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Discussion paper

Estimating the cost of future global energy supply

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Estimating the cost of future global energy supply. [1]

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Abstract This study produces an attempt to estimate the cost of future global energy supplies. The approach chosen to address this concern relies on a comparative static exercise of estimating the cost of three energy scenarios representing different energy futures. The first scenario, the business as usual scenario, predicts the future energy-mix based on the energy plans held by major countries. The second scenario is the renewable energy scenario, where as much of the primary energy supply as possible is replaced by renewable energy by 2050. The cost of the renewable energy generating technologies and their theoretical potential are taken into account in order to create a plausible scenario. The third scenario, the nuclear case, is based on the use of nuclear and renewable energy to replace fossil-fuels by 2050. Endogenous learning rates for each technology are modeled using an innovative approach where learning rates are diminishing overtime. It results from the analysis that going fully renewable would cost between -0.4 and 1.5% of the global cumulated GDP over the period 2009-2050 compared to a business as usual strategy. An extensive use of nuclear power can greatly reduce this gap in costs.

Key words primary energy supply, experience curve, scenario

1 Introduction

No agreement on the economical feasibility of replacing fossil-fuels with renewable energy has been reached to the present day [Brian, 2011]. A possible approach in measuring the cost of switching completely to renewables is to create different scenarios and compare their respective cost. Such scenarios usually forecast future energy costs by modeling endogenous learning as a way of justifying planned cost decrease overtime. The aim of this study is to discuss the tools needed to determine the cost of a scenario and their applicability. In addition, an alternative approach to forecast future technology costs is proposed.

Three scenarios representing possible energy futures over the period 2009-2050 are created and the following technologies are included in defining the energy mix of each scenario: black coal, natural gas and oil, nuclear, geothermal, modern biomass, onshore and offshore wind power, solar photovoltaic (PV), concentrated solar power (CSP) and small and large hydropower. The first scenario is a business-as usual scenario, which is built on past trends and includes major countries current energy strategy when forecasting the evolution of the total primary energy supply (TPES) until 2050. The second scenario is a nuclear scenario, where countries would meet the future gap between the primary energy supplied by the existing infrastructure and the forecasted primary energy demand, exclusively using nuclear or renewable energy. The third and final scenario, involves a near complete switch to renewable energy by 2050. All scenarios take the potential of renewable energy as well as feasible deployment rates for renewable energy into account. The existing energy infrastructure is progressively phased-out throughout the scenarios as it reaches the end of its economical life.

A number of elements are needed in order to create a scenario and estimate its cost. In particular, estimates on current energy costs are made using the levelized costs of energy approach, and future energy costs are predicted by using an innovative approach minimizing the drawbacks of existing techniques for forecasting future energy costs. In this study, future energy costs are predicted via traditional single-factor

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learning curve combined with a diminishing learning rate. The total cost of each scenario is eventually given as a share of the cumulative GDP over the 2009-2050 time period.

The three scenarios are introduced in Section 2. Methodologies used to estimate current and future energy costs are described in Section 3. Results are presented and discussed in Section 4, which is followed by a conclusion in Section 5.

2 Scenarios

There exist several types of scenario which differ based on their purpose. The category of scenario aiming at describing plausible futures is referred to as being explorative [Bakken, 2012]. These scenarios are quantitative and consistency throughout the scenarios can therefore be ensured. Explorative scenarios are based on current trends and possible futures diverge based on a limited number of factors. Our scenarios cover the period 2009-2050 and explore possible futures: the *business as usual* scenario, the *renewable energy* scenario and the *nuclear* scenario.

Population, future GDP and total primary energy supply (TPES henceforth) forecasts are common to all scenarios. Global population is expected to reach over nine billion humans in 2050 [UN, 2003, USCB, 2012]. GDP forecasts are obtained by using 2009 numbers [IEA, 2011] and assuming a steady 3% growth rate. Estimates on the future TPES are obtained by combining population forecasts and forecasted growth rate in average power consumption per capita. In this study, we assume that global energy consumption initially increases by 0.9% and declines by one percent annually until the end of the scenarios in order to reflect a slowdown in the growth of the average power consumed per capita in the long run. As a result of these assumptions, and combined to forecasts on future population growth, the TPES is expected to increase by 70% over the time period considered. Simultaneously, the average power consumption per capita increases from 2.4[2] to 2.8 kW between 2009 and 2050. Though the difference in average power consumption per capita between regions is not discussed in details here, the transition to 2.8 kW could be done in several ways. For instance, partial convergence in average power consumption per capita could take place, which implies that power consumption would decrease in developed countries and increase in developing countries. Using growth in average power consumption per capita rather than growth in TPES leads to slightly higher forecasts than those obtained in other studies (see Table 1).

Comparison				
Study	Name of scenario	Final year	TPES in mtoe	TPES in TW
IEA [2011]	New policies	2035	17,000	22.6
	Current policies	2035	18,300	24.3
	450	2035	14,900	19.8
Shell [2009]	Scramble	2050	21,000	27.9
	Blue	2050	18,400	24.4
EC [2006]	Reference	2050	22,300	29.6
This study		2035	19,800	26.3
		2050	24,600	32.7

Table 1: Forecasted TPES compared to other studies.

Locked-in power exists in all scenarios because existing power plants (and plants under construction) are kept in operation until the end of their economic plant life, because it is deemed not socially optimal to replace existing plants before the end of their economic plant lives. The quantity of locked-in power

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[2] In 2009, the TPES was equal to 16.3 TW [IEA, 2011] which is comparable to an average power consumption per capita of 2.4 kW.

is slightly exaggerated in order to allow the renewable energy technologies to fill the gap between the locked-in power and the TPES needed without requiring unrealistic diffusion rates in the *renewable energy* scenario. The power locked-in is the same in all scenarios and its cost is not part of each scenario's final cost. The aim of this study is therefore to estimate the cost of the power needed to meet the gap between the quantity of power locked-in and the demand for primary energy. The evolution of the contribution of various technologies to the TPES in the three scenarios is illustrated in Fig. 1.

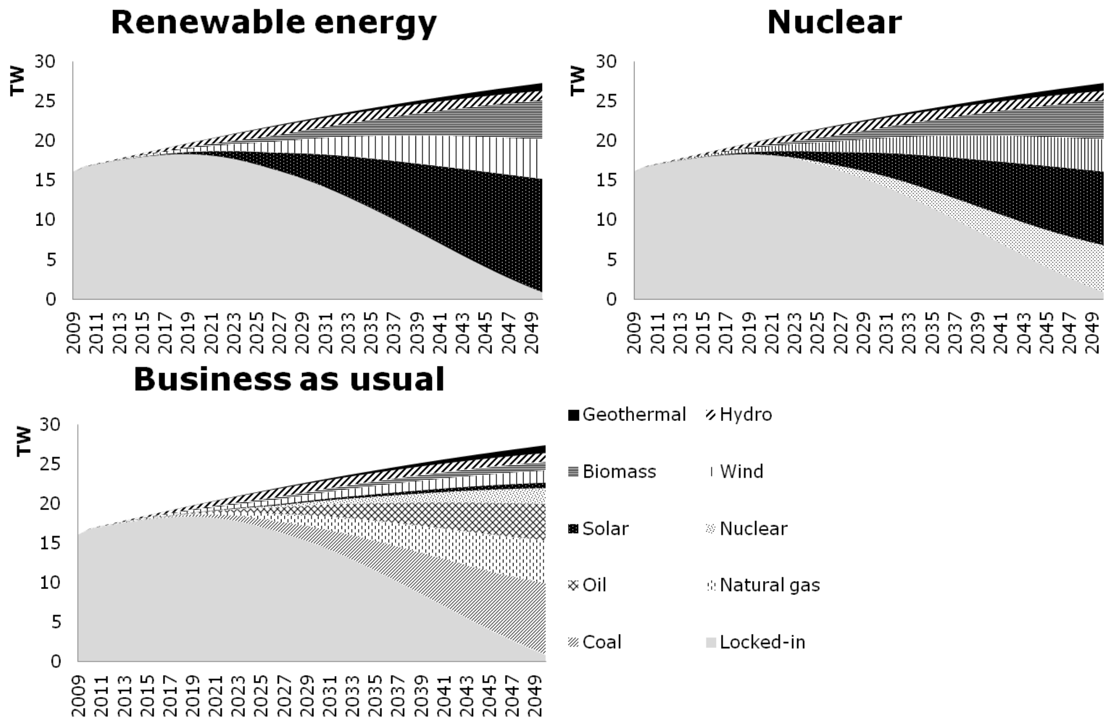

Figure 1: Evolution of the main technologies under the three scenarios.

The *business as usual* scenario predicts a future energy-mix incorporating major countries' current energy strategy and their recent past actions. Coal remains a key energy source throughout this scenario because it is among the cheapest source of energy in numerous countries and economically recoverable coal reserves will suffice to meet the demand for the upcoming decades. Unless externalities are included in the cost of energy, there is little reason to believe that the attractiveness of coal at a global level will decrease in the near future. Regarding the other fossil fuels, oil is expected to remain an important fuel, although the use of oil eventually declines due to limited proven reserves. The use of natural gas is forecasted to increase with the emergence of unconventional natural gas and potentially decreasing natural gas prices. Overall, the TPES share from the various fossil fuels is expected to decrease from 81% in 2009 [IEA, 2011] to 70% in 2050. The evolution of the nuclear-based energy supply is less straightforward. Several countries relying on nuclear energy have decided to phase out their nuclear reactors after the 2011 nuclear accident in Japan. At the same time, India [Indian Nuclear Agency, 2012] and especially China [Chinese Nuclear Agency, 2012] have plans to significantly expand their fleet of nuclear reactors due to increasing energy needs and shortage of domestic fossil fuels. China alone is planning to build 400 GW of new nuclear capacity by 2050 [Chinese Nuclear Agency, 2012]. Taking these different trends into account, the share of nuclear in the final TPES is expected to reach 7% at the end of the scenario. Modern renewables are playing an increasingly important role as to account for 20% of the global TPES in 2050. Solar alone would contribute for 3% and wind for 6% of the 2050 TPES. This evolution would mostly be driven by the efforts of the European Union to achieve a more sustainable primary energy supply in the case of solar power and to increasing competitiveness for wind power. In order to achieve such a share, a yearly growth rate of 12% of the yearly installed capacity is needed for solar PV and 20% in the case of concentrated solar power (CSP). These growth rates include the replacement of the plants that are decommissioned at the end of their economic lives.

The second scenario is the *renewable energy* scenario and the aim in this future is to supply as much of the 2050 primary energy supply with renewable energy as possible. How much energy can be obtained from the various renewables depends on their potential. The existing literature [de Vries et al., 2007, IPCC, 2011, Krewitt et al., 2009, Moriarty et al., 2012] converges towards a feasible potential of 1.5 TW for hydropower and of more than 50 TW for direct solar power. We will consequently use these as limits to how much power can be obtained from these energy sources. The global sustainable potential of bioenergy is uncertain, and varies in reports from a few TW [de Vries et al., 2007, IPCC, 2011, Moriarty et al., 2012] to 40-50 TW [Moriarty et al., 2012]. We estimate the resource potential to be of approximately 5 TW because of the following considerations. About 13% of the world surface area is considered arable land and another 40% is covered by forests. It thus seems reasonable that in an optimal situation, parts of the waste of the human agriculture production and parts of the world forest areas can be used in bioenergy production. We estimate that between 5% and 10% (i.e. 7.5%) of the world's surface area can be taken and turned into sustainable bioenergy production. In addition, we know that the power possible to extract per area from biomaterials depends on latitude, from up to 1 Wm^{-2} in rain forests region near the Equator to 0.1 Wm^{-2} or less in northern and southern regions. By taking an average energy production of 0.5 Wm^{-2} the global bioenergy potential becomes:

$$P_{bio} = 0.5Wm^{-2} \cdot 7.5\% \cdot 30\% \cdot 4\pi R_{Earth}^2 \approx 5TW. \tag{1}$$

The total theoretical available wind energy potential on earth, i.e. the total power originating from solar radiation and deposited in near surface wind energy is rather well known [Gustavson, 1979] and is about $1.3 \cdot 10^{14}$ W, which corresponds to 0.5% of the incoming solar radiation. The technical potential of wind energy is much more uncertain and it ultimately depends on how much land or sea can be transformed into working wind farms. In contrast to bioenergy which is harvested from ten percent of the world's arable or forest covered regions, ten percent of the land area for wind farms is assumed to be of an order of magnitude too large. One has to neglect urban areas, arctic regions, high altitude regions and similar due to different constraints, technical and/or political. Using a modest 2-3 percent of the world total land area results in a total technical potential of about 3 TW. In a thorough analysis, Hoogwijk et al. [2004] calculated the technical potential of global onshore wind energy to about 2-6 TW. We will adopt the upper region of this estimate by opening for the possibility that also offshore wind energy may be established at a sizable degree. Thus we assume the technical potential of wind energy to be about 5 TW as well. The case of geothermal is particularly uncertain with estimates ranging from 0.03 TW [Moriarty et al., 2012] to 158 TW [Krewitt et al., 2009]. In the context of this study, we retain a low resource potential of 1 TW for geothermal. Finally, some technologies (e.g.: ocean power) relying on non-negligible resources are being left out of the scenarios, because these are currently too expensive or because they have not penetrated the market yet.

At the end of the renewable energy scenario, fossil fuels account for only 3% of the TPES, due to the power locked-in. The share of non-solar renewable technologies reaches 44% and solar technologies are needed to match energy supply and demand, because of the other renewables limited potential. By 2050, the total solar PV installed capacity reaches slightly less than 44 TW . Compared to the 2009 installed PV capacity of 21 GW, 44 TW means that the existing capacity at the end of 2009 needs to be multiplied by 2,000 times over a period of 40 years. Said otherwise, an average yearly growth rate of 21% needs to be sustained over the following four decades, which remains significantly below the yearly growth rate of 2010, 2011 and 2012. Wind power (both onshore and offshore) is the second largest contributor to the TPES in 2050. Yearly installed wind capacity increases progressively to reach 480 GW of added onshore wind power capacity in 2050, which appears to be feasible because it represents 'only' ten times the new installed capacity in 2012. Biomass eventually contributes to 18% of the TPES. Finally and even though their feasible potential is fully exploited by 2050, geothermal (4% of the TPES) and hydropower (4%) play a lesser important role.

A third option can be envisaged to address the issues of climate change and the rarefaction of fossil-fuel resources: nuclear energy. In the nuclear scenario, countries avoid using fossil-fuels by relying on nuclear power and renewable technologies. The evolution in the use of nuclear power implies that inhabitants in developed countries shift their mindsets in favor of nuclear power, that pro-nuclear countries such as China and India set even higher targets and that other developing countries start their nuclear program. In this scenario, nuclear power supplies about 22% of the total primary energy in 2050. The use of nuclear power limits the need for costly renewable technologies.

3 Methodology

3.1 Estimates of current energy costs

We rely on the levelized cost of energy (LCOE henceforth) approach to estimate the current cost of the various energy technologies included in this study. Data on overnight costs, operation and maintenance costs, electrical conversion efficiencies and load factors are taken from a joint report by the IEA/NEA [2010], whereas fuel costs have been recalculated using more recent data. All monetary values are given in ^{2008}Euro.

The LCOE of the various energy generating technologies is illustrated in Fig. 2a. In addition to the technologies presented in that figure, the cost of oil is estimated to be of 64 Euro/MWh[3]. Large differences in costs can be observed, with conventional fossil-based technologies being cheaper than renewable technologies, with the exception of large hydropower and, to some extent, modern biomass. Among the technologies which have not reached grid-parity in terms of costs, onshore wind, biomass and some cases of small hydro are closer to grid-parity on a pure cost basis than the existing solar and offshore wind technologies.

3.2 Forecasting future energy costs

Costs detailed in Fig. 2a may not be representative of future energy costs, because economies of scale, upsizing of technologies and learning effects [Arzivu et al., 2011] via increasing volumes will lead to reduced costs overtime. It was already in the 1930s that hints on a relationship between costs and cumulative production were identified [Ferioli et al., 2009, Wright, 1936] and in the mid-60s, the Boston Consulting Group named this relationship the *experience curve*. Such curves are decreasing linear relationship between the double-logarithmic scales of unit costs and cumulative volumes. The equation related to the experience curve is of the type:

$$Y = a \cdot X^b \tag{2}$$

Where Y is the cumulative average cost per unit, X is the cumulative number of units produced, a is the cost required to produce a unit at a starting point and b is the slope of the function when plotted on a double logarithmic scale. Eq. (2) is a typical example of a single-factor experience curve. Multi-factors experience curves introduce multiple factors to account for learnings induced by R&D, scaling and learning-by-doing. Though the latter type of experience curve is more precise, it suffers from the difficulty to clearly distinguish between these effects. Moreover, estimating key parameters can be arduous [Yeh and Tubin, 2012], due to the availability and quality of the data. The single-factor experience curve is thus simpler in the sense that only a limited number of parameters are needed for forecasting future costs. It is however subject to a risk of omitted variable bias [Lindman and Soederholm, 2012] and it has the tendency of generating higher learning rates than the multiple-factors experience curve [Lindman

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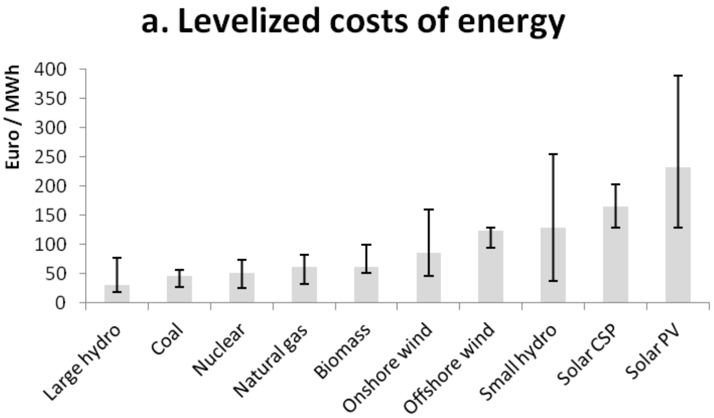
[3] The 2012 price of oil turns around 100 USD/bbl or 65 ^{2008}Euro/bbl. Assuming that the cost of fuel accounts for 60% of the LCOE (same as for the other fossil-based technologies), the full LCOE reaches 64 Euro/MWh.



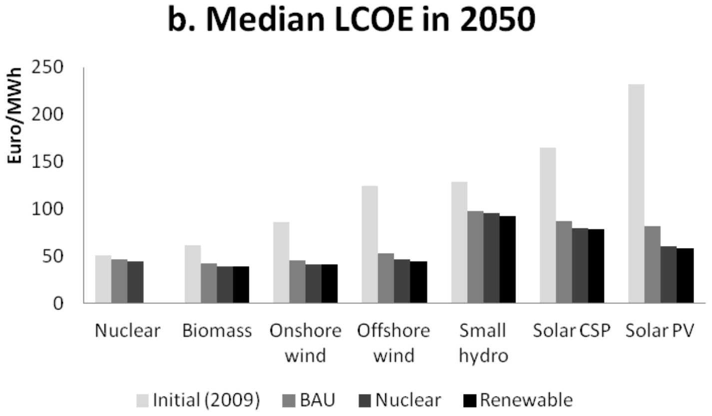


Figure 2: a. Median levelized cost of energy (LCOE), including the max and minimum LCOE for various energy generating technologies. b. Final median LCOE at the end of the three scenarios.

and Soederholm, 2012]. The single-factor experience curve has been applied to numerous products, processes and technologies to draw forecasts on future costs [Ferioli et al., 2009] and it is used by many to justify continued support towards renewable energy generating technologies since future cost decreases are expected.

Estimates on the learning rates for one technology can show substantial variation, a known issue which arises from the use of different datasets, geographical areas or dependent variable [McDonald and Schrattenholzer, 2001]. It is an indication that these learning rates must be treated with care. It however emerges from the existing literature [Arzivu et al., 2011, Jamasb, 2007, Kahouli-Brahmi, 2008, Timilsina et al., 2012] that mature technologies such as conventional technologies have smaller learning rates than newer technologies.

The main problem associated to the use of Eq. (2) for forecasting future costs is that this method relies on a constant learning rate. Costs are therefore assumed to be ever-decreasing [van der Zwaan et al., 2002] and applying this approach to our scenario would lead to improbable results. Taking the case of onshore wind power in the renewable energy scenario, a strong and fast increase in the use of this energy source is envisaged for the future (see Fig. 3) and future onshore wind power costs in 2050 would be as low as 30 Euro/MWh (see Fig. 4). Such low cost can be challenging to justify since it is as low as the current LCOE for large hydropower with reservoir. This result is rendered possible precisely because production costs are assumed to be ever-decreasing, hence the thought that experience curves perform poorly in the long run. Several aspects exist which challenge the assumption of ever-decreasing costs.

For example, some of the decrease in cost can be attributed to cost-efficient technological improvement, leading to higher technical efficiency levels. Laws of physics however impose a limit on the maximum efficiency reachable and progresses towards this limit are bound to slow down in the future. Based on this example, it is plausible to assume that learning is more challenging to obtain in the long run [Lindman and Soederholm, 2012], assertion supported by the fact that learning rates estimates are lowest for mature technologies. Although the use of experience curves for forecasting future costs is sometimes criticized [Nordhaus, 2009], it still remains popular [Yeh and Tubin, 2012] and research is ongoing to create an approach that can generate plausible long-term forecasts.

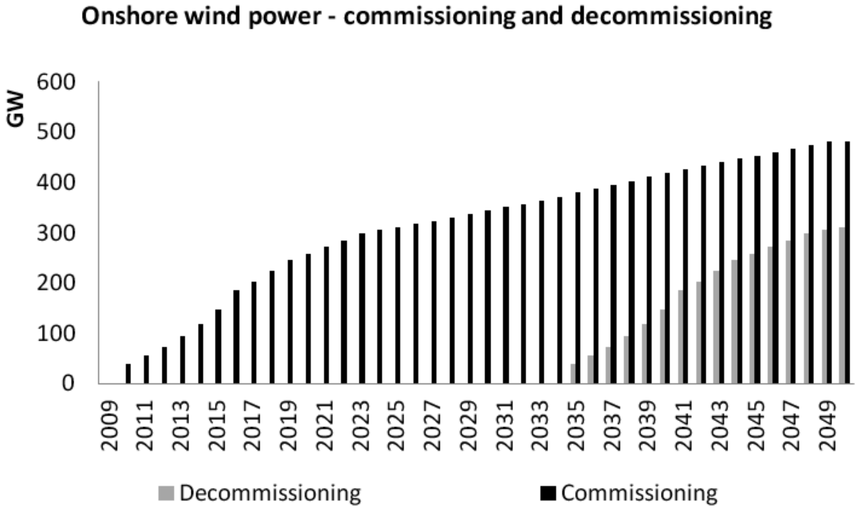


Figure 3: Commissioning and decommissioning of onshore wind power.

[Ferioli et al., 2009] proposed an approach which mitigates the limitations associated to the use of experience curves by introducing a component-learning hypothesis. Learning is not uniform for each component and splitting the experience curve into a component subject to learning and a component in which cost remains constant forever reflects this fact. The relationship between cost and cumulative capacity in a double logarithmic scale becomes convex and there is a point in time, named senescence, when costs stop decreasing. An alternative approach is introduced here, which tackles the issue of ever-decreasing costs and retains the straightforward aspect of the basic experience curve. The equation used to model future costs in this study is detailed below:

$$\begin{aligned} Y_t &= Y_{t-1} \cdot \left(\frac{X_t}{X_{t-1}} \right)^{b_t} \\ b_t &= log_2(1 - l_t) \\ l_t &= l_{t-1} \cdot \left((1-d)^{log_2\left(\frac{X_t}{X_{t-1}}\right)} \right) \end{aligned} \tag{3}$$

where l_t is the learning rate at time t and d is a rate at which learning diminishes. With this approach, the learning rate diminishes overtime to reflect that learning is more challenging to obtain in the long term. This rate is initially set to 10%. A sensitivity analysis will later be provided to show the impact of changing this rate on the final cost of each scenario. The forecasted levelized costs of onshore wind power using this alternative approach and an initial learning rate of 15%, are reproduced in Fig. 4.

In this example, the estimated LCOE of onshore wind power amounts to 86 Euro/MWh. As cumulative capacity increases, the cost of onshore wind power decreases (though at a decreasing rate) to reach 41

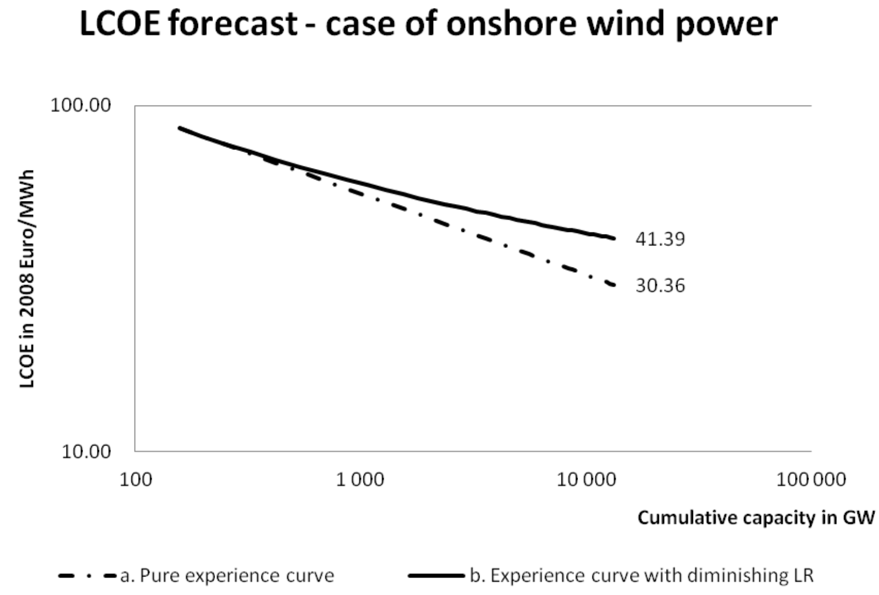


Figure 4: Forecasted LCOE with: a. Pure experience curve and b. Experience curve with a diminishing learning rate.

Euro/MWh in 2050, which appears more realistic than the 30 Euro/MWh obtained with the traditional experience curve. It is now possible to compute the cost of building and operating the onshore wind power capacity illustrated in Fig. 4. In this particular case, the cost of wind power between 2009 and 2050 amounts to $2.6 \cdot 10^{13}$ Euro. This number is obviously difficult to interpret and a more understandable approach is to compare this number to the forecasted world GDP over the whole time period. The cost of onshore wind power represents 0.7% of the cumulated world GDP and the contribution of onshore wind to the final TPES reaches 11%. The forecasted costs of the various technologies at the end of all scenarios are illustrated in Fig. 2b.

3.3 Remaining assumptions

Other elements are needed to make quantitative estimates possible, including some assumptions on initial technology costs and learning rates. The median LCOE, load factor and the learning rate for each technology retained for this study are shown in Table 2.

The median cost is chosen as a measure of the cost of the various technologies at the beginning of the study. Integrating different costs for a single technology would imply to properly estimate cost supply curves for each technology [de Vries et al., 2007], estimates that are not necessarily available or straightforward to obtain. Learning rates are based on the work from Neij [2009] because she combines experience curves and bottom-up assessments (i.e.: expected technological development) in estimating them. A learning rate of 0% is assumed for the fossil-fuel technologies, geothermal and hydropower, because fossil-fuel based capacity has been installed in large quantities and the cumulative capacity is not expected to increase by many folds in the future. In addition, the fuel, the cost of which is expected to increase, constitutes a large share of the overall cost. Therefore, the potential for further cost decrease is limited [Ferioli et al., 2009]. The cost of geothermal is not expected to decrease significantly because no major technological innovation is expected in the future. The cost of large hydropower is not expected to

Technology	LCOE	Load factor	Learning rate
Large hydro	30	60%	0%
Geothermal	34	85%	0%
Black coal	46	85%	0%
Nuclear	51	85%	4%
Natural gas	61	85%	0%
Biomass	61	75%	8%[1]
Oil	64		0%
Wind onshore	86	30%	15%[1]
Wind offshore	124	40%	15%
Small hydro	129	60%	8%
Solar CSP	165	38%	10%[1]
Solar PV	232	20%	20%[1]

Table 2: Data used as a base for the analysis. [1] from Neij [2009].

go down either because of the level of maturity of this technology and because the cost of large hydropower plant is largely location specific.

Finally, it is assumed that the installed capacity at the end of 2009 [REN21, 2010] is a good proxy for the cumulative installed capacity of the various technologies considered at the beginning of the analysis.

4 Results and discussion

Table 3 summarizes the costs of each scenario. The total cost for each scenario is the share of the cumulated GDP needed to fill the gap between the locked-in power and the total primary energy supply overtime.

	Business as usual		Nuclear		Renewable energy	
Technology	Cost	Share 2050 TPES	Cost	Share 2050 TPES	Cost	Share 2050 TPES
Coal	1.3%	33.1%	-	-	-	-
Crude oil	1.0%	17.1%	-	-	-	-
Natural gas	1.1%	19.7%	-	-	-	-
Nuclear	0.3%	7.1%	0.8%	21.8%	-	-
Large hydro	0.2%	3.0%	0.2%	3.0%	0.2%	3.0%
Small hydro	0.2%	1.0%	0.3%	1.4%	0.3%	1.4%
Biomass	0.2%	3.9%	0.7%	18.1%	0.7%	18.1%
Geothermal	0.1%	3.6%	0.1%	3.6%	0.1%	3.6%
Solar PV	0.2%	1.5%	1.7%	21.9%	2.2%	32.5%
Solar CSP	0.1%	1.2%	0.8%	12.2%	1.2%	20%
Onshore wind power	0.4%	5.0%	0.7%	11.0%	0.7%	11%
Offshore wind power	<0.1%	0.7%	0.2%	3.8%	0.3%	7.3%
Total	5.09%	96.78%	5.35%	96.78%	5.68%	96.78%

Table 3: Cost of the three scenario for the selected technologies and their contribution to the TPES in 2050 (in %).

Pursuing the *renewable energy* scenario would cost an extra 0.6% of the cumulated global GDP between 2009 and 2050 compared to the cost of the *business as usual* scenario, whereas the cost of the *nuclear* scenario reduces this gap in cost by half. Part of this difference in costs can be traced to the rather extensive use of solar PV in the *renewable energy* and the *nuclear* scenarios, with the LCOE of solar PV not expected to go below 60 Euro/MWh in any scenario.

The difference in total cost between the scenarios may appear limited and this seemingly low cost of going fully renewable is mainly the result of two factors. First, the business as usual scenario also relies on renewable energy generating technologies to some extent (13% of the TPES in 2050). From the approach chosen to forecast future LCOE costs, the first units installed are the most expensive. Because less renewable capacity is installed in the *business as usual* scenario than in the other two, it is the scenario where renewable energy will be the most expensive per MWh produced. The second factor is that fossil-based technologies are not subject to learning, whereas the other technologies are. By the end of the scenarios, it means that some renewable technologies get cheaper than some of the fossil-based technologies. For instance, wind power and biomass are expected to be competitive with natural gas by the end of all three scenarios.

It is clear that there is more uncertainty in the long term than in the short term. For instance, the occurrence or not of the oil peak during the period considered brings uncertainty in the future fossil fuel costs. The real future costs of renewable energy generating technologies in forty years can also be debated at length. These two elements will be discussed further with the help of sensitivity analyses in the next section.

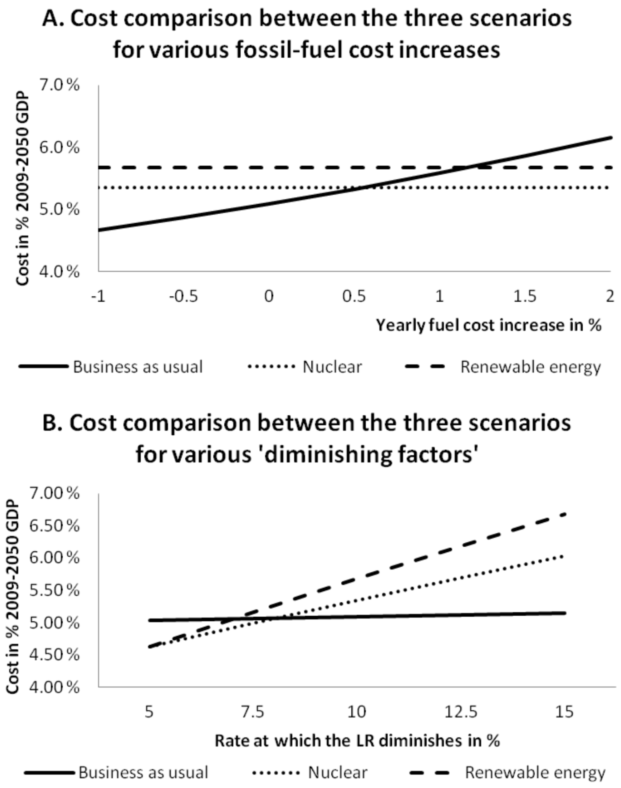
4.1 Sensitivity analysis

Pressures on fossil-fuel prices will be stronger in the *business-as-usual* scenario than in the other two. Yet, fuel prices were assumed to be escalating at the same rate in all scenarios, because future fuel prices are very uncertain. A higher escalation rate, due to diminishing fossil reserves for example, reduces the gap in costs between the three scenarios and can even make the *business as usual* scenario less attractive than the other scenarios (see Fig. 5a). The opposite case where fossil fuel prices would decrease is possible too, provided that unconventional fossil fuels are developed substantially, in which case the gap in costs between the scenarios would increase.

Diminishing learning rates overtime were introduced to incorporate the fact that learning is tougher to obtain in the long run. The overall costs of the three scenarios as a share of the cumulated GDP over the period 2009-2050 are reproduced in Fig. 5b for rates at which learning diminishes ranging from 5% to 15%. Fig. 5b indicates that the *business as usual* scenario is the least preferred scenario if a low rate at which learning diminishes applies. The other two scenarios rapidly become more expensive as this rate increases. Taken together, the sensitivity analysis indicate that the incremental cost of opting for the *renewable energy* scenario over the *business as usual* scenario could be between 0.4% and 1.5% of the cumulated GDP. These results are in line with the findings of more sophisticated models [Edenhofer et al., 2006].

5 Concluding remarks

This study produced an attempt to estimate whether we can afford to replace fossil-fuels with other energy sources. The approach chosen to address this important issue relies on a comparative static exercise of three scenarios representing different plausible futures. Endogenous learning rates for each technology have been modeled using a traditional single factor experience curve combined with diminishing learning rates. Our analysis shows that opting for the renewable energy scenario over the business as usual scenario would cost between -0.4 and 1.5% of the cumulated GDP and that using nuclear energy can reduce this difference in costs.



A. Cost comparison between the three scenarios for various fossil-fuel cost increases

B. Cost comparison between the three scenarios for various 'diminishing factors'

Figure 5: Sensitivity analysis for different escalation rates of the fuel prices.

Two sensitivity analyses were provided to illustrate how the final cost of a scenario evolves if important initial assumptions are changed. On one hand, it was shown that the gap in costs between the business as usual scenario and the renewable energy scenario is reduced if increasing fossil-fuel costs are introduced. On the other hand, augmenting the rate at which learning diminishes will make the latter scenario financially less attractive. Some aspects have been omitted in this study due to the absence of recognized methods to estimate their costs. The externality costs resulting from the use of various energy sources and the potential costs emanating from climate change [IPCC, 2011, Mideksa, 2010, Stern, 2007] and air pollution [Bollen, 2009] are not included in the *business as usual* scenario. Conversely, the cost of treating for intermittency and non-dispatchability issues, the cost of transforming electricity into a valuable fuel for the transportation sector, the cost of land area allocation and the cost associated to the construction of the infrastructure needed for storing energy and transporting electricity have not been included in the *nuclear* and the *renewable energy* scenarios. These categories of costs are however likely to be compensated to some extent by similar existing costs in the fossil sector. These aspects are nonetheless important and can impact the final cost of each scenario. Another important issue not incorporated in any of the scenarios is the possibility of technological breakthroughs which would open for the large scale exploitation of a new or an existing energy resource at a lower cost than existing technologies.

Overall, within the assumptions given in this study, the cost difference between the various scenarios is 'small'. However, the renewable path clearly requires a long term global political commitment in order to achieve the deployment needed to allow for a significant reduction in the cost of the renewable technologies via learning. This global political commitment may prove infeasible when confronted with the 'need' for short term economical growth. In this perspective, the initial investments needed to bring down the total cost of the renewable scenario may become too expensive for many countries.

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