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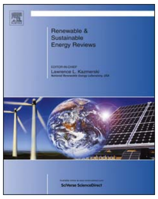

Vision and initial feasibility analysis of a recarbonised Finnish energy system for 2050

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ABSTRACT

An energy system based entirely on renewable energy (RE) is possible for Finland in 2050 based on the assumptions in this study. High shares of solar PV (photovoltaics) were deemed to be feasible at extreme northern latitudes when supported by flexibility harnessed from other aspects of the energy system, suggesting that high variations in solar irradiation throughout the year may not be a barrier to the implementation of solar PV closer to the poles. A 100% RE system corresponds to a highly competitive cost solution for Finland, as total system costs decrease through interaction between the power, heating/cooling and mobility sectors. We incorporate these sectors on an hourly resolution using historical data and the EnergyPLAN modelling tool. In addition, we offer full transparency of all assumptions regarding the Finnish energy system. In 2050, a 100% renewable energy scenario has the lowest overall annual cost, at 24.1 b€/a. This is followed by several scenarios that feature increasing levels of nuclear power, which range in annual costs to 26.4 b€/a. Scenarios were also modelled with varying levels of forest-based biomass. Results suggest that annual costs do not increase dramatically with reduced levels of forest-based biomass fuel use. At the same time, it must be kept in mind that assigning costs to the future is inherently uncertain. How future societies assign risk to technologies or place value on emissions can make the scenarios under investigation more or less attractive. The 100% RE scenarios under investigation were seen as less exposed to such uncertainty.

Contents

Abbreviations: RE, renewable energy; PV, photovoltaic; GHG, greenhouse gas; LPG, liquid petroleum gas; CHP, combined heat and power; DH, district heating; BAU, business as usual; $_e$, electric units; $_{th}$, thermal units; $_{gas}$, gas units; $_p$, nominal or peak capacity; TPED, total primary energy demand; PtG, Power-to-gas; PtL, Power-to-liquid; PtX, Power-to-chemical; V2G, Vehicle-to-grid; BEV, Battery electric vehicle; Capex, Capital expenditures; Opex, Operating and maintenance expenditures; LCOE, Levelized cost of electricity; WACC, Weighted average cost of capital; Crf, Capital recovery factor; GDP, Gross Domestic Product

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1. Introduction

Across the European Union, efforts are underway to achieve greenhouse gas (GHG) emission reduction targets set for 2020 [1]. Concurrently, many countries are looking beyond 2020 and examining the roles of various renewable energy technologies within energy systems. More and more, the concept of integrating the power, heating/cooling and transport sectors of the energy system becomes prominent in discussions [2–5], perhaps to the point that examining any of these sectors in isolation becomes almost meaningless. The most progressive actions to plan and model future energy systems appear to be in Denmark. Beginning in 2006, the Danish Association of Engineers (IDA) initiated discussions concerning the future of the Danish energy system for both 2030 and 2050 [6]. This work culminated in the IDA Energy Plan 2030 [7] and the IDA Climate Plan 2050 for Denmark. Since that time, several seminal studies of energy systems based entirely on renewable energy have been published [2,8–10]. Recently, the components and workings of a Smart Energy System were outlined based on the work of Coherent Energy and Environmental System Analyses (CEESA) researchers, also based in Denmark [11]. Such approaches aid in identifying least cost solutions for 100% renewable energy systems that fully integrate the power, heating/cooling and transport sectors, and unlock the potential flexibility throughout the entire energy system.

On a practical front, Germany has emerged as a global leader in deploying the physical elements of a Smart Energy System. According to the Fraunhofer Institute, Germany has more than 75 GW_e of installed capacity of wind and solar power plants, which reached a maximum output of almost 40 GW_e in late 2014 and 79 TWh_e in total for the year [12]. All renewable power systems reached a capacity of 93 GW_e by the end of 2014, generating electricity of 161 TWh_e in total for the year [13]. At the same time, the country is finding positive business models for energy storage solutions to support such high shares of RE, such as Power-to-Gas (PtG) [14], Power-to-Liquid [15], thermal energy storage [16] and battery storage [17]. These solutions not only provide the needed energy services for the entire country, but can provide the needed grid services often reserved for large, base load power plants.

Germany, Denmark and Finland are countries that share similar geographies, populations, levels of affluence, ways of life and climate. These similarities result in the question of whether an energy system based on high shares of renewable energy would be suitable for Finland. On the supply side, there appears to be great potential to add flexibility to the Finnish energy system [18] by integrating energy system components. However, the extent of this potential has not been explored in detail. It appears worthwhile at least to investigate how much more potential exists within the Finnish energy system, and to determine the components and workings of a fully-integrated, future energy system.

Several reports have documented the results of scenario-based modelling of the Finnish energy system [19–25]. In addition, peer-reviewed articles have recently appeared that have examined the role of high shares of variable renewable energy in Finland [18,26,27]. While each report and article has contributed greatly to discussions about the future of the Finnish energy system, each has its own limitations or lacks an essential quality. For this reason, new standards must be set for scenario modelling so that the following conditions are met:

- Analysis of integrated energy systems which include the power, heating/cooling and transport sectors
- Calculations made on at least an hourly resolution
- Incorporation of real demand and production data as much as possible
- Full transparency of technical and economic assumptions

The last criteria may be the most critical to the success of scenario modelling, which has two interrelated functions. First, it shows future possibilities in a detailed manner and invites comparison of several alternatives. Second, it invites reflection, criticism and discussion around the key assumptions and their sensitivities. The aim of modelling future scenarios must not be seen as prediction, nor must it be seen as directive ideology. Instead, it must be viewed as a representation of the possible or probable components of the future scenario under investigation given the assumptions used. In a best-case scenario, modelling will be robust enough to account for several plausible futures at the same time. In the end, the real value of future scenario modelling becomes the subsequent discourse around it. For there to be any real merit in such discourse, transparency is essential.

The most recent peer-reviewed study of the Finnish energy system [27] satisfies each of the above criteria. However, the main objective of determining a maximum limit to the integration of renewable energy into the existing energy system begs the question of how results might be different based on a future energy system that might be very different from the current one. In particular, the impact of high shares of solar PV, a technology emerging as a least cost solution around the world [12], is not well known in areas of such extreme northern latitudes. In many ways, Finland represents a proving ground for solar PV due to high variations in solar irradiation throughout the year. Although the country sees high amounts of sunlight in the summer months, the long, dark winters present a challenge for the energy system to find alternate resources at that time. Utilizing storage technologies to better match supply with demand seems obvious. However, the precise mix of production and storage technologies that would be optimal for Finland has not been explored for a fully integrated energy system. Further, demonstrating the feasibility of high shares of solar PV in Finland could have relevance to the other Nordic countries, and indeed serve as a model for other countries at high northern latitudes, such as Russia, the UK, Canada, and the USA. Results could even offer potential insights for countries at high southern latitudes. Naturally, such a future energy system would be speculative by nature and would therefore require several guiding principles to provide a framework of system requirements. These requirements will be discussed after a brief description of the components of the current Finnish energy system.

Demand for energy services in Finland is high due to the needs of an industrious society in a Nordic climate. Since 2000, Total Energy Consumption has stabilized at approximately 380 TWh_{th}, with final electricity consumption of approximately 85 TWh_e, final heat demand of 80 TWh_{th}, and transport demand of roughly 50 TWh_{th} [28]. Currently, the share of renewable energy of total consumption is 32% and is set to rise to at least 38% of final energy consumption by 2020 under Finnish commitments to EU energy climate targets [22]. In the power sector, the share of renewables is 41% [28]. The targets also include a 20% reduction in GHG emissions compared to 1990 levels, a 20% share of biofuel use in transport and a 20% increase in energy efficiency compared to 2007 levels. The sources of energy consumption are shown in