Applied Energy 156 (2015) 107–128

Contents lists available at ScienceDirect

Applied Energy

journal homepage: www.elsevier.com/locate/apenergy

Operational flexibility and economics of power plants in future low-carbon power systems

Anne Sjoerd Brouwer [a,b,*], Machteld van den Broek [a], Ad Seebregts [b], André Faaij [a,c]

[a] Copernicus Institute for Sustainable Development, Utrecht University, Heidelberglaan 2, Utrecht, The Netherlands
[b] Energy Research Centre of the Netherlands (ECN), Radarweg 60, Amsterdam, The Netherlands
[c] Energy Sustainability Research Institute Groningen, University of Groningen, Nijenborgh 4, Groningen, The Netherlands

HIGHLIGHTS

- Key flexibility parameters of current and future thermal power plants are quantified.
- Four power mix scenarios are designed and simulated with flexibility constraints.
- Low-carbon scenarios need more flexibility; which power plants can deliver.
- Power plant efficiency is reduced by variable residual load, not only renewables.
- The current market design only covers 84% (±30%) of total power costs per MWh.

ARTICLE INFO

Article history:
Received 12 February 2015
Received in revised form 19 June 2015
Accepted 23 June 2015

Keywords:
Flexibility
Thermal power plants
Renewable energy
Power system modeling
Carbon Capture and Storage

ABSTRACT

Future power systems will require large shares of low-carbon generators such as renewables and power plants with Carbon Capture and Storage (CCS) to keep global warming below 2 °C. Intermittent renewables increase the system-wide demand for flexibility and affect the operation of thermal power plants. We investigate the operation of future power plants by first composing a comprehensive overview of the operational flexibility of current and future power plants. Next, a combined long-term optimization and hourly simulation is performed with the soft-linked MARKAL-NL-UU and REPOWERS models for The Netherlands in 2030 and 2050. We quantify and compare the technical and economic performance of power plants for four distinctly different future scenarios. We find that future low-carbon power systems will have large shares of intermittent renewable sources (19–42%) and also a 2–38% higher variability in residual load compared to the Baseline scenario. Hence, power plant operation will be more variable, which reduces their efficiency by 0.6–1.6% compared to the full-load efficiency. Enough flexibility is present in future power systems to accommodate renewables, due to advances in power plant flexibility and interconnectors. As a result, generators with CCS have a large market share (23–64% of power generated). Moreover, the current energy-based market model generates insufficient revenues: the price received per MWh covers only 84% (±30%) of the total generation costs per MWh of 77 €/MWh (±12€). This will discourage new investments in generation capacity and reduce power system adequacy. New or additional market designs may be required to ensure system adequacy in future power systems.

1. Introduction

In order to mitigate the adverse effects of climate change, the European Commission has proposed to deeply reduce European Union greenhouse gas emissions by 40–44% by 2030 and 80–95% by 2050 compared to 1990[1] [1,2]. The largest emission reductions

---

Abbreviations: ASU, Air Separation Unit; CF, capacity factor; CCS, Carbon Capture and Storage; ECN, Energy research Centre of The Netherlands; ECF, European Climate Foundation; EU, European Union; FOM, fixed operation and maintenance; HRSG, hear recovery steam generator; IGCC, integrated gasification combined cycle; IEA, International Energy Agency; IRES, intermittent renewable energy sources; GT, gas turbine; LHV, lower heating value; NGCC, natural gas combined cycle; PBT, pay back time; PC, pulverized coal; PV, photovoltaic; RES, renewable energy sources; SR, spinning reserve; SRP, short run profit; UCED, unit commitment and economic dispatch.

* Corresponding author at: Heidelberglaan 2, 3584CS Utrecht, The Netherlands.
E-mail address: a.s.brouwer@uu.nl (A.S. Brouwer).

[1] Emission of greenhouse gasses amounted to 5.6 Gtonne CO_2-eq in the EU-28, excluding land use change emissions [143].

http://dx.doi.org/10.1016/j.apenergy.2015.06.065

are projected for the power sector: reductions of 54–68% by 2030 and 93–99% by 2050 compared to 1990 [1]. The transition to such low-carbon power systems will require a shift to low-carbon generators such as renewable energy sources (RES), nuclear power plants and generators with Carbon Capture and Storage (CCS) [3–5].

The new low-carbon generator mix may affect the technical and economic workings of the power system. From a technical perspective, the system could run out of flexibility: intermittent RES require flexibility from the power system, whilst coal fired power plants (which are likely candidates for CCS), and nuclear power plants are relatively inflexible [6,7]. Moreover, intermittent RES may slightly reduce the efficiency of power plants [8]. From an economic perspective, intermittent RES may reduce the profitability of nuclear plants and generators with CCS by decreasing their capacity factor and lowering wholesale electricity prices. Moreover, the profit of these thermal power generators is reduced by lower electricity prices through the *merit order effect* [9] and lower capacity factors of thermal power generators. As stated by the IPCC SRREN report: “combined integration of IRES and IGCC/CCS or nuclear may pose special integration challenges” [10].

Few studies have explicitly looked at the technical (i.e. flexibility) and economic feasibility of multiple long-term low-carbon scenarios, and the differences between them. Five studies looked at low-carbon energy systems with flexibility constraints of 2030 and beyond. Two studies of these considered the future EU energy system at large. The Roadmap 2050 study by the European Climate Foundation (ECF) found that “capacity factors of nuclear and coal plus CCS remain high throughout the year,” and that reduced generator flexibility has small impacts, but without providing details about power system operation [3]. The European Commission ordered a study on low-carbon energy scenarios for the EU, which does not specifically mention flexibility constraints, and only reports aggregated outcomes [4]. Bertsch et al. studied a future European low-carbon power system with a 80% RES penetration by 2050. They concluded that flexibility will largely be provided by gas turbines, and that operation of nuclear power and generators with CCS will break even [11,12]. Cohen studied the operation of power plants with CCS in detail for the Texas power system, but only considered wind penetrations up to 20% [13]. Lastly, Hundt et al. studied the effect of nuclear power plant lifetime extension on the 2030 German power system with 40–50% RES, without accounting for CCS [14]. Moreover, a number of studies have investigated the role of CCS in future power systems with less detailed power system models, which have lengthy time slices (>1 day) and do not account for flexibility constraints e.g. [14,15].

Overall, these studies are either not explicit about the flexibility constraints that are used and the role of flexibility in the power system [3,4], or they do not consider fundamentally different scenarios: high levels of RES are commonly assumed as a starting point [11,13,14]. This study aims to fill this research gap by providing a consistent dataset on the flexibility of thermal power generators. Next, we perform a hourly simulation with these flexibility parameters, for four distinctly different scenarios with the REPOWERS model. These scenarios are calculated as part of this study with the MARKAL-NL-UU long-term optimization model. The goal of the study is to answer the main question “*How flexible are future power plants, and how do they perform in future low-carbon electricity systems from a flexibility and an economic perspective?*.”

Part 2 describes the method and the two models that are used in this study. Part 3 presents the input data for these two models, and Part 4 shows the results. Part 5 and 6 contain the discussion and conclusion.

2. Methods

A comprehensive overview of flexibility parameters is first compiled as an input dataset. Next, four scenarios are defined. Lastly, we describe the combined MARKAL-NL-UU and REPOWERS models, which model the four scenarios to assess the technical and economic operation of power plants in distinctly different future power systems.

2.1. Flexibility parameters

Data on the current and future flexibility of power plants were collected from equipment manufacturers, gray literature and scientific articles, and confirmed with 5 experts. We provide the typical values, as well as the range that is provided in literature (Table 3). Whenever little or no information is available for the 2020 and 2030 cohorts, we extrapolate the 2000 and 2010 data if literature mentions that specific improvements are available. A detailed description of power plant flexibility is provided in Appendix B.

2.2. Scenarios

Four scenarios are considered in this study: Baseline, Stalemate, Global Union, and Fuel Shift, based on Van den Broek et al. [16]. The four scenarios were updated in this study based on recent scenarios [3–5,17]. These scenarios are chosen because they explore a range of different climate action policies (Table 1). The study focusses on the Netherlands, because it has a diverse, modern power system with the potential for large shares of IRES, and modern coal fired power plants that can be equipped with CCS [18].

Long term projections of the electricity demand in the Netherlands show annual growth rates that range from 0.3% to 1.1% per year, depending on end-use efficiency and electrification of transport and heat. Based on the shared trends shown by other studies, electricity demand increases by 1.0% per year for the Baseline scenario, of 0.8% per year for the Stalemate and Global Union scenarios, and of 0.45% for the Fuel Shift scenario [3,4,17].

CO_2 prices are calculated with the MARKAL model for the Netherlands based on European CO_2 emission reduction targets. Predetermined CO_2 prices are only used in the Fuel Shift scenario to simulate the effect of high CO_2 prices. Overall, a range of CO_2 price levels is considered (0–195 €/tCO_2 across the scenarios) (Table 6), which reflects the large uncertainty in CO_2-price projections [19].

All costs are expressed in $€_{2011}$ based on historical exchange rates and the European Power Capital Cost Index [20,21]. Fuel prices are adopted from the World Energy Outlook 2012, because these long-term projections align well with the scenarios of this study (Table 2) [5]. CO_2 transport and storage costs are estimated at 6 €/tCO_2 and 8 €/tCO_2 respectively for future deployment of CCS in the Netherlands with a large CO_2 transportation network and storage offshore in depleted oil and gas fields [22].

2.3. Models

Two soft-linked models are used to simulate the dispatch of power plants in the Dutch power sector for four electricity mix scenarios. Input data and model properties are summarized in Fig. 1. First, future power plant portfolios and CO_2 prices are calculated with the MARKAL-NL-UU optimization model for each scenario, whilst optimizing for the lowest cost. Next, these generator portfolios are simulated in more detail with the REPOWERS unit commitment and economic dispatch power system model, which accounts for flexibility constraints. In the post analysis step, the outcomes of