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Multi-criteria decision analysis of energy system transformation pathways: A case study for Switzerland

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ABSTRACT

Two recent political decisions are expected to frame the development of the Swiss energy system in the coming decades: the nuclear phase-out and the greenhouse gas (GHG) emission reduction target. To accomplish both of them, low-carbon technologies based on renewable energy and Carbon Capture and Storage (CCS) are expected to gain importance. The objective of the present work is to support prospective Swiss energy policy-making by providing a detailed sustainability analysis of possible energy system transformation pathways. For this purpose, the results of the scenario quantification with an energy system model are coupled with multi-criteria sustainability analysis. Two climate protection and one reference scenario are addressed, and the trade-offs between the scenarios are analysed based on a set of 12 interdisciplinary indicators. Implementing a stringent climate policy in Switzerland is associated with co-benefits such as less fossil resource use, less fatalities in severe accidents in the energy sector, less societal conflicts and higher resource autonomy. The availability and implementation of CCS allows for achieving the GHG emission reduction target at lower costs, but at the expense of a more fossil fuel-based energy system.

1. Introduction

Recently, the regulatory boundary conditions of the Swiss energy system have substantially changed: On the one hand, the Swiss Federal Council decided in 2011 that Switzerland will gradually phase-out domestic nuclear power generation (SFOE, 2011b). If the referendum is not successful, that means – assuming a hypothetically constant domestic electricity demand and a 50-year lifetime of the reactors – about 40% of the Swiss supply has to be replaced by either additional domestic power generation or electricity imports around the year 2035. On the other hand, Switzerland issued a law on carbon dioxide (CO_2) emissions with the goal of reducing domestic greenhouse gas (GHG) emissions by 20% by 2020 compared to the 1990 level in order to contribute to the international efforts of limiting the global temperature rise to 2 °C by the end of this century. (The Federal Assembly of the Swiss Confederation, 2013). The advisory body of the Swiss federal council in climate change issues (OcCC) recommended a more stringent Swiss GHG emission reduction target of 60% by 2050 (OcCC, 2007). This recommendation has been tightened to minus 80–95% by 2050 (OcCC, 2012) recognising that climate change mitigation scenarios suggest negative global energy system CO_2 emissions in the second half of the century (Herrerasa and van Vuuren, 2014). In 2014, 81% of the domestic Swiss GHG emissions were CO_2 emissions (FOEN, 2016).

The two abovementioned political decisions will lead to a transformation of the Swiss energy system: Nuclear power must be replaced by other low-carbon electricity generation such as renewable energies and possibly Carbon Capture and Storage (CCS) technologies, but also low-carbon end-use technologies in residential, commercial, transport and industrial sectors (e.g. biomass and solar heating systems, alternative transportation fuels, energy efficiency measures) must contribute to eventually achieve the ambitious domestic GHG emissions reduction target. Besides the GHG reduction target and the nuclear phase-out, there are other policy concerns, such as assuring security and affordability of energy supply, and preventing human health and ecosystem damages, which are considered as being important in the context of the sustainable transformation of the Swiss energy system (The Swiss Federal Council, 2013).

The objective of the present work is to support Swiss energy policy-making by providing a detailed sustainability analysis of possible energy system transformation pathways. Namely, complete and consistent Swiss energy system scenarios are compared based on various environmental, economic and social criteria. The analysis focuses on the year 2035 when nuclear power generation is assumed to be phased-out in Switzerland.

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Table 1
Overview of recent sustainability analysis of electricity and energy system scenarios.

Study	Scope	System model	Scenarios	Indicators	Life-cycle inventory (LCI) data	MCDA method
(Atilgan and Azapagic, 2016)	Electricity Turkey 2010	no model	current system	11 environment 3 economy 6 societal	ecoinvent v2.2 Flury and Frischknecht Kouloumpis et al. PE International	Multi-attribute value theory (MAVT)
(García-Gusano et al., 2016)	Electricity Spain 2014–2050	TIMES-Spain energy model	2 scenarios	9 indicators	ecoinvent v3.0 Lechón et al. Dahlsten	
(Rahman et al., 2016)	Electricity Bangladesh 2010–2040	Long-range Energy Alternatives Planning System (LEAP)[a]	4 scenarios	24 indicators	–	Stochastic Multicriteria Acceptability Analysis (SMAA)
(Shmelev and van den Bergh, 2016)	Electricity UK 2050	MARKAL (Loulou et al., 2004)	7 scenarios	8 indicators	indicator values from literature	Aggregated Preference Indices System (APIS)
(Hertwich et al., 2015)	Electricity World 2010–2050	no model (assessment of IEA scenarios)	2 scenarios	10 indicators	mostly ecoinvent v2.2 LCI, some ecoinvent 3 LCI; ecoinvent 2.2 background database	–
(Brand and Missaoui, 2014)	Electricity Tunesia 2030	Own electricity market model	5 scenarios	4 cost 4 technology 5 emission 4 society and security of supply	–	Technique for order preference by similarity to ideal solution (TOPSIS)
(Santoyo-Castelazo and Azapagic, 2014)	Electricity Mexico 2050	no model (made up scenarios)	11 scenarios	17 indicators	Dones et al., Jungbluth et al., Bauer et al. (2008), SENER, GEMIS (Oko Institute), Lecointe et al., Sørensen and Naef, Viebahn et al., Frankl et al., DONG Energy	Multi-attribute value theory (MAVT)
(Hong et al., 2013)	Electricity South Korea 2010–50	no model	4 scenarios	12 indicators total cost assessment	–	ranking orders
(Ribeiro et al., 2013)	Electricity Portugal 2020	Own Mixed Integer Linear Programme (MILP)	5 scenarios	13 indicators	–	value measurement methods
(Streimikiene and Balezentis, 2013)	Energy Lithuania 2012/2020	Model for Energy Supply Strategy Alternatives and their General Environmental Impact (MESSAGE)[b]	7 scenarios	12 indicators	–	Full Multiplicative Form of Multi-Objective Optimisation by Ratio Analysis (MULTIMOORA)
(Sheinbaum-Pardo et al., 2012)	Energy Mexico 1990/2008	no model	historic years	8 indicators	–	–
(Eckle et al., 2011)	Energy 47 regions today–2050	Prospective Outlook on Long-term Energy Systems (POLES)[c]	14 scenarios	2 environment 2 economy 4 society 5 security of supply	–	Weighted Sum Approach (WSA)
(Browne et al., 2010)	domestic heating and electricity city-region in Ireland 2010	no model (current system)	6 scenarios	4 environment 1 security of supply 2 economy	–	Novel Approach to Imprecise Assessment and Decision Environments (NAIADE)
(Jovanović et al., 2009)	Energy Belgrade 2015	Model for Analysis of the Energy Demand (MAED)[d]	15 scenarios	4 environment 4 economy 4 societal	–	–
(Haldi and Pictet, 2003)	Electricity China 2000–2025	Electric Generation Expansion Analysis System (EGEAS)[e]	12 scenarios	3 economy 8 environment 1 society 1 technology	LCI data from various Chinese institutions	Elimination and Choice Expressing Reality (ELECTRE) III

[a] https://www.energycommunity.org/(Accessed 19 September 2016).
[b] http://www.iiasa.ac.at/web/home/research/researchPrograms/Energy/MESSAGE.en.html (Accessed 19 September 2016).
[c] https://ec.europa.eu/jrc/en/poles (Accessed 19 September 2016).
[d] http://www-pub.iaea.org/MTCD/publications/PDF/CMS-18_web.pdf (Accessed 19 September 2016).
[e] http://www.epri.com/abstracts/Pages/ProductAbstract.aspx? ProductId=000000003002001929. (Accessed 19 September 2016).

For the analysis, the energy system transformation pathways quantified by a bottom-up partial equilibrium energy system model are combined with multi-criteria decision analysis (MCDA). The idea is to make use of the complementary characteristics of these two methods, i.e. the whole system perspective of the bottom-up partial equilibrium energy system model and the detailed technology assessment of an MCDA. With this combination, energy system scenarios can be analysed from the perspective of multiple sustainability criteria instead of techno-economic indicators only. Such analyses provide the basis for policy-makers to make sustainable long-term decisions. Switzerland is selected as a case study region because of the recent political decisions which are expected to influence the sustainability of the future energy system. Additionally, the data availability and quality is good what eases the data collection and reduces the uncertainty of the analysis. By formalising the method, it is ensured that the approach can be applied to other regions which also undergo an energy system transformation.