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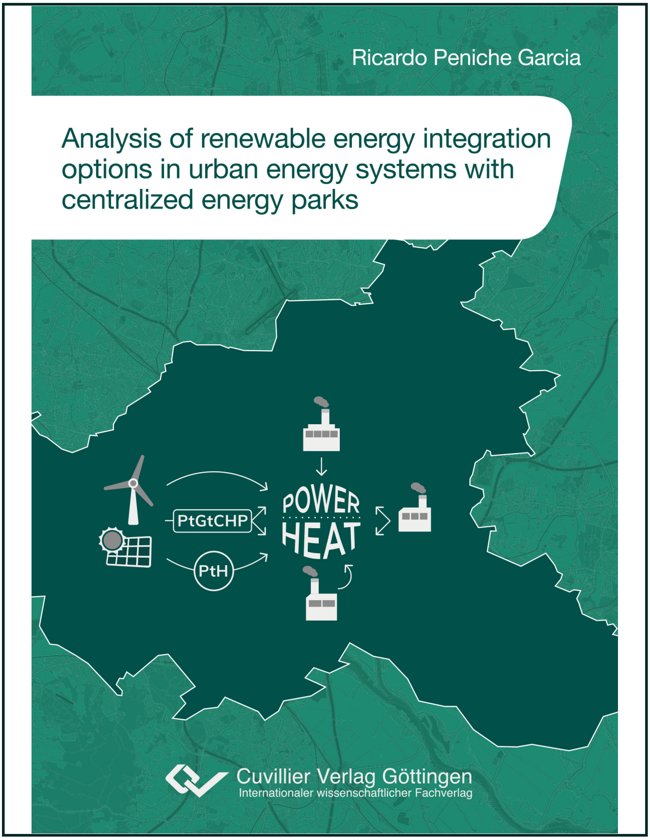
Analysis of renewable energy integration options in urban energy systems with centralized energy parks



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1 INTRODUCTION

1.1 Motivation

Since the end of the twentieth century, several countries have established mechanisms to promote the installation of renewable energy (RE) generation capacity. In particular, Germany has witnessed a significant increase in its RE capacity thanks to the feed-in-tariffs defined in its Renewable Energy Sources Act (in German: EEG) [1]. In 2016, the installed capacity of PV, onshore and offshore wind energy in Germany reached 40.8 GW_{el}, 45.5 GW_{el} and 4.1 GW_{el} respectively, leading to a total of 90.4 GW_{el} [2]. As a comparison, Germany's highest annual electric power demand is currently around 80 GW_{el}. The RE generation capacity is expected to increase further in the following years.

High shares of RE in energy systems usually lead to two types of balancing issues. The first issue is related to the fluctuating nature of the RE production profiles. The power production profiles of PV and wind power plants depend mainly on two variable meteorological parameters: global horizontal irradiance (GHI) and wind speed. Therefore, the production profiles of these RE plants cannot be scheduled to meet a given demand. If, for instance, the power output from RE is weak at a moment of high demand, then conventional power production units will have to supply the residual load. Residual load is defined as the difference between the net electricity demand and the RE production. On the other hand, if the RE power output is available at moments with low demand, it is usually curtailed.

The second issue is related to the regional clustering of RE plants. These plants are usually concentrated in regions with favorable meteorological parameters, such as high GHI and wind speed values. In Germany, this fact has led to a concentration of large amounts of onshore and offshore wind energy in the northern states. The transmission capacity to transport the RE production from generators in the north to demand centers in the south is currently insufficient. Although there are national plans for expanding the transmission capacities, these measures are costly and require several years to be completed. Currently, the excess power is either transmitted through the electric grids of neighboring countries or curtailed by the transmission system operators (TSO) by means of re-dispatch measures.

Cities and metropolitan regions have potential to integrate RE in their energy systems and contribute to solving the previously described issues. The German city of Hamburg is a good example of the potential of cities in the integration of renewable energies. Hamburg has significant electricity demand and consumption. With an annual electricity consumption of 12.9 TWh_{el} and a peak demand of around 2 GW_{el} in the year 2012, Hamburg accounts for around 2 % of the German total consumption and peak demand. Although the RE capacity within the city boundaries is small relative to the city's demand, the city's neighboring states allocate large RE production capacities, especially onshore and offshore wind energy. Furthermore, Hamburg has electricity and natural gas distribution grids as well as a large district heating grid. This infrastructure could facilitate the integration of RE by means of power-to-heat (PtH), power-to-gas (PtG) and central storage technologies. Finally, Hamburg has a conventional power park for the local production of electricity and heat, which could meet the net demand at moments with low RE production. For these reasons, Hamburg is chosen in this work as a case study to evaluate the integration of RE in urban energy systems.

To achieve this, the system can be regarded as an energy island capable of satisfying its own energy demands by minimizing the exchange of energy flows outside of the system boundaries. If this kind of regional balancing is replicated in other metropolitan regions, the curtailment of RE, the unplanned power flows through neighboring transmission systems, and the need of additional transmission lines could be reduced. In other words, the balancing of RE within self-sufficient metropolitan regions could lessen the stresses in the national transmission grid, in this case, the German transmission system. Finally, applying similar balancing methods at a national level could contribute to reduce future transmission bottlenecks in the continental energy system, in this case the European transmission system. This is the approach followed in this work.

1.2 Aim and scope

The goal of the present work is to analyze variations to Hamburg's centralized energy park and its operation strategy in order to find ways to increase the share of RE in the city's electricity and heat consumption, while reducing the exchange of energy flows through the system boundaries and ensuring the security of supply.

The reference system of this study is the energy system of the Hamburg metropolitan region in the year 2012. In addition, eleven system variations are defined in which an increase in the installed RE capacity is assumed for a representative year in the future (2050 or beyond). Each of the analyzed system variations are individually modelled and simulated for this representative year. The demand and potential RE production profile are the same for all variations. After simulation, a set of energetic, economic and environmental performance indicators allow the analysis and comparison of the system variations. These performance indicators include share of RE and combined heat and power (CHP) in electricity consumption, total annual costs, total annual CO_2 emissions and share of RE in district heating consumption.

The variations to the centralized energy park analyzed in this work include fossil power and combined heat and power plants with and without hydrogen co-firing, PtH and PtG units as well as hydrogen storage. Centralized variations to the energy park are favored because they usually have a better economic performance than decentralized schemes. This is, among other reasons, because large scale systems usually have lower specific investment costs and better efficiencies.

The described variations to Hamburg's central energy park were conceived in order to define a so-called "central oriented scenario". This and other three scenarios are the subject of research in a larger joint research project [3]. The other scenarios analyzed within the joint research project are focused mainly on distributed generation, demand side management as well as gas production and storage solutions. Some of the sub-system models used in this work were created by the project's programming development team.

1.3 Outline

The technologies implemented in the system variations in order to improve the integration of RE are presented in Chapter 2. These technologies include conventional power and CHP plants with hydrogen co-firing, electrode boilers, electrolyzers, as well as hydrogen storage. Besides, this chapter also addresses balancing issues of RE in different countries and gives an overview of studies addressing these issues with different approaches.

In Chapter 3, the reference energy system and the system variations are described in detail. The description includes the definition of the system boundaries and the composition of the energy park. The common dataset used in all system variations is also presented in this chapter. This includes electricity and heat demand profiles as well as RE production profiles.

The modeling of the energy system variations and its constituting subcomponents is the main topic of Chapter 4. The subcomponents include the production, storage and conversion units. The implementation of the selected operation strategies is also described in this chapter.

The simulation results are analyzed in Chapter 5 and Chapter 6. These include energy flow profiles as well as annual energy, costs and CO_2 emissions balances. The system variations which achieve a better trade-off between costs, CO_2 emissions and share of RE in the system's energy consumption are identified and discussed. Final remarks on this work are included in Chapter 7

2 Current situation, research and technologies

2.1 RE integration issues in regional energy systems

Issues related to the regional balancing of electricity production and demand are common in countries with large variable RE production capacities. To illustrate this point, balancing issues in China, Denmark and Germany are presented in this section.

According to [4], the government of China requires that all utilities should have 8 % of RE capacity in their electricity production portfolio by the year 2020. But the installed wind power production represents already today a challenge for some of the country's inter-provincial transmission grids. Besides, most part of the wind parks in China are located mainly in the north of the country, whereas the hydro plants, which could be used to balance the fluctuations of RE, are mainly located in the country's south and center. Because of the lack of sufficient transmission lines, curtailment has led to a reduction in the wind energy's capacity factor despite an increase in installed capacity. An interesting fact about the Chinese case is that, according to [4] and [5], controlled trials of electricity dispatch schemes in which RE have feed-in priority (such as the German scheme) led to conflicts between RE and CHP plants, which are the primary heating source in Northern China.

Another example of regional balancing issues is offered by Denmark's "Great Belt Link". According to [6], Denmark's wind parks are mainly located in the country's west side (Jutland and Funen), which is synchronized with the central European grid, whereas the country's east side (Zealand) is synchronized with the Nordic grid, i.e. with Finland, Sweden and Norway. Because of this, both regions participate in different electricity markets: DK1 for West Denmark and DK2 for East Denmark. The electricity price in the DK1 market has been traditionally lower than the price in the DK2 market. This is, to a large extent, due to the high wind penetration and the merit order effect [7]. RE integration strategies, such as the use of electric boilers for district heating, flourished in Western Denmark mainly due to these favorable electricity prices. However, on the 26th of August of 2010 both regions got interconnected via the "Great Belt Link", a 600 MW High Voltage Direct Current transmission line. This increase in the available transmission capacity led to an increase in prices at the western side (see [8] for additional information regarding this effect). With higher electricity prices, the economic feasibility of RE integration technologies, such as electric boilers, has been significantly reduced. It has been estimated, that operating hours of these plants were reduced by 77 %, from around 1,772 h to 400 h [6]. This example shows that the regional RE integration approach can be in direct conflict with the approach of increasing the transmission capacity.

Finally, the regional balancing issues in Germany are addressed. Two evident technical consequences of these issues are the increasing interventions of the TSO by means of feed-in management and congestion management measures. The feed-in management (in German *Einspeisemanagement*) is defined in § 14 of the EEG and allows the TSO to curtail RE's power output to avoid situations in the electric grid which could jeopardize the security of supply. The congestion management (in German *Engpassmanagement*) is defined in § 13 of the German Energy Industry Act (EnWG) [9] and allows the TSO to interfere in the scheduled power production and trade to avoid situations in which the grid could become unstable. Re-dispatch and counter-trading are two of these congestion management measures.

A recent example of how these interventions are becoming an increasing concern for the German TSO took place between January 9th and 11th of 2015 [10, 11]. In this weekend, the storm fronts "Elon" and "Felix" led to wind speeds of up to 160 km/h, leading to very high wind power outputs. It was reported that during this period, the wind power production was up to 30.7 GW_{el}. The geographic and timely imbalance of production and demand forced the TSO TenneT to intervene with re-dispatch measures accounting for 4.8 GW_{el}, leading to costs of €6 million. The TSO 50Hertz reported interventions on 6.7 GW_{el}, resulting in costs of around €7 million. This led to total costs of at least €13 million for the mentioned weekend. According to the German law, the costs derived from these measures are then charged to the consumers by means of increased grid fees. Similar situations were reported by the TSO in Winter 2011/2012 [12].

Another balancing issue in Germany which is worth mentioning is related to the so-called "dark doldrums" (in German: *Dunkelflaute*). As reported by [13] and [14], certain metrological conditions can lead to several days of low wind speeds and low solar irradiance. Additionally, low temperatures lead to higher electricity demand. Such an event occurred in the days around the 24th of January of 2017, which led to the fact that around 90 % of Germany's power demand had to be supplied by conventional power plants, such as coal, gas and nuclear power plants. These extreme examples put in evidence the issues related to increasing RE capacities in regional energy systems.

2.2 Related research studies dealing with RE integration

Over the last years, several studies have addressed technical and economic questions regarding the integration of RE in international, national and regional energy systems. Table 1 provides an overview of selected RE integration studies sorted according to their geographic scope.

Table 1 – Overview of related studies

Short name	Reference	Geographic scope	Analyzed region	Analyzed technologies	Time resolution	Simulation tool
EWIS	[15]	International	Europe	EG	1 h and ms	EWIS market and grid model, Netomac
SteinEtal	[16]	International	Europe	EG, STOR	1h	GAMS/CPLEX
DENA II	[17]	National	Germany	EG, STOR	1 h	DIME, DIANA (EWI-Köln)
WWSIS	[18, 19]	National	USA (West)	EG	1 h	GE-MAPS
EREIS	[20]	National	USA (East)	EG	1 h	GE-MARS, PROMOD IV
HK	[21]	Regional	Hong Kong	EG, DHG	1h	EnergyPLAN
AUGS	[22]	Regional	Augsburg	EG, DHG, GG	1h	URBS (C++ Tool)
BERL	[23]	Regional	Berlin	EG, DHG	1h	deeco
SYMBIOSE	[24]	Regional	Wien	EG, DHG, GG	n. a.	PSS SINCAL. MATLAB.
InsHHWilh	[25]	Regional	Hamburg	EG, DHG, STOR	1h	RESSI
MorbHH	[26]	Regional	Hamburg	Power plant, CHP, electricity market	1 h	deeco and deeco-s
MastPlaHH	[27]	Regional	Hamburg	Cumulative balances: el. energy, heat, and transportation	n. a.	n. a.
ExpHamb	[28]	Regional	Hamburg	DHG, STOR, renewable heat sources	1 h	BET-SysMod

** EG: Electric Grid, DHG: District heating grid, GG: Gas Grid, STOR: Storage*

International studies, such as EWIS [15] and SteinEtal [16] aim to identify power transmission challenges imposed by high RE in electric grids in very large areas, such as the European Union. These studies take a rather holistic approach which sometimes includes the modeling of electricity markets and physical power flows. In [15], a market model calculates dispatching schedules for the energy park of several market areas for one year. Each market area is considered as a “copper plate”, i.e. internal transmission bottlenecks are neglected. Only cross-border transmission limitations between the market areas are considered by means of Net Transport Capacities. Additionally, steady-state load flow simulations of selected operation points with high regional wind outputs and low demand are conducted with a detailed grid model. This model considers national transmission capacities. Finally, dynamic simulations of disturbances such as frequency and voltage drops due to short circuits are conducted to analyze the transient stability of the system with a time resolution of milliseconds.