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Higher renewable energy integration into the existing energy system of Finland – Is there any maximum limit?

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A B S T R A C T

Finland is to increase the share of RES (renewable energy sources) up to 38% in final energy consumption by 2020. While benefiting from local biomass resources Finnish energy system is deemed to achieve this goal, increasing the share of other intermittent renewables is under development, namely wind power and solar energy. Yet the maximum flexibility of the existing energy system in integration of renewable energy is not investigated, which is an important step before undertaking new renewable energy obligations. This study aims at filling this gap by hourly analysis and comprehensive modeling of the energy system including electricity, heat, and transportation, by employing EnergyPLAN tool. Focusing on technical and economic implications, we assess the maximum potential of different RESs separately (including bioenergy, hydropower, wind power, solar heating and PV, and heat pumps), as well as an optimal mix of different technologies. Furthermore, we propose a new index for assessing the maximum flexibility of energy systems in absorbing variable renewable energy. The results demonstrate that wind energy can be harvested at maximum levels of 18–19% of annual power demand (approx. 16 TWh/a), without major enhancements in the flexibility of energy infrastructure. With today's energy demand, the maximum feasible renewable energy for Finland is around 44–50% by an optimal mix of different technologies, which promises 35% reduction in carbon emissions from 2012's level. Moreover, Finnish energy system is flexible to augment the share of renewables in gross electricity consumption up to 69–72%, at maximum. Higher shares of RES calls for lower energy consumption (energy efficiency) and more flexibility in balancing energy supply and consumption (e.g. by energy storage).

1. Introduction

The confluence of climate change mitigation, security of energy supply, and promotion of distributed generation has stimulated national energy policies towards higher integration of RES (renewable energy sources). The EU energy targets aim to reduce the greenhouse gas emissions by over 80% by 2050, compared to 1990 levels [1]. This necessitates more efforts across the EU to augment the share of RES in final energy consumption by 30% and RES-E (renewable-based electricity) up to 50% by the year 2050 [2].

Finland is one of the successful EU States on the path in meeting 2020's energy targets [3], with over 30% RES in final energy consumption in 2012 [4]. The recent update of Finland's Energy and Environmental Policy [5] underlines fossil fuel consumption and power imports as two events that should be alleviated with new decarbonized energy production, e.g. by employing nuclear power, wind power, and more bioenergy. While Finland is committed to maintain 38% RES in final energy use by 2020, further increase in the share of RES beyond this target has attracted a wide attention in common energy debate. In other words, it is not evident for the policy makers and energy experts that what limits of RES are achievable and what techno-economic implications await the whole energy system under higher levels of RES integration. These salient questions should be properly answered when undertaking a new commitment to the EU or planning national RES-based energy scenarios.

The large-scale integration of RES in energy systems has long been subject to a wide range of researches, e.g. Refs. [6,7]. Other studies have further analyzed the case of 100% RES in electricity production, e.g. in Australia [8], Japan [9], New Zealand [10], as well as storage demand for 100% RES electricity in a global scale [11]. Considering the whole energy system, Ref. [12] examines the case of high-RES for Germany, Ref. [13] highlights the role of energy storage in a 100% RES Europe, whereas Refs. [14] and [15] postulate

Abbreviations: CHP, combined heat and power; CEEP, critical excess electricity production; DH, district heating; HDD, heating degree days; HP, heat pump; MREI, maximum renewable energy index; NPE, net power exchange; PEC, primary energy consumption; PFC, primary fuel consumption; RES, renewable energy source; RES-E, renewable-based electricity; VTT, Technical Research Center of Finland.

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a roadmap towards 100% RES by 2050 for Denmark and Macedonia, respectively. The results of these contributions typically call for structural changes in the energy system; such as electrification of heat sector and transportation, employment of innovative technologies for large-scale energy storage, establishment of power-to-gas supply chain in energy infrastructure, and adoption of supportive regulations for diffusing the mentioned solutions. While the technical feasibility of such structural changes should be thoroughly examined, the economic consequences for achieving such ambitious plans are also unavoidable questions to be addressed. The other quintessential outcome of these researches is the necessity of studying the “flexibility” based on the particular characteristics of each energy system, including demand regime, available resources, existing infrastructure, and the possible interconnection of heat, power, and transport sector. The term “flexibility” is used to assess the capability of an energy system to encounter with variation and uncertainty in both load and generation [16].

The integration of higher shares of RES in Finland's energy system has been subject for research in a number of contributions. Lund [17] and Niemi et al. [18] have investigated the possibility of increasing wind power in Helsinki region by analyzing spatial aspects and multi-carrier energy flows. Other studies have also examined the role of RES in Finland's energy system from policy and dependency viewpoint [19,20], rather focusing on detailed technical consequences. In a study [21] by VTT, Technical Research Center of Finland, a number of low-carbon scenarios are developed based on radical technological changes as well as non-technical (behavioral and consumption-related) recommendations. Finnish Energy Industry [22] has also outlined a future low carbon by emphasizing the role of electrification and district energy systems. In this study, however, we aim at portraying the maximum flexibility of the existing energy system in integration of RES with addressing both technical and economic implications in national level. By exploring the flexibility of the existing energy system, we are to establish a signpost for energy experts and policy makers to build their future high-RES scenarios on a more realistic basis.

To this end, by applying hourly analysis, the Finnish energy system is modeled in an integrated manner (heat, power, industry, and transport sectors) for the year 2012 as a reference model. Next, the increase in the share of RES is investigated by exploring the maximum potential of different technologies including bioenergy, hydropower, solar energy, wind power, and individual HPs (heat pumps). Finally, a combination of different RES systems that promises the highest RES in final energy consumption is realized. The remaining of this contribution is structured as follows. The methodology applied in this study is described in Section 2. A new indicator for assessing the maximum RES integration is proposed in this Section. The current situation of Finnish energy system is briefly reviewed in Section 3 and resource potential of different RES technologies is discussed. The results are presented and discussed in Section 4, followed by conclusions in Section 5. Solar cooling and concentrated solar thermal are not addressed in this analysis, as well as other RES technologies such as tidal, wave, and geothermal.

2. Methodology

2.1. Modeling of national-level energy systems

Different studies have highlighted the main challenges in modeling of energy systems bundled with recommendations for future developments [23,24]. Pfenninger et al. [25] categorizes national energy models as energy system optimization models, energy system simulation models, power system and electricity market models, and qualitative and mixed-method models. As suggested by Dodds et al. [26], the characteristics that distinguish energy system models from each other can be sorted as the model's paradigm and equations, locational and temporal dimensions, model's structure or topology, model's constraints and boundaries, and required parametric data. While some models suggest energy planning based on some selective operational occasions in the system, like summer and winter peaks, other models examine more temporal details. For example, an hourly-based energy system analysis offers more capabilities in illustrating the fluctuating nature of RES-based energy scenarios, where the corresponding data is available [27]. Furthermore, hourly resolution in energy system modeling offers opportunities in capturing the hourly variability of the heat and power demands, as well as power exchanges based on hourly electricity prices available. Despite the fact that collecting sub-hour data for energy system modeling is rather difficult and complex, it has been shown that modeling with resolutions of 5 min improves the results of hourly analysis just by 1%, in terms of yearly costs and benefits [28]. While detailed comparison of different energy models is beyond the scope of this study, based on the review of different energy system modeling tools [29–31], the authors recognized EnergyPLAN as a suitable tool for the scope and details of this analysis.

EnergyPLAN [32] is a deterministic model capable for hourly analysis of nation-wide energy systems by offering various options for integration of different RES systems. Since EnergyPLAN is applicable for the energy systems with high shares of CHP [33] interlinked with high shares of variable RES [6,34], and possibility to convert power into different energy carriers, it was selected for the purpose of this study. EnergyPLAN has already been employed for the modeling of RES integration into different national and regional energy systems, including Ireland [35], China [36], the province of Ontario, Canada [37], the UK [38], and other countries and regions (e.g. Refs. [39–46]). More information about the tool, its structure, documentation, case studies, and built models can be seen in Ref. [32].

2.2. The maximum limit for integration of variable RES

As the integration of variable RES is still in its primary stages in many countries, defining an upper limit for the share of variable RES is not so relevant either widely discussed in the literature. However, in RES-based energy planning and modeling of large-scale variable RES (e.g. in wind integration studies), the maximum integration level of variable RES into an energy system should be addressed by a proper criterion. From energy system viewpoint, the magnitude, duration, frequency, and time of occurrence of such fluctuations are important for calculating required flexibility solutions, like power ramping and/or energy storage. In other words, a proper measurement index is required to quantify under which occasion higher variable RES is undesirable, costly, and problematic for the energy system.

Different studies have proposed metrics for the assessment of the flexibility of power systems, e.g. see Refs. [47,48]. Ma et al. [16] defines a flexibility index by evaluating and aggregating the ramping rate of generation fleet considering their scheduled generation. Lannoye et al. [49] calculates the net load ramps by investigating ramping availability of individual plants in different time horizons. The mentioned methods require rather detailed information about different individual plants and their functional capabilities in different conditions. From energy system perspective, Lund [50] suggests the term CEEP (critical excess electricity production), expressed in TWh/a, for those levels of wind production that cannot be integrated in domestic energy system, cannot be stored or converted to other energy carriers, and are beyond the cross-border transmission capacity. In addition to the magnitude, Hedegaard and Meibom [51] examine the issue of wind oversupply in different time scales, from hourly to daily and longer periods.