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Global long-term cost dynamics of offshore wind electricity generation

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ABSTRACT

Using the IMAGE/TIMER (The Targets IMage Energy Regional) long-term integrated assessment model, this paper explores the regional and global potential of offshore wind to contribute to global electricity production. We develop long-term cost supply curve for offshore wind, a representation of the potential suitable for inclusion in global integrated assessment models. For this, we combine available data on resource potential and cost estimates to estimate regional and global characteristics of offshore wind electricity generation. We find that for 2050, a baseline scenario would include about 4% of the total electricity production based on offshore wind. The findings also show that in most regions, technical potential is not a limiting factor. In some regions, that have a seriously constrained resource base for onshore wind, offshore wind could provide a key source of renewable energy, including South-East Asia, Indonesia and Brazil.

1. Introduction

In order to control climate change, greenhouse gas emissions need to be reduced substantially [10,18,32]. One of the key options to achieve this is to use more renewable sources of electricity [10,18,38]. However, there are several practical barriers to a rapid expansion of renewable energy: limitations in potential, issues related to intermittent supply, geographic limitations and opposition from the general public. Some of these barriers can be reduced by expanding the portfolio of renewable options: for example, exploiting the potential of offshore wind power as an alternative to onshore wind power. The IPCC SSREN (Intergovernmental Panel on Climate Change Special Report on Renewable Energy Sources and Climate Change Mitigation) report recently estimated the global offshore wind potential to range from around 15 EJ to 130 EJ per year, compared to an estimate for onshore wind energy potential of around 70 EJ per year [36].

Although offshore wind power is more costly than onshore wind power, there are four factors that could make its use attractive: 1) potential for offshore wind power is easily accessible from large and densely populated coastlines, 2) offshore wind farms may face fewer obstacles to planning and siting than do onshore wind farms, 3) offshore wind resources are of higher quality (higher average wind speeds and lower shear near hub height), and 4) offshore turbines can be larger, gaining additional economies of scale [39–41]. Wind turbines of up to 10 MW are anticipated [36].

While the first offshore wind farm was built in 1991 (5 MW in Denmark), deployment of such farms stagnated for years and has only recently started to grow. The current cumulative global capacity is nearly 3.5 GW, almost all in Western Europe. Further expansion is expected, given the ambitious policy targets for 2020 in various parts of the world: 40 GW installed offshore wind capacity in the EU [9]; 10 GW in the US and 30 GW in China [12].

The strength of the resource and the growing recognition of the technology's advantages mean that offshore wind power has potential to be a key factor in future energy systems. Yet most integrated assessment models have not included offshore wind power in their mitigation portfolio. For instance, the set of data on the potential for renewable energy developed by Ref. [14]; used in many models, included onshore wind power, photovoltaics and bio-energy [26]. recently developed supply curves for the technical potential of offshore wind power. These curves are an updated version of the ones developed by Ref. [2] which can be used in integrated assessment models. In this paper, we describe how we

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reinforced the supply curves with economic assumptions in order to use the information in the IMAGE/TIMER (The Targets IMage Energy Regional) framework. The model was used to develop a set of scenarios that explore offshore wind application under different assumptions.

The article is organised as follows. First, we briefly describe the IMAGE/TIMER energy model and the method of including offshore wind in this model (Section 2). We also discuss the scenarios used to explore the influence of offshore wind in future energy systems. In Section 3, we describe how the model was calibrated for offshore wind power. Costs are estimated using literature on the technological development of offshore wind farms. In Section 4, we present and discuss the results and finally draw key conclusions.

2. Method

2.1. The offshore wind model in IMAGE/TIMER

IMAGE (Integrated Model to Assess the Global Environment) is an integrated assessment model that is used to study long-term global environmental change [30]. It was one of the models used to develop the Representative Concentration Pathways to support climate policy assessment for the IPCC [32]. The model focuses particularly on the environmental consequences of energy consumption and land use. To do so, IMAGE includes submodels that describe future agricultural demand, energy consumption and production, emission of air pollutants and greenhouse gases, climate change, land use and land cover and the biogeochemical cycles. TIMER is the energy system simulation model used within IMAGE to describe the demand and supply of 12 different primary energy carriers for 26 world regions, as described by Ref. [35]. Key outputs of the TIMER model in the context of IMAGE are energy-related greenhouse gas emissions, air pollution emissions and land-use requirements for energy crops.

The relevant module of IMAGE/TIMER for this paper is the EPG (Electricity Power Generation) submodel that has been described by Refs. [14,35] and . It simulates the generation of electricity by various technologies, including fossil fuel and renewable power plants [35]. These power plants compete for a share in investments on the basis of relative LCOE (levellised costs of electricity). The LCOE, in turn, changes over time, as it is subject to technology development and depletion effects. The EPG model describes 20 different combinations of fossil fuel and bioenergy electricity plant [33]. For each fuel (coal, oil, gas, bio-fuel), the model distinguishes conventional technology, gasification and combined cycle technology, CHP (combined-heat-and-power) technology, CCS (carbon capture and storage) technology and CHP combined with CCS technology. As an alternative to these 'thermal' plants, the modeller can choose to select nuclear power or one of four alternative non-thermal renewable energy sources: solar, onshore wind, hydropower and (only recently) offshore wind power. We have embedded offshore wind into the IMAGE/TIMER model in a similar way as onshore wind. Fig. 1 shows a schematic representation of the EPG submodel, with factors of key importance to offshore wind highlighted in bold.

In the model, the market share of new technology investment is determined by the relative LCOE of competing options: a multinomial logit function (MNL) that assigns the bulk of new investment to least cost options, but still also assigns some market share to technologies with somewhat higher costs [34]. This represents some of the market heterogeneity in the model:

$$\mathrm{IMS}_i = \frac{\exp - \lambda(\mathrm{LCOE}+p)_i}{\sum_j \exp - \lambda(\mathrm{LCOE}+p)_j)} \quad (1)$$

In this formula, IMS_i the indicated market share of investment in production method i, is a function of the LCOE of the technology; p, an additional calibration factor representing factors other than cost which could lead to greater or less market penetration; and λ, the so-called logit parameter, which reflects the sensitivity of markets to relative differences in prices. The latter was chosen so that the model behaviour reflects the historically observed sensitivity to prices in various energy markets.

After the investment decisions, a power system operation algorithm describes the use of the technologies for power generation. Here, renewable technologies are assumed to be preferentially used, limited only by the load factor and potential overcapacity during times of low electricity demand (curtailment). For other technologies, generation is assumed to be a function of their characteristics in fulfilling base load and peak load demand, as described by Ref. [14].

The costs of electricity generated by alternative technologies are described as:

$$\mathrm{LCOE}_i = \frac{ann \cdot (I_i + \varepsilon_i) \cdot y_i \cdot \mathrm{DF}_i + F_i + \mathrm{Add}_i}{E_i} \quad (2)$$

where LCOE_i is the cost of electricity, ann the annuity factor, I_i the investment costs, ε_i the operation and maintenance costs, γ_i the learning factor, DF_i the depletion fator, F_i the fuel costs, Add_i the additional system integration costs and E_i the electricity produced by technology i.

For fossil fuel and bio-energy plants, a key factor in the total costs is fuel costs (including a potential cost related to greenhouse gas emissions). The cost of renewable alternatives, however, consists only of capital and O&M costs. We assume that offshore wind power shares critical technology components with onshore wind

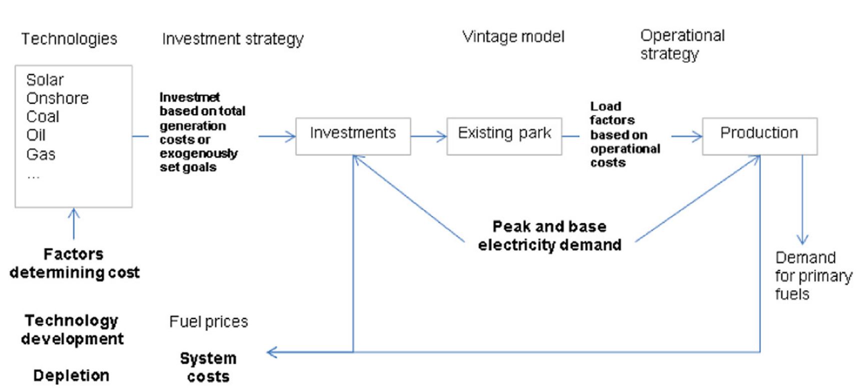

Fig. 1. Schematic presentation of the Electric Power Generation model, with factors of key importance to offshore wind highlighted in bold [34].