Energy Conversion and Management 103 (2015) 871–885

Contents lists available at ScienceDirect

Energy Conversion and Management

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

Cost-effective design of ringwall storage hybrid power plants: A real options analysis ☆

Sebastian Weibel [a], Reinhard Madlener [b,c,*]

[a] RWTH Aachen University, Templergraben 55, 52056 Aachen, Germany
[b] Institute for Future Energy Consumer Needs and Behavior (FCN), School of Business and Economics/E.ON Energy Research Center, RWTH Aachen University, Mathieustrasse 10, 52074 Aachen, Germany
[c] JARA-ENERGY, Templergraben 55, 52056 Aachen, Germany

ARTICLE INFO

Article history:
Received 14 November 2014
Accepted 15 June 2015
Available online 23 July 2015

Keywords:
Pumped storage hydro power
Hybrid power plant
Real option
Irreversible investment
Risk and uncertainty

ABSTRACT

We study the economic viability and optimal sizing and siting of a hybrid plant that combines a ringwall hydro storage system with wind and solar power plants (ringwall storage hybrid power plant, RSHPP). A real options model is introduced to analyze the economics of an onshore RSHPP, and in particular of the varying storage volume in light of the stochastic character of wind and solar power, as well as the optimal investment timing under uncertainty. In fact, many uncertainties arise in such a project. Energy production is determined by the stochastic character of wind and solar power, and affects the optimal size of the storage device. Monte Carlo simulation is performed to analyze the following sources of uncertainty: (i) wind intensity and solar irradiation; (ii) future electricity price; and (iii) investment costs. The results yield the optimal size of the storage device; the energy market on which the operator should sell the electricity generated; numerical examples for two different RSHPP scenarios; and a real options model for analyzing the opportunity to defer the project investment and thus to exploit the value of waiting.

1. Introduction

Due to the ongoing significant changes in the energy markets, shifting away from fossil and nuclear sources towards renewable energy systems, the contribution of wind and solar photovoltaics (PV) in particular has increased a lot over the last few years. Since this development can be expected to continue, fluctuations in power supply from wind and solar PV are rising as well. To tackle this problem effectively and to balance the load fluctuation, energy storage concepts, especially for the longer-term storage (several weeks instead of just minutes or several hours), are an essential element of energy systems. In recent years, the scientific literature on combining volatile renewables with pumped storage hydro power systems has grown rapidly (e.g. [1–10]). Circular, so-called Ringwall Storage Hybrid Power Plants (RSHPP), which are based on the principle of pumped storage power plants and either constructed as sealed mounds or as mass concrete artificial structures, are an innovative storage concept [11]. A combination of such a storage plant with wind turbines and PV systems can be referred to as an RSHPP (cf. Fig. 1). This paper presents a real options-based model to analyze the economic viability of and the optimal investment timing for an RSHPP in dependence of its stochastically varying energy production and the future evolution of the electricity price.

1.1. A favorable development causing problems

In recent years, the expansion of renewable energies in Europe, and especially in Germany, has progressed rapidly and still does. In 2002, only about 2.7% of the electricity consumed in Germany came from wind and solar power, whereas the contribution of solar power was negligible. By 2012, the share had risen to 12.4%, of

Abbreviations: AEP, annual energy production; CAPEX, capital expenditure; CCGT, Combined Cycle Gas Turbine Plant; CCS, Carbon Capture and Storage; CF, cash flow; DCF, Discounted Cash Flow; ECB, European Central Bank; EEX, European Energy Exchange; ELIX, European Electricity Index; eNPV, expanded net present value; EPEX, European Power Exchange; EU-27, European Union (the 27 members as of April 2013); MCS, Monte Carlo simulation; NPV, net present value; O&M, operation and maintenance; PSPP, pumped storage power plants; PV, photovoltaic; PVCF, Present Value of Cash Flows; ROA, real options analysis; RSHPP, Ringwall Storage Hybrid Power Plant; WACC, weighted average cost of capital.

☆ This article is based on a four-page proceedings paper in Energy Procedia Volume 61 (2015). It has been substantially modified and extended, and has been subject to the normal peer review and revision process of the journal.

* Corresponding author at: Institute for Future Energy Consumer Needs and Behavior (FCN), School of Business and Economics/E.ON Energy Research Center, RWTH Aachen University, Mathieustrasse 10, 52074 Aachen, Germany. Tel.: +49 241 80 49 820; fax: +49 241 80 49 829.

E-mail address: RMadlener@eonerc.rwth-aachen.de (R. Madlener).

http://dx.doi.org/10.1016/j.enconman.2015.06.043
0196-8904/

Fig. 1. Illustration of the RSHPP concept [11].

Table 1
Secured capacity of various types of power plants [13].

Power plant	Secured capacity (%)
Wind turbine	5–10
Photovoltaic	1
Pumped storage	90
Coal	86
Lignite	92
Nuclear	93
Gas turbine	42

which 7.7% came from wind power and 4.7% was generated by PV systems [12]. The energy concept of the German government foresees that the share of renewable energies will reach 50% by 2030. A similar development and projection can be found for the European Union (EU-27) as a whole.

Two key problems accompany the increasing contribution of wind and solar PV. In the foreseeable future, the majority of wind power will be generated near the coast or on offshore farms, which are usually far away from major metropolitan areas and industrial centers, where the power is consumed. New high voltage transmission lines must be built to transport the electricity from the generation sites to the densely populated areas. The second and more important problem is the fluctuating energy supply from wind turbines and PV systems, due to the stochastic nature of the wind intensity and the solar irradiation. These fluctuations, which can vary considerably daily, weekly, seasonally and annually, lead to inaccuracies in the prediction of electricity supply. This is the reason why today only 5–10% of the installed capacity of wind power can be considered as secured generation capacity; for a PV system, the share is only about 1% [13] (cf. Table 1).

To ensure a reliable supply of electricity, especially with a high contribution of renewable energy, large amounts of reserve energy must be available within a short time, both in case of a lack or an oversupply of wind or PV power. Positive reserve energy is often provided by gas-fired power plants, which have a short start-up time but produce at high costs. Base load power plants, such as lignite-fired, coal or nuclear plants, can provide both positive and negative balancing power. Therefore, they are usually operated in a throttled-down state to retrieve their full power when demanded. With an oversupply of renewable energies, these units need to be throttled down even further or shut down completely. This will also lead to increased production costs and waste of resources, because a throttled-down power plant no longer works at its optimal operating point. Moreover, such base load power plants are not designed for frequent load changes, and especially large-scale steam turbines suffer greatly from such suboptimal operation modes. A fact that further reinforces this problem is the priority feed-in of renewable energy into the grid, as stipulated, e.g. in the German Act on Granting Priority to Renewable Energy Sources [14].

Energy storage is a viable solution to counteract the problems of fluctuating supply from wind and solar power. If supply exceeds demand, the storage device is charged, whereas vice versa it is discharged. Storing energy helps to relieve the electrical grid and thus reduce the demand for balancing power. There are several concepts to store electric energy, e.g. compressed air energy storage systems or electrolysis for hydrogen production (Power-to-Gas, P2G), albeit most of them are not yet technologically mature and/or cost-competitive [15].

Today, conventional *pumped storage power plants (PSPPs)* are the only well-proven technology for storing large amounts of energy effectively. Due to their high efficiency and low technical effort, such systems have been in use successfully for many years. The average total efficiency of PSPPs in Germany is about 70% [16]. Today, newer systems can reach efficiencies of up to 85%. In 2012, Germany had a total of 30 commercially operated PSPPs, providing a rated power of 6.7 GW in total. In the European electricity supply system, there was an installed capacity of about 43 GW available in 2011.

Conventional PSPPs can only be built in regions where a certain height difference between the upper and lower basins can be ensured. These regions are often far away from coastal areas where most of the onshore and the offshore wind energy will be generated. Furthermore, there are only a few suitable sites left for the construction of new PSPPs. Especially in Germany, almost all sites with appropriate natural preconditions are already in use. Thus, installed capacity has remained nearly constant in recent years, both in Germany, and in the EU. Fig. 2 illustrates the development of the capacity of PSPP, wind turbines, and PV systems installed in Germany.

All of these facts show that new energy storage concepts will be essential for the future development of electricity supply with a growing share of renewables. Artificially constructed PSPPs, such as RSHPPs, could help to mitigate at large scale the load imbalances induced by intermittent wind and solar power supply.

1.2. Economic analysis of RSHPP

With such a large-scale project, a number of uncertainties arise that need to be taken into account. These include the investment costs, which are risky because of a lack of experience and the fact that an enormous amount of earth moving is necessary to construct the ringwall and the upper and lower basins.

In our study, we investigate a ringwall hydro power plant that is combined with wind turbines and PV cells. The stochastic character of wind and solar power is an important determining factor for energy production. It is also decisive for filling up the storage device, and influences the optimal device size. The required storage volume itself also has a significant influence on the project's profitability. A further economic uncertainty is the future development of the prevailing electricity prices on the various energy markets. The operator of an RSHPP has to choose on which energy market to offer his generated power. He can offer it either on the day-ahead or the intraday spot market, or, alternatively, he can enter into long-term contracts on the futures market. Still another possibility is to offer the large capacity of an RSHPP on the balancing energy market.

During the long period of planning and constructing, many issues can arise that may affect the project's economic viability.