Applied Energy 172 (2016) 152–168

Contents lists available at ScienceDirect

Applied Energy

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

Alternative low-carbon electricity pathways in Switzerland and it's neighbouring countries under a nuclear phase-out scenario

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HIGHLIGHTS

- Development of a TIMES electricity model to study nuclear phase-out, CO_2 mitigation.
- Optimal for Switzerland to import electricity than invest in renewable technologies.
- Achieving CO_2 emission reduction on European scale optimal than national targets.
- CCS technology indispensable for achievement of climate mitigation targets.
- Non-nuclear supply options increase the cost of electricity supply by 30–70%.

ARTICLE INFO

Article history:
Received 8 January 2016
Received in revised form 17 March 2016
Accepted 18 March 2016
Available online 31 March 2016

Keywords:
Nuclear phase-out
Decarbonisation of power sector
TIMES model
Switzerland
Electricity model

ABSTRACT

Switzerland and Europe are currently at a crossroads with respect to its electricity policy. Several existing nuclear and fossil fuel power plants are to be retired in the coming years. Meanwhile, ambitious carbon dioxide (CO_2) emission reductions are envisaged, which could penalise fossil power plants and encourage investments in renewable-based electricity generation. Switzerland and a few other countries in Europe have decided to phase-out their nuclear capacity, thereby removing a low-carbon source of electricity in the medium- to long-term future. In order to understand possible electricity transition pathways for Switzerland, electricity supply options for Switzerland and its four neighbouring countries namely Austria, France, Germany and Italy are analysed to assess non-nuclear alternatives under a stringent climate mitigation policy. The cross border Swiss TIMES electricity model (CROSSTEM), a cost optimisation framework with a long time horizon and an hourly temporal resolution, is used for this analysis. In the absence of any CO_2 emission reduction targets, gas-based generation supplemented by electricity imports is the cost-effective alternative to nuclear for Switzerland. For a low carbon electricity system, natural gas based generation with Carbon Capture and Storage (CCS), complemented by an accelerated investment in renewable generation is required. Traditional electricity trade patterns have to be revised, with significant increases in cross-border interconnector capacities necessary to transfer electricity to Switzerland from countries with abundant renewable resources such as Germany and Italy. The average cost of electricity in a decarbonised electricity sector would increase in the range of 30–120% by 2050 compared to today, depending on the scenario assumptions. The availability of CCS technology and the requirement for electricity storage are particularly important to achieve a complete decarbonisation of the electricity sector with a nuclear phase-out.

1. Introduction

The electricity sector is an important contributor to the Swiss energy system and economy, providing one quarter of the Swiss final energy demand, whilst generating an annual turnover of about CHF 32 billion or about 5% of the Swiss national GDP in 2013 [1,2]. Hydro and nuclear power dominate the Swiss electricity generation mix, with approximately 56% of the electricity generated from hydro, 38% from nuclear, and 6% coming from fossil fuel, waste and new renewables (solar PV and wind) in 2014 [1]. Due to its ideal positioning between northern and southern Europe, Switzerland also acts as an interconnecting hub, linking the three biggest central European national markets of Germany–Austria, France and Italy. The cross-border interconnector capacities of Switzerland are

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http://dx.doi.org/10.1016/j.apenergy.2016.03.084
0306-2619/

around 10 GW, amounting to approximately 20% of the EU interconnector capacity [3]. As a result, developments in the Swiss electricity system will influence European grid expansions due to its transit role and vice-versa [4]. Hence, exploring transition pathways to future electricity systems for Switzerland is incomplete without accounting for the developments in Europe, in general, and neighbouring countries, in particular.

A wind of change is currently sweeping through European energy policies. The "nuclear renaissance" that was expected to provide a low-carbon alternative source of electricity in the medium- to long term future came to a shuddering halt in many European countries after the Fukushima nuclear accident [5]. Switzerland, which has approximately 38% nuclear-based electricity generation, originally envisaged to replace some of its existing nuclear fleet with new nuclear plants [6]. However, on the 25th of May 2011, the federal government decided to gradually phase-out nuclear energy as part of its new energy strategy until 2050 [7]. Germany, which until March 2011 produced a quarter of its electricity from nuclear energy, immediately shut down eight of its oldest reactors (around 8.3 GW of 20.3 GW installed nuclear capacity), whilst the remaining nine reactors are to be shut down by 2023 [8]. Italy intended to produce 25% of its electricity supply from nuclear power by 2030, but decided to continue with its nuclear moratorium after a referendum in June 2011 [9]. France, a traditional nuclear powerhouse with over 75% nuclear-based electricity generation, also faces political problems in terms of expanding or replacing their existing nuclear fleet [10]. The current government proposed to reduce the share of nuclear to 50% of the total electricity generation by 2025 [11].

Whilst the decision to abstain from nuclear power is not very drastic in itself, discussions continue on alternative sources of electricity supply. For instance, Germany has been substituting nuclear generation with coal-fired electricity generation. More than half (52%) of Germany's electricity generation was from coal in 2013, compared to 43% in 2010. This in turn has increased Germany's CO_2 emissions despite the country's efforts to support renewable development [8]. Italy is heavily dependent on fossil fuel generation (46% from natural gas, 16% from coal, 9% from oil), and is also Europe's largest net importer of electricity (about 15% of total demand) [9]. Switzerland foresees a combination of natural gas, renewables and/or electricity imports as possible substitutes for outgoing nuclear power plants [12].

The European Union (EU) emphasises a low-carbon energy pathway for the long-term future and the EU Roadmaps foresee an almost complete decarbonisation of the electricity sector by 2050 [13]. Phasing-out of nuclear in the aforementioned countries could undermine their policy objectives on climate change mitigation. These conflicting developments pose considerable technological and economic challenges. Hence, it is important to explore non-nuclear alternative sources of electricity supply and understand their implications in a wider context.

To generate insights on alternative future electricity supply options for Switzerland, this paper focuses on five countries: Switzerland (CH), France (FR), Germany (DE), Austria (AT) and Italy (IT). Together, these five countries account for over half of the total electricity generation in Central and Western Europe [14]. The aim of this paper is to assess non-nuclear alternatives for these countries given their technical and resource constraints. Using a "what-if" framework, the following research questions are addressed: What are the technological options for Switzerland and its neighbouring countries to decarbonise their power sector? What would be the associated cost? How can the electricity system cope with the variability in electricity supply and demand under an increasing share of intermittent renewable-based electricity generation? What would be the role of cross-border electricity exchange in balancing the supply and demand?

Section 2 provides a literature review of existing electricity system modelling frameworks for Switzerland and Europe. Section 3 describes the analytical framework and key assumptions used in the model for this study. Section 4 elucidates the three scenarios analysed in this paper. The results of the scenarios are discussed in Section 5. Section 6 draws key conclusions with potential policy options.

2. Literature review

A number of studies have explored alternative technology and CO_2 mitigation pathways using energy economic models. Some of these models are based on macroeconomic frameworks with limited or no representation of technologies, and are referred to as computable general equilibrium (CGE) models. Examples of CGE models for Switzerland include the GENESwIS model by Econability [15], the CITE model developed by the Centre of Economic Research at ETH [16], the CEPE model by the Centre for Energy Policy and Economics at ETH [17], and the SWISSGEM_E model developed by ECOPLAN [18]. These models have highly aggregated technology data and limited intra-annual details, which make them unsuitable for analysing intermittency issues of variable renewable technologies such as solar photovoltaic (PV) and wind.

Numerous bottom-up models also exists, which have a much better representation of technological characteristics. Examples of Swiss bottom-up models include SwissMod by FoNEW Basel [19], Energy Technology Environment Model (ETEM) by [20,21], Swiss MARKAL Model (SMM) by Paul Scherrer Institute [22], ZEPHYR by Pöyry [23], "Energiezukunft Schweiz" model by the Energy Science Centre at ETH [24], SCS Energiemodell by SCS Supercomputing Systems AG (Super Computing Systems (SCS) [25]), Mesap/PlaNet model developed by DLR and used by Greenpeace for Switzerland [26], ENERPOL by the Laboratory for Energy Conversion, ETH [27] and finally the model developed by PROGNOS for the Swiss Energy Strategy 2050 [12]. Whilst all of these analytical tools are unique on their own, they do have certain limitations. The scopes of these analyses vary in terms of their technology representations, geographical boundaries, and temporal representation, amongst other factors. SwissMod, ENERPOL and the SCS Energiemodell are unit dispatch models with very high inter-annual detail (hourly or quarter-hourly). These models are aimed at analysing dispatchability of electricity generation technologies through optimisation or simulation frameworks. However, they do not consider investment decisions or capacity expansion due to their shorter time horizon (1–5 years). Other models like the ones from PROGNOS, VSE and Greenpeace consider long time-horizons, but the generation mix is largely defined exogenously, depending on scenario assumptions [12,23]. Models such as SMM, ETEM and the ETH/ESC model are capacity expansion models where the generation mix is optimised on a cost basis over a long time-horizon. These long-term planning models, however, do not capture intra-annual variability in renewable resources due aggregated intra-annual representation. This could lead to suboptimal investment decisions, with overestimation of renewable penetration and/or underestimation of storage or flexible capacities required to balance the system, which further implies an underestimation of total system costs [28].

In order to understand the evolution of the electricity sector, it is important to understand investment cycles (i.e., capacity expansion) as well as variability in supply. But in reality, combining both dimensions is challenging with respect to several aspects such as computational complexity, and data availability [29–32]. The Swiss TIMES electricity model (STEM-E) developed at PSI [33] was the first attempt at combining these feature for a Swiss model. The model has a very detailed depiction of the Swiss electricity system