buffered by the energy system. Coal would demand more plants than nuclear and natural gas, since Italian hard coal consumption in 2005 was 48,4 million tons[5].

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[4] Source: Eni's *World Oil and Gas Review 2006*.

[5] Source: International Energy Agency 2007 database, expressed as sum of import and domestic supplies.

4. Conclusions

From an economic standpoint, solar and nuclear power suffer from sizable total and fixed costs, respectively. Natural gas, though promising, gives up a lot to oil market fluctuations, to which its price is benchmarked. Wind is rather competitive in all of the considered scenarios. Coal gasification appears to be the most cost-effective solution from a financial perspective. Since this work is limited to outlining the economic framework, the environmental impact of the different energy sources ought to be included to draw a final conclusion on which feedstock would be preferable as policy choice.

With regards to the infrastructure needed, a moderately positive message arises. Except for solar and nuclear power, the other three alternatives seem to impact the energy system minimally. This means that there are ways to slowly adopt hydrogen, even without revolutionizing the current energy infrastructure. Nevertheless, the viability of hydrogen introduction is limited to energy production.

As pointed out earlier, how RES potential would be allocated between electricity and hydrogen is key. In particular, what remains to be determined is how investing in RES instead of hydrogen would impact the energy system differently in terms of global and local emissions. Pairing up these results is necessary to understand which option is best.

Not only does the competition with electricity needs to be considered, but also transport and distribution infrastructure. Since this work is concerned with fuel production, it provides only a partial view that ought to be pondered in a broader context. Research on the downstream side of the hydrogen chain could well complement the production cost and infrastructure estimates.

Completing the current work would include an analysis on the energy efficiency differential between internal combustion engines and fuel cells. The tank-to-wheel is already known story: fuel cells can be up to three times more efficient than internal combustion engines in employing energy[6]. Because the difference so striking, a comprehensive analysis could not be oblivious of such a fact.

The current model could be developed further along two lines. One is computing global and local emissions under different scenarios. This way, the more environmentally-friendly technologies would get proportional credits they deserve. With respect to global emissions, market values of CO_2 per ton provide a good reference of the financial benefit of emitting less. As the Kyoto protocol will become effective starting in 2008, the European Emission Trading Scheme gives the evaluation a sound indicator. Local emissions impact is a bit more complicated to assess, but the Externality Theory can help in this sense.

Another improvement could be modeling technology. In the past, simulation models suffered from having systematically downplayed the technology potential that could unfold in the future. Technology's role, however, is pivotal and influences forecasts significantly. Instead of taking a conservative stand on scientific development, it would be interesting to draw more dynamic and realistic evolution patterns.

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[6] Source: http://www.fuelcells.org/basics/benefits_transp.html.

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6. Appendix

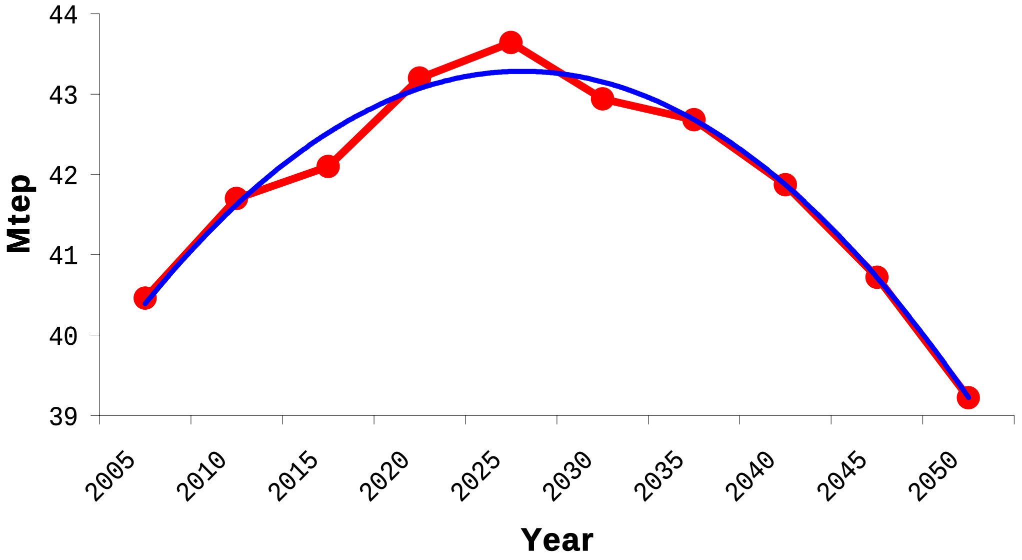
Annex 1. Data sources.

Data sources	
Road transport scenario forecast	Bianchi and Di Giulio 2005 European Commission (2003)
Nuclear power	Energy Intelligence Agency (2006) World Nuclear Association (2005)
Solar power	Stoddard, L. et al. (2006)
Wind power	The European Wind Energy Association (2004)
Natural gas reforming	Barreto, L. and Yamashita, K. (2003) Mintz, M. et al. (2003)
Coal gasification	Mintz, M. et al. (2003)

Annex 2. Energy demand in road transport forecast.

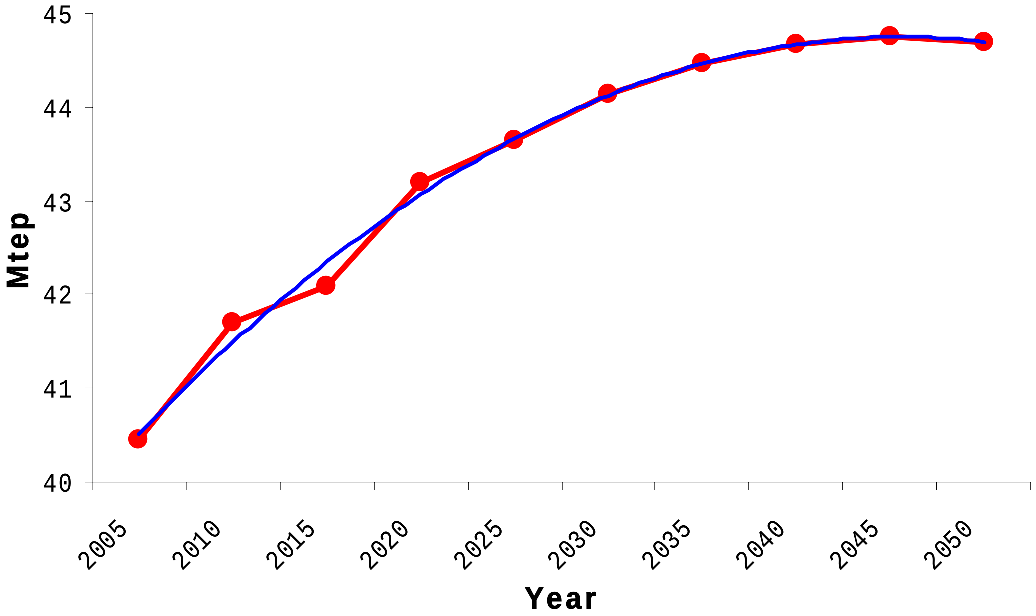
Low scenario

Mtep = $-0.171\ t^2 + 1.745\ t + 38.816$; $R^2=0.98$



Medium scenario

Mtep = $-0.064\ t^2 + 1.172\ t + 39.41$; $R^2=0.99$



High scenario
Mtep = 0.549 t + 40.46; R^2=0.96