



Charting the course: A possible route to a fully renewable Swiss power system

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ARTICLE INFO

Article history:

Received 6 March 2018

Received in revised form

20 July 2018

Accepted 2 August 2018

Available online 15 August 2018

ABSTRACT

The prospect of a renewable transition seems plausible for many countries, but can be shrouded in risks, costs and challenges. This paper illuminates a path for such a transition with a numerical investigation, aimed at resolving the power dynamics of a country powered only by renewable generators. The focus was Switzerland, with its considerable hydropower infrastructure and plans to phase out nuclear energy. The model uses optimal power flow calculations to compute the transmission of electricity, and also accounts for the movement of water within the hydropower system. Results suggest that the renewable goal is attainable and will not require radical re-building of the country's transmission infrastructure. Under our assumptions, it was found that the transmission grid is placed under slightly lower stress on average, in renewable scenarios. Despite matching supply and demand on average, the fully renewable system required a ~ 107% increase in electrical exchange with neighbouring countries to compensate for seasonal variability, and additional intermittency of electrical supply. Simulation results are described for three scenarios: Current, Intermediate, and Renewable. The bulk power statistics, temporal dynamics, distributions of line use, and spatial patterns are presented, and the implications of the results are discussed.

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1. Introduction

The destructive impacts of climate change are being increasingly felt across the world, provoking humanitarian crises and presenting a dire vision of potential futures for our civilisation [12,18]. However, simultaneously, progress in the penetration of renewable energy technologies has been impressive. There are a range of encouraging recent statistics including the achievement of Denmark, where 42% of electrical demand was satisfied by wind energy alone during 2015 [14]. Likewise in Germany, 32.5% of electricity consumed was sourced from renewables during the same year [16]. More recently, in the UK, offshore wind power is

now cheaper than new nuclear installations [19]. The costs of solar infrastructure also continue to show an encouraging decline, and new technologies, such as Perovskite solar cells, may accelerate these trends even further [38].

There has also been a vast amount of work on so-called smart systems for renewable resource utilisation. Frontier-level methods from machine learning and optimal control theory have allowed great progress to be made in dealing with the inherent variability of renewable energy [4,22,26,35,41,59]. Despite the advances in many aspects of renewable power, there remains a need for insight into the dynamics and operational risks of *fully* renewable energy systems at large scales (national and international). Risks in the context of this work include failure to meet demand, both in the short term (e.g., large fluctuations in renewable output that could cause grid level failures) and long term (e.g., large scale production deficits from seasonal differences in renewable output). Other risks

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of renewable investment include the opposite case, in which significant volumes of renewable production have to be curtailed in order to protect grid integrity. There are further socio-political risks associated with renewable energy. A prime example was the induced seismicity events caused by geothermal drilling operations in Basel in 2006 and 2007 [8,27,33].

In the long term, all future power systems will have to be free of non-renewable generators. While this is an ambitious goal, it is appearing more and more attainable with each passing year. There has been a plethora of modelling efforts in this direction, at various levels of resolution and locations including continental Europe [6,10,21,39,50], the Nordic countries [36], the United States [3,5,25,34], and the entire globe [9,23,24,49]. These and other works have provided insights and candidate solutions, including oversizing the generating capacity of the system [11,20] and moving towards more highly meshed transmission networks [42,49]. Given the inherent risks of investing in new energy infrastructure, there is still a compelling need for guidance on how different future renewable systems could be operated. This was the primary motivation for the present work: to provide detailed insights into the spatio-temporal dynamics of a hypothetical, fully renewable national power system.

Many European countries have the potential to become fully renewable. The United Kingdom has one of the world's largest wind resources, Spain and Italy receive vast amounts of solar energy, and Iceland has more than enough hydropower and geothermal energy to satisfy its electrical and heating requirements. In this work the focus was Switzerland, which presents a different, but equally viable set of alternatives. The country has long sourced the majority of its electricity from hydroelectric power. At present this accounts for approximately 56% of electricity production [52]. The remainder comes almost exclusively from nuclear power and in the long term, these plants will not be replaced after de-commissioning [51]. This leaves a considerable deficit which could be alleviated by a range of sources including solar, wind and geothermal energies.

While various calculations have shown that on average, Switzerland can be fully renewable [2,11] (note also the less optimistic outlook of [40]), there is still a need for ensembles of modelling data concerning exactly how a renewable Switzerland would function. Planning bodies need to know where solar and wind installations should be optimally placed in terms of not only maximising yield, but also minimising the risk of failure to meet local demand, and assisting with temporal smoothing of other sources [28]. We must explore the scenario space and seek bottlenecks in the transmission grid where upgrades might be required. It is important to investigate how different degrees of climate change might perturb the system in coming decades. Reduced future snow cover [47] will help to close the winter energy gap through earlier snow melt [30], while some authors predicted glacier loss to have a negative impact on Swiss hydropower [43,45]. The extent to which upgrades to hydropower infrastructure could foster additional flexibility to the system should also be investigated.

There has been work in this direction previously [11,40,58], but those investigations were aggregated at the national level and hence could provide no insight into spatial dynamics. Given the considerable spatial heterogeneity of potential renewable energy supplies in Switzerland [2], effective future planning will require an understanding of the spatial flows of electricity within the system.

This paper presents a combined energy and water model that simulates the Swiss power system at the transmission level for extended periods (typically single or multiple years). It uses optimal power flow calculations to find ideal generation portfolios at each time step in the considered period. Reservoir levels are updated based on the output of the hydropower plants and natural

inflows. Numerical details of the system's operation can then be analysed.

This paper presents an overview of the results from our first phase of modelling. In the following section, the power system model is described. In Section 3, the most important findings from the simulations are presented, including bulk power statistics, analysis of transmission line use and exchange volumes, seasonal energy trends, and spatial distributions of power surpluses and deficits. The implications of the results for the future evolution of the Swiss and European power systems are discussed in Section 4. Conclusions are drawn in Section 5, and we outline the future directions of our research in Section 6.

2. Model construction

At its heart, our power system model is relatively simple. However there is a certain degree of complexity arising from the processing of input data and initialisation steps. The goal was to predict the medium and short term (periods of years, but resolved to sub-hourly time scales) dynamics of the power flows within Switzerland and with its neighbours. This section will first define the general methodology before moving onto the various power sources and effective costs. Note that the objective was to optimise the technical features and operation of this national power system. Market effects were not considered since this was not the focus of the present work. Once there is a clear and plausible case for a fully renewable Swiss power system, future studies that consider market dynamics can be undertaken.

2.1. Overview

The inputs to the model consist of data for electrical demand, solar insolation, wind speeds, river flow rates and reservoir inflows for a given period. This period is discretised into timesteps. The finest resolution timestep is 15 min with the current data set, but coarser resolutions can also be chosen for the sake of computational speed. The model is driven by an optimal power flow (OPF) algorithm which, at each timestep, calculates the generating portfolio for satisfying demand at minimum cost. This algorithm consists of a library of functions and routines for power system modelling known as Matpower [61–63]. The OPF within this library uses a primal-dual interior point solver and is run within a Matlab environment. At each timestep, effective cost functions are calculated for all generators, including virtual generators beyond the country's borders, which represent electricity import. There are also despatchable loads at the same nodes, that allow electricity export to neighbouring countries. The OPF algorithm is supplied with the details of the grid configuration (properties of the transmission lines, transformers, electrical nodes, generators, demand), and carries out its computation of the optimal distribution of power production by the available generators. This procedure is iterated for the entire time period being analysed. Fig. 1 shows the overall structure of the algorithm that implements the model.

2.2. Hydropower

For many years hydropower has been the most important electricity source in Switzerland, both in terms of production volume, and provision of balancing services. Hydropower remains an invaluable component of the power system, and in the year considered in this paper, 2014, hydropower sources provided 39.3 TWh of energy, of which 22.1 TWh came from storage plants and the remaining 17.2 TWh from 'run-of-river' (RoR) plants [31].

Since hydropower accounts for $\sim 56\%$ of domestic electrical production (in a typical year), it was essential to faithfully represent

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