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Cross-impact analysis of Finnish electricity system with increased renewables: Long-run energy policy challenges in balancing supply and consumption☆

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ABSTRACT

Climate change and global economic pressures are strong drivers for energy economies to transition towards climate-neutrality, low-carbon economy and better energy and resource efficiencies. The response to these pressures, namely the increased use of renewable energy, creates a set of new challenges related to supply-demand balance for energy policy and electricity system planning. This study analyses the emergent problems resulting from the renewable energy response. These complex aspects of change in the electricity system are analysed with a cross-impact model based on an expert-driven modeling process, consisting of workshops, panel evaluations and individual expert work. The model is then analysed using a novel computational cross-impact technique, EXIT. The objective of the study is to map the important direct drivers of change in the period 2017–2030 in electricity consumption and production in Finland, construct a cross-impact model from this basis, and discover the emergent and systemic dynamics of the modeled system by analysis of this model.

1. Introduction

This paper describes a problem-oriented study of the future electricity system and energy policy of Finland. motivated by the research aims of the EL-TRAN project (see https://el-tran.fi/in-english/). The EL-TRAN consortium works to fundamentally rethink the energy system in Finland, in an attempt to help resolve policy challenges involved in a transition to a resource efficient, climate neutral electricity system. The initial phase of such a transition is currently underway in Finland. It is a response to global megatrends and roadmaps, including climate change, the Paris agreement to limit the global warming, increasing competition for fossil fuels among Asia's emerging economies, and European Union (EU) visions such as the 2050 Roadmap to a Resource Efficient Europe and the low-carbon objectives of the Energy Roadmap 2050 (see (Lund, 2007; Van den Bergh, 2008; EU Commission, 2011)).

These roadmaps make it necessary for Finland, as well as other EU member states, to rethink long-run targets and policies in the domain of energy. The policy challenges call for a new approaches to energy research, such as systems thinking approaches that respond to the inability of normal disciplinary science to deal with multidimensional complex problems as outlined by the Intergovernmental Panel on Climate Change (IPCC) (Metz, 2007). There is need to develop and organize interdisciplinary international studies, which recognize these new long-run challenges of energy policy in the context of global energy sector changes (Aalto, 2011; Aalto and Korkmaz Temel, 2012; Kaivo-oja et al., 2014; Luukkanen et al., 2015; Vehmas et al., 2016).

In addition to decades of prominent technical global energy and emission studies through complex scenario analysis such as Nakicenovic et al. (2000), scenario analysis methods have often been used by policy makers and in strategic foresight as an instrument to manage uncertainty and to support the shaping of long-term policies and decision-making (Enzer, 1971, 1972; Bañuls and Turoff, 2011).

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Cross-impact methods have been used in conjunction with energy scenario construction (see e.g. (Al-Saleh, 2009; Medina et al., 2015; Vögele et al., 2017)). The cross-impact approach can be seen as a systems modeling approach, using mainly expert-sourced data in lieu of statistical or empirical data in model construction. Cross-impact methods, as modeling and analysis approaches, fall in between empirical data-driven computational models and argumentative systems analysis. They exhibit a high degree of disciplinary heterogeneity and focus on expert-sourced soft system knowledge (Weimer-Jehle, 2006), making them exceptionally applicable in foresight-oriented modeling.

Typically, complex systems are very challenging to analyse (see (Andersson et al., 2014)). The process of building a cross-impact model of such complex systems has the advantage of partitioning and modularizing the complexity. Instead of trying to intuitively assess the dynamics and operating logic of the entire system and its interaction web, the human expertise mobilized for the modeling can be used to assess individual system aspects and components and their bilateral relationships. Starting from a conceptual-level and argumentative system model, the cross-impact approach provides a tool for going further, proceeding towards a more formal and systematic model of the analysed system. A more formal system model can then undergo a computational transformation to reveal non-obvious, emergent characteristics of the system. Cross-impact modeling is also a way to go beyond argumentative systems analysis in modeling cases where data-driven models are not feasible due to lack of empirical data and difficulties in quantification of essential system characteristics.

The cross-impact approach can be thought to be relatively strong, compared to the data-driven approaches, when there is a lot of variety and heterogeneity in the utilized theoretical or methodological approaches. The cross-impact methods provide possibilities to analyse systems, which have too complex interactions to be meaningfully analysed by mere qualitative reasoning (Weimer-Jehle, 2006; Helmer, 1981; Gordon and Hayward, 1968b; Bañuls and Turoff, 2011; Thorleuchter and Poel, 2014; Medina et al., 2015). Several different modeling languages and computational processes of varying complexity have been proposed for the analysis of complex interactions between system components and processes, based on mostly expert-sourced data. These approaches have shared characteristics and overlapping utilization areas, but are referred to by various labels by different authors. Labels such as structural analysis (Godet et al., 1991, 1994), morphological analysis (see Ritchey (2006)), and cross-impact analysis (Gordon and Hayward, 1968b; Gordon, 1994; Honton et al., 1984; Weimer-Jehle, 2006), all refer to approaches for doing expert-based systems modeling.

In this study, we utilize the *Express Cross-Impact Technique (EXIT)* (Panula-Ontto et al., 2016), (see also (Panula-Ontto, 2016b, Panula-Ontto and Piirainen, 2017)) in foresight-oriented analysis of the Finnish energy system. EXIT takes a model of statements or *hypotheses* describing a hypothetical or future state of the modeled system, and the valuations of the direct supporting or negating interactions between the hypotheses as its input. From this information, the EXIT computational process mines the valuations for *indirect* impacts in the system model. Together, the direct (input) interactions and the indirect (computed) interactions can be used to valuate the *emergent* or *systemic* interactions between the hypotheses describing the system, accounting for the influence the different system parts and processes have on each other through the system's complex web of interactions. This information helps understand the system and the relationships of its parts better and serves to identify those that are pivotal. Identification of the most important parts with highest systemic leverage is useful in intervention point evaluation in strategic decision-making. The EXIT input data can be collected in expert workshops or in a multi-stage expert survey process. The EXIT approach can help organisations and agencies in the boundary work between policy, strategy and knowledge about the future (Steen and Twist, 2013).

The aims of the study described in this paper were to

1. Recognising emerging challenges related to increasing wind and solar penetration, formulate a specific, compact set of system descriptors relevant to the near-term future of the Finnish energy system
2. Model and valuate the direct interactions of this set of essential system descriptors using the EXIT modeling language, based on an expert group process supplying the necessary inputs
3. Discover the internal dynamics of the modeled system, using the EXIT computational process to valuate the indirect impacts extant in the system, and to gain understanding of the systemic relationships between the descriptors and the emergent system characteristics
4. Identify the critical system aspects from the perspective of the EL-TRAN project premise, to support and facilitate the process of defining different paths for strategic policy actions in the long-run electricity market policy in Finland

The study is also a trial of the EXIT cross-impact approach in the high-level modeling case of a complex energy system. It demonstrates the use of the EXIT approach in this domain, using a relatively small and high-level set of system descriptors. The built system model, and the transformation performed on it, illustrate the possibilities of investigating the emergent and systemic properties of systems in a cross-impact setting. The trial study lays a basis for more extensive modeling efforts in the domain, using the same approach.

2. Methodology

The modeling and analysis of the Finnish energy system undertaken in this study is based on the EXIT approach, which falls into the category of cross-impact analysis approaches. The cross-impact approach could be described as a high-level systems modeling approach, with emphasis on utilizing expert-sourced inputs, and capacity to use heterogeneous theoretical and methodological approaches in the definition of the characteristics of the model. The different cross-impact modeling and analysis methods diverge in terms of their modeling languages and the nature of their analytical output. What is referred to as cross-impact analysis is really a family of methods for modeling and analyzing systems and problem complexes. The best-known methods are Gordon's cross-impact method (Gordon and Hayward, 1968b; Gordon, 1969, 1994), SMIC (Godet et al., 1991, 1994), BASICS (Honton et al., 1984), (see also Luukkanen, 1994), MICMAC (Godet et al., 1991, 1994), KSIM (Kane, 1972) and the cross-impact balances approach (Weimer-Jehle, 2006). The cross-impact approach has been utilized and further methodologically developed in many projects and studies, and it already has a relatively long history in systems analysis and various foresight applications (see (Gordon and Hayward, 1968a; Gordon, 1969; Turoff, 1971; Dalkey, 1971; Kane, 1972; Blackman,1973; Godet, 1976; Bloom, 1977; Martino and Chen, 1978; Nováky and Lóránt, 1978; Kaya et al., 1979; Burns and Marcy, 1979; Ishikawa et al., 1980; Brauers and Weber, 1988; Godet et al., 1991, 1994; Gordon, 1994; Jeong and Kim, 1997; Weimer-Jehle, 2006; Choi et al., 2007; Pagani, 2009; Thorleuchter et al., 2010; Agami et al., 2010; Bañuls and Turoff, 2011; Bañuls et al., 2013)).

The cross-impact method used in this study, the EXIT method ((Panula-Ontto et al., 2016), see also (Panula-Ontto, 2016b; Panula-Ontto and Piirainen, 2017)), is a computational technique for processing a model consisting of expert input about the direct impacts that different events, phenomena, drivers and forces have on each other. The computational aspiration of EXIT is to use the information of the model to compute how the network of effects works, and how the system descriptors affect each other *systemically*, over the complex network of effects. An event, phenomenon, driver or force considered in a particular cross-impact analysis setting can be called in a more generic fashion a *system descriptor*, a *cross-impact item*, or a *hypothesis*, as is done in EXIT. The method is useful for comparing the cross-impact items in terms of the magnitude of their total (direct + indirect) effect

Table 1
Example cross-impact matrix.

	H_a	H_b	H_c	H_d
H_a	∅	+ 3	+ 1	− 2
H_b	+ 1	∅	0	+ 4
H_c	0	+ 3	∅	− 1
H_d	− 2	+ 1	+ 1	∅

on any particular cross-impact item included in the model. As direct impacts between items are an input to the analysis, the added value of the calculation is the consideration of the indirect impacts, effectuating over the multi-nodal impact chains.

Formally, the components of the EXIT model are (a) the cross-impact items or *hypotheses* representing events, phenomena, drivers and forces, (b) the cross-impact matrix that describes the direct impacts the items have on each other as impact indices, and (c) an absolute value for the maximum impact The hypotheses have descriptions that should be estimable, in terms of their probability, by the experts contributing to the cross-impact modeling. In practice, the description of a hypothesis should be verbalized in the form of a statement or a claim about the future (or hypothetical state of the system). A statement has a yet-unknown truth value. Formulation of such a statement could be "The energy consumption in Finland will grow from 2017 levels by 2030".

The direct impact valuations of the model can be presented in a cross-impact matrix (see Table 1). The impacts *of* a particular hypothesis are read row-wise in the matrix, so that the impacts of item H_a (Hypothesis *a*) on other hypotheses are read from the first row; The impacts *on* a particular hypothesis are read column-wise from the matrix, so that the impacts of other hypotheses *on* hypothesis H_a are read from the first matrix column. We can use the notation $H_a \rightarrow H_b$ to represent the direct impact of hypothesis *a* on hypothesis *b*. The markup logic of direct impacts is illustrated in Table 2.

The maximum impact value is used to interpret the impact index values; it is simply the greatest allowed or used impact index value in the cross-impact model. In the example cross-impact model, the maximum impact value is 4. The range of the impact index values in the example model is therefore $[-4, +4]$. Impact index value + 4 means a strong positive effect on the probability of the impacted hypothesis, while impact index value − 4 would mean an equally great negative effect. The strengths of the other used impact values are interpreted in a linear fashion: impact with an index value of + 2 would represent an impact of half the strength of + 4. While the impacts are understood to mean probability-changing influences, the impact index values do not correspond to specific, defined changes in probabilities of the impacted hypotheses. They simply relate the impacts in the model *to each other* in regards to strength and direction. This level of modeling detail is enough to extract structural information and insights about the system from the system model, and the modeling process remains fairly easy.

Impact valuations for the direct impact matrix should be supplied by experts individually, or a panel of experts jointly. The direct impacts are valuated so that only the direct causal association of impactor hypothesis on the impacted hypothesis is considered. The indirect impacts are computed by the software implementing the EXIT method on the basis of the expert-supplied direct impacts.

The cross-impact methods comparable to EXIT in terms of inputs, namely MICMAC (Godet et al., 1991, 1994) and MICMAC-inspired ADVIAN (Linss and Fried, 2010), are based on matrix multiplication method. In the matrix multiplication method, the cross-impact matrix is squared and the cross-impact items are ordered on the basis of their systemwide influence or dependence: this is calculated as the row sum of each item (for influence) or the column sum of each item (for dependence). The power matrix is iteratively squared as long as the ordering of items changes as a result of squaring the matrix. When a stable ordering is reached, the iteration is stopped (Godet et al., 1994). In the matrix multiplication approach, this stable ordering is the new ordering that now reflects the influence or dependence of the cross-impact items system-wide, based on the indirect impacts specifically (instead of total systemic impact). While this approach gives an interesting cue about the non-obvious, systemic significance of the investigated system components, it loses most of the information that could be gained through an expert process that results in the kind of cross-impact model that is fed to MICMAC and EXIT. The EXIT method is based on a completely different approach to accounting for the indirect impacts in the system model: the computation of relative impacts of impact chains. The set of possible impact chains in the system model represents the set of possible causal impacts in the system, direct and indirect.

The relative impact of an impact chain of *n* hypotheses (consisting of the impactor hypothesis, impacted hypothesis and $n - 2$ mediating hypotheses) is computed as $r = \frac{\prod_e^n i_e}{m^{n-1}}$, where *r* is the relative impact of the chain, *n* is the number of hypotheses in the chain, *e* is an hypothesis in the chain, *i* is an impact index value of hypothesis *e*, and *m* is the maximum impact value defined for the cross-impact model. Using this approach on the cross-impact model presented in Table 1, the total relative impact of H_a on H_d ($H_a \rightarrow ... \rightarrow H_d$) can be computed as the sum of the relative direct impact of H_a on H_d ($H_a \rightarrow H_d$) and all relative indirect impacts between H_a and H_d possible in the cross-impact model ($H_a \rightarrow H_b \rightarrow H_d$, $H_a \rightarrow H_c \rightarrow H_d$, $H_a \rightarrow H_b \rightarrow H_c \rightarrow H_d$, and $H_a \rightarrow H_c \rightarrow H_b \rightarrow H_d$).

Table 3 presents the impact chains from H_a to H_d possible in the cross-impact model presented in Table 1 and the computation of the relative impact for these impact chains. The result of computation of the total relative impact for all hypothesis pairs in the cross-impact model yields a new matrix called summed impact matrix. Table 5 presents a normalized summed impact matrix that results from the computation of summed impacts for the cross-impact model presented in Table 4, followed by the normalization operation discussed at page 9. The values of the summed impact matrix reflect the pairwise relationships of the hypotheses of the cross-impact model, when all the systemic interactions have been accounted for.

In a small cross-impact model, such as the example model of Table 1, relative impacts of all possible impact chains can easily be computed even by hand, but when the number of hypotheses grows, the number of possible impact chains grows fast. In a larger model, with more than 13–15 hypotheses, full computation of relative impacts of possible impact chains becomes unfeasible due to the size of the search space, and an estimation strategy is needed. For advanced estimation strategies, see (Panula-Ontto, 2016b) and Panula-Ontto and Piirainen

Table 2
Impact markup logic in the example cross-impact matrix.

	H_a	H_b	H_c	H_d
H_a	∅	$H_a \rightarrow H_b$	$H_a \rightarrow H_c$	$H_a \rightarrow H_d$
H_b	$H_b \rightarrow H_a$	∅	$H_b \rightarrow H_c$	$H_b \rightarrow H_d$
H_c	$H_c \rightarrow H_a$	$H_c \rightarrow H_b$	∅	$H_c \rightarrow H_d$
H_d	$H_d \rightarrow H_a$	$H_d \rightarrow H_b$	$H_d \rightarrow H_c$	∅

Table 3
Impact chains and computation of relative impact.

Impact chain	Computation	Relative impact (*r*)
$H_a \xrightarrow{-2} H_d$	$r_1 = \frac{-2}{4^1}$	− 0.5
$H_a \xrightarrow{+3} H_b \xrightarrow{+4} H_d$	$r_2 = \frac{+3 \times +4}{4^2}$	+ 0.75
$H_a \xrightarrow{+1} H_c \xrightarrow{-1} H_d$	$r_3 = \frac{+1 \times -1}{4^2}$	− 0.0625
$H_a \xrightarrow{+3} H_b \xrightarrow{0} H_c \xrightarrow{-1} H_d$	$r_4 = \frac{+3 \times 0 \times -1}{4^3}$	0
$H_a \xrightarrow{+1} H_c \xrightarrow{+3} H_b \xrightarrow{+4} H_d$	$r_5 = \frac{+1 \times +3 \times +4}{4^3}$	+ 0.75
$H_a \rightarrow \cdots \rightarrow H_d$	$r_1 + r_2 + r_3 + r_4 + r_5$	+ 0.9375

Table 4
Valuated, normalized direct impact matrix of the Finnish energy system model. Direct impact of A on C is read from row 1, column 3 of the matrix.

		A	B	C	D	E	F	G	H	I	J
Electricity price will increase	A	∅	+ 2.5	+ 1.7	+ 2.0	+ 1.6	− 1.8	+ 0.9	+ 1.2	+ 1.1	− 1.6
Wind and solar power production will increase considerably	B	− 0.1	∅	+ 2.6	+ 2.3	− 2.1	+ 0.1	+ 2.9	+ 1.1	+ 1.5	− 0.2
Electricity storage will increase considerably	C	− 0.2	+ 2.2	∅	.0	− 0.5	+ 0.4	− 1.5	− 1.0	− 0.5	+ 0.1
Market based elasticity of electricity consumption will increase	D	− 1.9	+ 1.1	+ 0.1	∅	.0	− 0.1	− 1.2	− 0.6	− 0.4	− 0.1
New nuclear power plants will be constructed	E	− 0.3	− 1.6	− 0.4	− 0.4	∅	+ 1.3	− 0.8	+ 0.9	− 0.4	− 0.8
Electricity consumption will increase	F	+ 2.1	+ 1.9	+ 1.0	+ 1.6	+ 1.9	∅	+ 1.9	+ 1.7	+ 1.3	+ 0.6
Electricity price fluctuations will increase	G	+ 1.0	− 0.4	+ 2.7	+ 3.2	− 0.3	− 0.1	∅	+ 1.0	+ 1.9	− 0.2
Electricity transmission capacity from neighbouring countries will increase	H	− 1.2	+ 0.1	− 1.5	− 0.8	0.0	+ 0.5	− 1.3	∅	− 0.6	+ 0.1
Fluctuations in electricity consumption will increase	I	+ 1.9	− 0.3	+ 2.3	+ 2.3	− 0.8	+ 0.1	+ 2.9	+ 0.8	∅	− 0.1
Subsidies for solar and wind power will increase	J	+ 0.2	+ 3.9	+ 1.5	+ 1.4	− 1.0	+ 0.2	+ 1.8	+ 1.0	+ 1.0	∅

(2017). The results presented in Section 4 of this study have been obtained by full computation of all the impact chains extant in the 10-hypothesis cross-impact system presented in Section 3.

3. Data

The EXIT cross-impact approach was used to investigate the internal dynamics of the near-future development of the Finnish energy system. The analytical focus was on the balance of the electricity supply, electricity transmission system, and electricity demand, in the case of increased amount of intermittent supply of wind and solar power. An EXIT cross-impact model was built in an expert process for the analysis. The cross-impact items or hypotheses in the model were generated in three consecutive expert workshops. A choice of framing the modeling to 10 hypotheses was made, based on the opinion of the experts in the workshops. This meant valuation of 90 directed pairwise interactions for the model valuation phase. A set of 30 variables would have, in comparison, meant valuation of 870 directed pairwise interactions. A larger set of included variables would have enabled inclusion of several interesting aspects of the studied system. However, as the cross-impact modeling effort was not the sole purpose of the expert workshops and practical concerns limited the access to the expert resource, a framing choice for modeling had to be made. The final selection of the included hypotheses was made, in alignment with the expert-driven nature of the modeling approach, on the basis of the expert feedback arising the workshops.

The number of experts participating in this part of the study was 61. This is a relatively big expert group to deliberate the considered system components, aspects and forces, and the inclusion and exclusion of model hypotheses. However, there is no justified recommendation about the number of experts who should take part in this process. The quality of the experts, their expertise coverage of the modeled domain and the quality of the facilitation of the work are more important for robust outcomes from an expert-judgement approach, rather than the number of participants. The direct impacts between the selected key electricity sector items were discussed in another larger expert workshop including researchers from universities and research institutes, energy industry, NGOs and energy administration. The participants were high-level experts in electricity technology, energy economics, energy policy and other fields of expertise of the modeled socio-techno-economic energy system.

16 of the experts individually valuated the direct interactions in the cross-impact model by supplying a cross-impact matrix via e-mail. Mean of the 16 expert valuations of each cross-impact matrix entry was used as the impact valuation of the final EXIT model. This way, if the valuating experts disagreed about the direction of the impact, the unclear impact would be mostly eliminated from the model. The maximum impact value of the 16 individually valuated models was 4, so that the range of direct impact valuations is [−4, +4], − 4 being a strong negative impact and + 4 a strong positive impact, and the strengths of other valuations interpreted linearly (see Section 2). The time horizon in the study was defined as the year 2030: The hypotheses and their interactions were considered in a temporal frame ranging from 2017 to 2030.

Table 4 presents the cross-impact model of 10 hypotheses and their direct impact valuations, made by the 16 experts. The presented direct impact matrix has been normalized by dividing each matrix entry value by the mean of absolute values in the matrix (or the average distance from zero). In this normalized matrix, the unit for the values can be understood to be the *cross-impact unit*, the average impact of an average impactor on an average impacted hypothesis in the model. Normalization of the both direct impact matrix (input matrix) and the summed impact matrix (output matrix) is necessary to bring their valuations into the same scale and enable comparisons between matrices.

The system descriptors in EXIT modeling can represent events, precisely defined system states or trends or drivers. The system descriptors in the model presented in this paper represent general high-level drivers or trends. They are not explicated as precise descriptions of the future state of the system at the end of the temporal horizon (year 2030), but rather as deviations from the present state or the "expected" development. The modeling exercise aims to discover the emergent, systemic interactions: The EXIT transformation reveals the level of support or antagonism the drivers have on each other. The cross-impact model hypotheses presented in Table 4 are short labels for the hypotheses. The detailed content of each hypothesis was formulated in the workshops preceding the model valuation. The following list explains the model hypotheses in more detail and presents the argumentation for their modeled direct impacts as formulated by the expert group in the valuation workshop.

(A) **Electricity price will increase.** This hypothesis describes a general upward trend in electricity prices in the modeling exercise time frame from current price levels. Currently electricity price in Finland from consumer perspective is relatively low, compared to the EU average. The electricity price for industry is also relatively low, and energy-intensive industries benefit from the co-ownership of power generation model, being able to use electricity at cost price.
Increasing electricity price quite obviously incentivizes to increase electricity production, with a strong positive direct impact on wind and solar power production increase (+ 2.5) and nuclear power capacity increase (+ 1.6). Increasing price also incentivizes other electricity investments, such as increase in electricity storage (+ 1.7). Conversely, the increasing price strongly curtails (− 1.8) growth of electricity consumption. Price hikes are also modeled to support market based elasticity increase (+ 2.0), as especially a very significant electricity price hike would make many consumers ready to be more elastic in their consumption. Increasing electricity price are modeled to be antagonistic to increasing subsidies for solar and wind power (− 1.6), as policymakers are expected to see the subsidies as less necessary in a high electricity price scenario. Overall, electricity price is a very strong direct driver in the system

model and has an impact of about one cross-impact unit or more in all the other hypotheses.

(B) **Wind and solar power production will increase considerably** The wind power capacity is relatively low compared to the rest of the nordic countries. The share of wind power was 3.6% of the total electricity consumption in Finland in 2016 (Statistics Finland, 2017). The potential for growth in the wind power capacity is considerable, and the expert group argued that it is feasible that the capacity might be more than doubled by 2030 under favourable regulatory and subsidy policy conditions. Increasing wind and solar power production strongly supports increasing electricity price fluctuations (+ 2.9). The fluctuating electricity price is one of the problems linked to the main theme of the EL-TRAN project, the increasing use of larger amounts of intermittent power sources in the Finnish electricity system. Wind and solar power production is also modeled to have strong direct support for with the increase of electricity storage (+ 2.6) and increasing market based elasticity of consumption (+ 2.3). The expert valuators argued that the increasing intermittent electricity production will force investments and require advancements in electricity storage technology, and be coupled with more tolerance of the consumers to exercise market based elasticity in their consumption decisions.

Increasing wind and solar power production is also modeled to be a clear trade-off against construction of new nuclear power plants, with a negative direct impact of − 2.1: if the additional electricity demand will be covered mostly with wind power generation there is little need for new nuclear capacity. Experts argued that if the expansion of wind (and solar) capacity would turn out to be very significant in magnitude, it would also support the expansion of the electricity transmission capacity to neigbouring countries (+ 1.1), with the idea of selling the excess electricity to the Nordic electricity market during peak production times.

(C) **Electricity storage will increase considerably** Electricity storage, in the context of the presented model, conceptually covers battery storage technologies, but also pumped-storage hydroelectricity facilities used in load balancing. The pumped-storage hydroelectricity allows the use of intermittent energy sources to be saved when they are available and can be seen as an important enabler for the use of intermittent renewable energy sources.

In the valuation workshop, the expert informants discussed the mechanism of emerging trends influencing the system by showing a techno-economic solution to be feasible. In this way, the electricity storage solutions can support directly investment in solar and wind power production, even when their actual role in the system in the timeframe 2018–2030 would be small. The strongest direct impact the increase of electricity storage has is on increasing wind and solar power production (+ 2.2). Electricity storage will also naturally reduce price fluctuation (− 1.5) and reduce need for increasing transmission capacity (− 1.0).

(D) **Market based elasticity of electricity consumption will increase** Hypothesis D describes a change in the consumer behaviour and expectations, that would make the higher-than-present price fluctuations more palatable for consumers and change their readiness to alter the level of electricity consumption based on the electricity price. This can be thought to be accompanied by providing consumers information on the price changes more efficiently through communications technology.

Increased market elasticity is modeled to strongly hinder the rise of electricity price (− 1.9), and curtail the electricity price fluctuations (− 1.2), as demand becomes more elastic to price, going down when price goes up and not supporting the higher electricity price. Market elasticity also supports increased wind and solar power generation (+ 1.1), as these intermittent forms of electricity production are likely to be more palatable to the consumers if the market based elasticity of consumption is higher.

(E) **New nuclear power plants will be constructed** The new unit 3 of Olkiluoto nuclear power plant with a nameplate capacity of 1600 MW is currently under construction and is expected to be in operation before 2020. The construction of another new nuclear power plant in Pyhjoki is expected to commence in 2018, with a commission date in 2024. The older units in Loviisa are planned to be decommissioned before 2030. Hypothesis E refers to decisions to increase capacity by construction of additional new units in the time frame 2018–2030. While these new units will likely not be commissioned in the time frame of the cross-impact model, the decisions, if made, will impact the rest of the modeled system by e.g. changing the investment outlook for other types of power generation units.

New nuclear power capacity is an alternative to wind and solar power from the perspective of new energy investments, and if reasonably priced nuclear sourced electricity is available, there is not much incentive to invest in solar and wind power capacity. The direct impact of new nuclear power plants on wind and solar power is − 1.6. Construction of new nuclear power plants also supports increase in overall electricity consumption, being synergetic with further investments of energy-intensive industries in Finland.

(F) **Electricity consumption will increase** Hypothesis F simply describes an upward trend in overall electricity consumption. The electricity consumption in Finland in the period 2008–2016 has been in the range of 81.3–87.7 TWh (Statistics Finland, 2017), with no clear trend of increase. The presence of energy-intensive heavy industry in Finland is an important determining factor for the electricity use trend. The share of industry of the total electricity use is slightly less than 50% (Statistics Finland, 2017). The forestry, paper and pulp industry in turn uses about 50% of that share, or 25% of the total electricity consumption. The future presence of paper and pulp industry, chemical and steel industries will greatly influence the trend of consumption.

Increasing electricity consumption is a strong direct driver in the system overall, with positive impacts on all other hypotheses, averaging + 1.6 cross-impact units. It supports strongly electricity price increase (+ 2.1) and new capacity for both nuclear and renewable energy (+ 1.9 and + 1.9). Increasing consumption has a direct causal effect on increased production in addition to the impact coming through the price signal: policymakers will determine public investments on energy infrastructure based on consumption and forecasts of consumption. The impact on increasing solar and wind subsidies (+ 0.6) is positive but small, and the experts saw that there is not much need for subsidies when the consumption is increasing: new capacity will be built anyway. In the current electricity market conditions, where the price of electricity is quite low, there is a much greater need for subsidies as the price does not give much incentive to invest in any kind of power generation, renewable or not. Increasing electricity consumption is also modeled to increase price fluctuation (+ 1.9). The argumentation is that in conditions of high demand and intermittent supply the price fluctuations will increase. The increasing consumption can be baseload-type consumption, or more intermittent. In the case of intermittent consumption, the high consumption phase will increase price fluctuation, as it is unclear how the demand can be met in different situations.

(G) **Electricity price fluctuations will increase** Hypothesis G describes a change trend in the electricity system where electricity price fluctuations of magnitude great enough to start influencing consumer behaviour and investment decisions. Currently the price of electricity is very stable and fluctuation is low.

Increasing price fluctuations quite naturally support increased consumption fluctuations (+ 1.9). Price fluctuations are also strong drivers for electricity storage increase (+ 2.7) and increase of market-based consumption elasticity (+ 3.2). High price fluctuation creates incentive for electricity retailers to invest in storage to be able to sell during price peaks. Consumers are also likely to consider the timing of their electricity use in an electricity market with high price fluctuation.

(H) **Electricity transmission capacity from neighbouring countries will increase** Finland is integrated into the Nordic electricity market, and imports electricity from Russia. The average share of net imports of total electricity consumption was about 18% in the period 2008–2016 (Statistics Finland, 2017). At the mentioned period, the highest annual share of net imports was more than 22%. The general trend for transmission capacity is that it is increasing, albeit slowly. The motivation for increasing the transmission capacity can obviously be, in addition to importing electricity, exporting it. In a scenario of building a lot of additional nuclear power generation capacity, the vision could be that the electricity is exported to Nordic or Central European markets. Hypothesis H describes a trend of investments on transmission capacity and a higher rate of increase in the capacity for the period 2018–2030.
Transmission capacity increase inhibits the electricity price increase (− 1.2), as the demand can more easily be met by importing more electricity from abroad. For the same reason it also inhibits electricity price fluctuations, as price hikes will encourage neighbouring countries to export their electricity to Finland. Increase in transmission capacity is modeled as quite strong constraining factor to electricity storage increase (− 1.5), as the demand for storage would be smaller.

(I) **Fluctuations in electricity consumption will increase** Hypothesis I describes a trend of relative increase in electricity consumption fluctuation. A significant amount of energy-intensive industry operates in Finland. In case of a development where Finland is not attracting much further investments in heavy industry, the constant base load of electricity consumption declines, lowering the electricity consumption and increasing the consumption fluctuation in relative terms.
Higher electricity consumption fluctuation is also a strong driver for storage increase (+ 2.3) and electricity consumption increase (+ 2.3). High consumption fluctuation gives a signal for the retailers to invest in electricity storage, to be able to supply electricity during peak consumption. Consumption fluctuations also increase electricity price (+ 1.9) and electricity price fluctuations (+ 2.9). Preparing for the increasing fluctuations obviously means investing in the power generation capacity in order to be able to respond to the higher demand, raising the electricity price. Also, as price will fluctuate higher during high demand and on average, the electricity price will therefore be higher.

(J) **Subsidies for solar and wind power will increase** Currently, wind power is subsidized with a system of guaranteed price: electricity distribution companies are obligated to buy the produced wind-sourced electricity at a set price. The current subsidy policy defines a minimum and maximum capacity and a limit on power output, which limits the application area of the subsidies, effectively limiting the guaranteed price subsidy policy to medium to big operators. Additionally, there are direct investment subsidies, which enable smaller operators to produce wind power and be compensated. The subsidy policy is a central driver for the growth in wind power capacity. Hypothesis J refers to a development where the wind power subsidy policy changes into a more favourable direction for further wind power investments through a combination of reduction of regulatory limitations, increase of the guaranteed price, and increase of the direct investment subsidy. Similar policies can be implemented for solar power, although it was seen by the expert informants to be of secondary importance in the Finnish case.
Increasing subsidies for solar and wind power are a strong direct driver overall in the system, like the increase in electricity price. It has average to strong direct impacts on all other hypotheses than electricity price increase and increase in electricity consumption. Increasing subsidies were modeled to also directly support electricity storage and market based consumption elasticity, as storage infrastructure was seen as a likely target of investment subsidies as well, and consumption elasticity was assumed to be supported by changes in the regulatory framework. Subsidies were argued, also based on research (Nicolini and Tavoni, 2017), to be the strongest driver for increasing wind and solar power production (+ 3.9). If a strategy emphasizing renewables in electricity production, and heavily subsidizing them, is chosen, new permits for additional nuclear power plants are likely not granted. By this argumentation, the direct impact of increased subsidies for solar and wind power are antagonistic to the construction of new nuclear power plants (− 1.0).

The presented system model is high-level and macro in its characteristics. The hypothesis count is low, resulting in fairly high abstraction level. The causal chains are not fully opened in the model, as some mediating links in the causal mechanisms of the system are not explicitly present in the model. The influence of these system components is implicitly considered by the experts in model valuation but not modeled. A cross-impact model opening the causal chains of the modeled system fully by modeling all the mediating components relevant to the system in a very atomic way would be ideal, but would also require a more sustained expert group involvement and result in a slower and more work-intensive valuation phase. In a high-level model with a small number of system descriptors, the positive impact valuations for some seemingly causally non-related system descriptors might reflect some indirect causation through system components not included in the high-level system model. Ideally, the valuating experts should only consider direct causation in the direct impact valuation. When some mediating system component that is not included in the model arises in their thought process, this component should preferably be added to the model. However, this sort of iterative mode for the system modeling was not feasible in the EL-TRAN cross-impact modeling case due to time and resource constraints.

It should also be noted that this high-level model of the electricity system presents the causalities as linear and symmetric. For some system descriptors, the causality could be thought to be activated only at a certain level of change: for instance, the level of increase in wind power production is meaningful to the causality on increase in electricity transmission capacity. A small increase in wind power will probably not have a great deal of impact on the transmission capacity, whereas a major increase would. The same observation could be made about the impact of electricity price increase: some impacts associated to it can be thought to only occur at a specific level or magnitude of price increase. It could also be thought that the causalities are not necessarily symmetric, in the sense that a price decrease in electricity will not really have the opposite impacts to price increase. To take the described conditionalities and non-symmetrical causality properties into account in a cross-impact model, a more complicated system modeling language such as AXIOM (Panula-Ontto, 2016a), would have to be employed.

4. Results

4.1. Quantification of systemic impacts

The EXIT software implementation (Panula-Ontto, 2017), was used to compute the relative impacts of impact chains (see Section 2). This transformation gives a valuation for the directed total, systemic impacts between the model hypotheses, on the basis of the model of the direct causal relationship reported by the direct impact matrix, presented in Table 4. The resulting *summed impact matrix* is normalized in the same way as the direct impact matrix (see Section 3). The normalized summed impact matrix is presented in Table 5.

The values of the summed impact matrix reflect the total (direct + indirect) impact of the model hypotheses on each other. In a case of a

Table 5
Normalized summed impact matrix. Summed (total) impacts of A on C are read from row 1, column 3 of the matrix.

		A	B	C	D	E	F	G	H	I	J
Electricity price will increase	A	∅	+ 0.7	+ 0.9	+ 1.3	+ 0.2	− 0.9	− 0.5	− 0.1	+ 0.1	− 1.1
Wind and solar power production will increase considerably	B	− 0.6	∅	+ 3.3	+ 3.6	− 1.8	− 0.2	+ 1.4	− 0.1	+ 0.9	+ 0.1
Electricity storage will increase considerably	C	0.0	+ 1.5	∅	+ 0.8	− 0.9	+ 0.1	+ 0.3	− 0.4	+ 0.4	+ 0.2
Market based elasticity of electricity consumption will increase	D	− 1.4	+ 0.3	− 0.5	∅	− 0.3	+ 0.2	− 0.6	− 0.8	− 0.4	+ 0.6
New nuclear power plants will be constructed	E	+ 0.1	− 1.4	− 1.8	− 1.8	∅	+ 0.8	− 0.9	+ 0.6	− 0.7	− 0.3
Electricity consumption will increase	F	+ 0.6	+ 2.4	+ 3.2	+ 4.2	− 0.1	∅	+ 1.6	+ 1.7	+ 1.5	− 0.3
Electricity price fluctuations will increase	G	− 0.1	+ 1.2	+ 2.2	+ 3.0	− 0.9	0.0	∅	+ 0.1	+ 1.1	− 0.2
Electricity transmission capacity from neighbouring countries will increase	H	− 0.5	− 0.9	− 1.9	− 1.6	+ 0.5	+ 0.5	− 0.6	∅	− 0.4	+ 0.4
Fluctuations in electricity consumption will increase	I	+ 0.3	+ 1.7	+ 2.6	+ 3.1	− 1.0	− 0.1	+ 1.6	+ 0.1	∅	− 0.5
Subsidies for solar and wind power will increase	J	− 0.3	+ 3.9	+ 4.6	+ 4.9	− 2.5	0.0	+ 2.6	+ 0.8	+ 1.9	∅

successful mapping of direct causalities of the modeled system, the summed impact values derived from the model should reflect the emergent, systemic relationship between the system parts. The summed valuations for the causal relationships take into account, in addition to the direct impacts, the complex network of indirect impacts and aim to provide a better understanding of the true relationships between the system components. Additional utilities of discovery of the systemic impacts are revealing hidden relationships, unintended consequences, and neutralized or reversed causal relationships.

The difference matrix in Table 6 derived from Tables 4 and 5 shows the difference between the direct impacts Table 4 and the summed (direct + indirect) impacts Table 5. From the perspective of emergent system properties, which the cross-impact analysis aims to reveal, relationships of particular interest can be those that change the most as a result of the discovery of indirect impacts. These are the pairwise relationship where the difference in the greatest. The differences with an absolute value greater than one cross-impact unit are highlighted in Table 6.

Accounting for the indirect impacts change the impact valuations considerably (i.e. more than one cross-impact unit) in 24 of the 90 directed pairwise impacts. If a change in the valuation of one cross-impact unit or more is the threshold of significance for the change, consideration of the indirect impacts changes the picture of overall influence on other hypotheses especially for electricity price (A, 5 significant valuation changes) and increasing electricity consumption (F, 4 significant valuation changes). Also the changes in the magnitude of valuations of impacts of increasing wind and solar power subsidies (J) are noteworthy.

For about 37% of the relationships in the cross-impact system, the indirect impacts are greater than the direct impacts. The absolute mean of the indirect impact in the system is 0.78, and absolute median 0.6: the direct impacts dominate the relationship of most system components. About 34% of the relationships remain more or less the same as the indirect impacts are accounted for. 20% of the relationships are supported and strengthened by the indirect impacts. 19% are hindered or curtailed, but remain influencing in the same causal direction. About 14% are neutralized, meaning that a directly positive or negative impact is cancelled out by the indirect impacts, bringing the total impact close to zero. 9% are systemically activated, so that the relationship between model components is only manifested in the indirect impacts. Three relationships are reversed in terms of the direction of their causality, meaning that a directly positive influence turns out negative when indirect impacts are considered, or vice versa.

The EL-TRAN project investigates the problematique of increasing amount of intermittent electricity supply in the energy system, systemic coping mechanisms for the intermittent supply and the steering and policy options to reduce the emerging problems related to the intermittent electricity production. From this perspective, items of special interest are increasing wind and solar power (hypothesis B), electricity storage (hypothesis C), and subsidies on wind and solar power (hypothesis J).

4.2. Systemic influence and dependence of increasing intermittent electricity production

Overall, the systemic impacts of increased solar and wind power turn out to be largely aligned with the direct impacts, with differences mostly in the magnitude of impacts. Increasing wind and solar power production is modeled to be a strong direct driver for increase in electricity storage and increasing market based elasticity. The indirect impacts compound to both of the relationships, significantly strengthening them: the total impact of increased wind and solar power on increased electricity storage is + 3.3 and on increased market based consumption elasticity + 3.6. Expansion in solar and wind power production can be seen as synergetic with especially electricity storage, but also increased market based elasticity of consumption: development of electricity storage techniques, most likely pumped storage facilities, is required to make the increased wind power generation viable.

The intermittent electricity production remains also a driver for the increasing electricity price fluctuations. However, this impact is greatly moderated by the indirect impacts (from + 2.9 to + 1.4). Increased wind and solar power directly supports quite strongly the increase of electricity storage, increase of market based elasticity in consumption and electricity transmission capacity, which in turn have a negative

Table 6
Difference matrix derived from summed and direct impact matrices. Matrix values report the sum of all *indirect* impacts between hypotheses. Indirect impacts of A on C are read from row 1, column 3 of the matrix.

		A	B	C	D	E	F	G	H	I	J
Electricity price will increase	A	∅	− 1.8	− 0.8	− 0.7	− 1.4	+ 0.9	− 1.4	− 1.3	− 1.0	+ 0.5
Wind and solar power production will increase considerably	B	− 0.5	∅	+ 0.7	+ 1.3	+ 0.3	− 0.3	− 1.5	− 1.2	− 0.6	+ 0.3
Electricity storage will increase considerably	C	+ 0.2	− 0.7	∅	+ 0.8	− 0.4	− 0.3	+ 1.8	+ 0.6	+ 0.9	+ 0.1
Market based elasticity of electricity consumption will increase	D	+ 0.5	− 0.8	− 0.6	∅	− 0.3	+ 0.3	+ 0.6	− 0.2	0.0	+ 0.7
New nuclear power plants will be constructed	E	+ 0.4	+ 0.2	− 1.4	− 1.4	∅	− 0.5	− 0.1	− 0.3	− 0.3	+ 0.5
Electricity consumption will increase	F	− 1.5	+ 0.5	+ 2.2	+ 2.6	− 2.0	∅	− 0.3	0.0	+ 0.2	− 0.9
Electricity price fluctuations will increase	G	− 1.1	+ 1.6	− 0.5	− 0.2	− 0.6	+ 0.1	∅	− 0.9	− 0.8	0.0
Electricity transmission capacity from neighbouring countries will increase	H	+ 0.7	− 1.0	− 0.4	− 0.8	+ 0.5	0.0	+ 0.7	∅	+ 0.2	+ 0.3
Fluctuations in electricity consumption will increase	I	− 1.6	+ 2.0	+ 0.3	+ 0.8	− 0.2	− 0.2	− 1.3	− 0.7	∅	− 0.4
Subsidies for solar and wind power will increase	J	− 0.5	0.0	+ 3.1	+ 3.5	− 1.5	− 0.2	+ 0.8	− 0.2	+ 0.9	∅

relationship on increase of price fluctuations.

The positive relationship on increased electricity transmission capacity is systemically neutralized. The increased electricity storage, synergetic with the increased wind power, ends up reducing the need for investment in transmission capacity.

4.3. Systemic dependence of electricity storage and market based consumption elasticity

Electricity storage and elasticity of consumption are the main strategies for making an increased reliance on intermittent renewable sourced electricity production possible. It is important to discover their chief drivers and antagonists from the systemic perspective. Both are systemically reactive drivers, that do not have very significant impacts on other components of the system. For electricity storage, the most influential direct driver in the model is the increase of electricity price fluctuations, followed by the increasing wind and solar power production. Price and consumption fluctuations are other important drivers. Subsidies on solar and wind power are a positive driver, but less important than electricity price and consumption.

In the systemic perspective, electricity price turns out to be relatively unimportant driving factor for electricity storage. Also the importance of price fluctuations is decreased. The level of subsidies on solar and wind power is clearly the most influential supporting driver for electricity storage systemically. The systemic effects greatly buttress the effect of subsidies. The electricity consumption level, directly only a driver of average importance, appears as a strong driver for electricity storage. New nuclear power plants and increased electricity transmission capacity from neighbouring countries are the most important systemic antagonists for increased electricity storage. New nuclear capacity appears rather insignificant factor directly to the storage increase, but systemically it proves to be a strong hindering factor. This relationship is activated mainly through indirect impacts.

The pairwise relationship between electricity storage and market based elasticity of electricity consumption is weak in both direct and total impacts. However, the systemic dependence on drivers of market based elasticity of consumption has a very similar profile as increasing electricity storage. The level of subsidies for solar and wind power is clearly the most important driver, followed by the level of electricity consumption. Both hypotheses appear very volatile, in the sense of having a high dependence on most other system descriptors. For both, the high dependence is mostly systemic, manifested by the impacts of drivers being indirectly strengthened in other cases than electricity price.

4.4. Systemic role of subsidies on wind and solar power

In the analysed system model, solar and wind power subsidies are modeled to be a very independent factor in the system, largely unaffected by the other system descriptors. The most important direct drivers are electricity price and new nuclear capacity, which have an antagonistic direct relationship with subsidy level. Accounting for the indirect impacts does not change the picture of the dependence of subsidy level dramatically, and it remains a very independent policy variable, most strongly dependent on electricity price, that relationship being that rising prices work against increasing subsidies, as subsidies are not needed in a high electricity price scenario.

Systemically, the impacts of level of subsidies on renewable electricity production do not undergo systemic reversals or neutralizations, but influence according to the same logic that modeled direct impacts indicate. In many relationships, the impact of subsidy level is strongly reinforced and the indirect impacts imply that the wind and solar power subsidies support the main enabling developments of increased intermittent electricity production, the increase of electricity storage and consumption elasticity, as well. Overall, the subsidy level is systemically a central driver.

4.5. Key findings

The most important conclusions of the cross-impact analysis of the Finnish energy system are:

- Revealing the systemic effect of increasing wind and solar power production highlights its importance system-wide, as this development remains a key factor even as the indirect impacts are accounted for: there are no emergent systemic effects that would undermine its importance.
- Increasing electricity price is systemically a much less important determinant than what its direct impacts would seem to indicate
- Subsidies for solar and wind appear to be systemically even more important than direct impacts would seem to indicate, and based on the cross-impact analysis, subsidy level appears to be a high-leverage intervention point, with a great deal of systemic impact supporting their direct impacts. Growing electricity consumption and increasing consumption fluctuations are also influential in the systemic perspective.
- Development towards increased wind and solar power production is systemically tightly coupled with increased electricity storage and greater market-based elasticity of electricity consumption.
- Based on the modeled structure of the relationship between the energy system development trends, further investments on nuclear power plants and a greater reliance on wind power appear to be somewhat mutually exclusive, and bifurcation into a more nuclear power based system arrests the systemic prerequisites for increasing wind power production significantly
- Systemically, there are not many drivers supporting increased electricity transmission capacity from neighbouring countries. Most of the direct supporting impacts are largely systemically neutralized and a significant expansion in the transmission capacity seems unlikely as it is not aligned with the possible future development scenarios of the Finnish electricity system.

In synthesising the outcomes of the large increase in low-carbon energy transition studies globally, Kirby and O'Mahony (2018) concluded that they are converging towards a common set of conclusions:

1. The low-carbon transition is technically and economically feasible
2. Transition comes with multiple co-benefits
3. Replacement of fossil energy systems with renewables, increased electrification of energy consumption and strong pursuit of energy efficiency, are identified as the necessary elements of technological change.Delucchi and Jacobson (2011, 1154) proposed that the barriers to global technological transition are not economic or technical, but predominantly social and political. This is consistent with what is known about transition, which according to the IPCC must begin with sustainable development pathways (Sathaye et al., 2007), also predominantly social and political challenges. The Finnish cross-impact analysis in this study does not disagree with these conclusions, but in prominent new findings, it also suggests that energy price is less important, and nuclear energy will hamper the development of renewables. This places social and political factors in the future transition of the Finnish energy system front-and-centre, suggesting that there is agency to choose.

5. Discussion

It is often necessary to prepare robust scenarios in areas where quantification is difficult. The cross-impact approach provides an interesting and valuable tool for assessing the future developments of the energy and electricity system. It enables inclusion of several multi-dimensional assessment categories in the analysis, that are not easily modeled with traditional quantitative methods, and have complex interconnections which are difficult to grasp intuitively or with argumentative logic. Our analysis in this study was based on a compact set of key factors of electricity demand, electricity supply and electricity network. Understanding the complex interlinkages and systemic relationships between these key factors are grand challenges for long-run policy design (Nakicenovic et al., 2000; Metz, 2007). Our cross-impact analysis provides new insights into the internal dynamics of the Finnish energy system, based on expert evaluation of cross-impacts.

The main challenge in utilizing the cross-impact approach is, without question, the modeling of the system. The selection and exact formulation of the hypotheses or cross-impact items is crucial, and a notable modeling challenge. The question about model framing and bounding of the inclusion of possibly-important system components is there, as in all modeling. Having an extensive set of hypotheses describing the modeled system is ideal in the sense that the direct causal effects can be modeled with more clarity and precision, and without a great deal of ambiguity and possibilities for differentiated interpretations of the hypotheses. However, a larger set of hypotheses will conversely mean more work in the model valuation phase. Successful cross-impact modeling requires a compromise between high abstraction and overloading of content in the hypotheses, making individual impact valuations difficult and possibly ambiguous (as in a model with a small number of hypotheses) and a possibly overwhelming number of pairwise impacts to valuate (as in a model with a high hypothesis count). The modeling can be quite labour intensive for the experts involved, and an important factor of success is securing their commitment to the effort. The selection of hypotheses and appropriate facilitation of the valuation process are necessary preconditions for implementation of the technique.

Considering further development of the presented cross-impact model, an important improvement would be to model more specific policy instruments as system descriptors. This will enhance the ability to draw clear conclusions and policy-relevant recommendations. It will obviously also increase the difficulty and time requirements of the model valuation. The number of system descriptors in the presented model is quite low and the abstraction level remains high. A more atomic presentation of the system would likely result in less ambiguity in the valuation phase and more uniform understanding of causalities, albeit at a greater time cost in modeling. In an interaction model exhibiting a high level of abstraction, it is possible that in the valuation of a single direct impact of a hypothesis on another, some indirect influence will "bleed" into the direct impact valuation. This is unavoidable in a high-level model and does not necessarily compromise the value of the model, as in all causal models there are some unmodeled intermediary components, that are simply left out because explicitly including them is unnecessary considering the aims of the analysis: any model is always a compromise between practicality and conceptual precision.

This study tested the process of defining the hypotheses for the model and valuating their interactions using expert workshops and questionnaires. The results of the study showcase the analytical aspect of the EXIT cross-impact approach and its possibilities. The experiences and the results that can be extracted from the presented model warrant a more extensive modeling endeavor, resulting in a larger, more complex and more finely grained model, with greater potential for highly actionable analytical outputs.

References

Aalto, P., 2011. Organizing interdisciplinary international studies: from puzzlement to research programmes. In: International Studies. Springer, pp. 66–91.

Aalto, P., Korkmaz Temel, D., 2012. Towards a wider European energy security society: From vulnerability and viability to sustainability. In: In: Aalto, P., Harle, V., Moisio, S. (Eds.), Global and Regional Problems: Towards Interdisciplinary Study 14. Ashgate, Farnham, pp. 79–104.

Agami, N., Saleh, M., El-Shishiny, H., 2010. A fuzzy logic based trend impact analysis method. Technol. Forecast. Social. Change 77 (7), 1051–1060(URL 〈https://doi.org/10.1016/j.techfore.2010.04.009〉).

Al-Saleh, Y., 2009. Renewable energy scenarios for major oil-producing nations: The case of Saudi Arabia. Futures 41 (9), 650–662.

Andersson, C., Törnberg, A., Törnberg, P., 2014. Societal systems-complex or worse? Futures 63, 145–157.

Bañuls, V.A., Turoff, M., 2011. Scenario construction via Delphi and cross-impact analysis. Technol. Forecast. Social. Change 78 (9), 1579–1602(URL 〈https://doi.org/10.1016/j.techfore.2011.03.014〉).

Bañuls, V.A., Turoff, M., Hiltz, S.R., 2013. Collaborative scenario modeling in emergency management through cross-impact. Technol. Forecast. Social. Change 80 (9), 1756–1774(URL 〈https://doi.org/10.1016/j.techfore.2012.11.007〉).

Blackman, A., 1973. A cross-impact model applicable to forecasts for long-range planning. Technol. Forecast. Social. Change 5 (3), 233–242(URL 〈https://doi.org/10.1016/0040-1625(73)90002-4〉.

Bloom, M.F., 1977. Time-dependent event cross-impact analysis: results from a new model. Technol. Forecast. Social. Change 10 (2), 181–201(URL 〈https://doi.org/10.1016/0040-1625(77)90044-0〉.

Brauers, J., Weber, M., 1988. A new method of scenario analysis for strategic planning. J. Forecast. 7 (1), 31–47(URL 〈https://doi.org/10.1002/for.3980070104〉).

Burns, J.R., Marcy, W.M., 1979. Causality: Its characterization in system dynamics and KSIM models of socioeconomic systems. Technol. Forecast. Social. Change 14 (4), 387–398(URL 〈https://doi.org/10.1016/0040-1625(79)90036-2〉.

Choi, C., Kim, S., Park, Y., 2007. A patent-based cross impact analysis for quantitative estimation of technological impact: The case of information and communication technology. Technol. Forecast. Social. Change 74 (8), 1296–1314(〈https://doi.org/10.1016/j.techfore.2006.10.008〉).

Dalkey, N.C., 1971. An elementary cross-impact model. Technol. Forecast. Social. Change 3, 341–351(URL 〈https://doi.org/10.1016/s0040-1625(71)80022-7〉.

Delucchi, M.A., Jacobson, M.Z., 2011. Providing all global energy with wind, water, and solar power, Part II: Reliability, system and transmission costs, and policies. Energy Policy 39 (3), 1170–1190.

Enzer, 1971. Delphi and cross-impact techniques. Futures 3 (1), 48 – 61.

Enzer, S., 1972. Cross-impact techniques in technology assessment. Futures 4 (1), 30–51.

EU Commission, 2011. Roadmap to a resource efficient europe. Tech. rep., EU Commission.

Godet, M., 1976. Scenarios of air transport development to 1990 by SMIC 74 - A new cross-impact method. Technol. Forecast. Social. Change 9 (3), 279–288(URL 〈https://doi.org/10.1016/0040-1625(76)90012-3〉.

Godet, M., Bourse, F., Chapuy, P., Menant, I., 1991. Futures Studies: A Tool-box for Problem Solving. Futuribles (series). GERPA Prospective.

Godet, M., Coates, J., Unesco, 1994. From Anticipation to Action: A Handbook of Strategic Prospective. Future-oriented studies. Unesco Publishing.

Gordon, T., Hayward, H., 1968a. Initial experiments with the cross impact matrix method of forecasting. Futures 1 (2), 100–116.

Gordon, T.J., 1969. Cross-impact matrices: an illustration of their use for policy analysis. Futures 1 (6), 527–531.

Gordon, T.J., 1994. Cross impact method. Tech. rep., United Nations University Millennium Project.

Gordon, T.J., Hayward, H., 1968b. Initial experiments with the cross impact matrix method of forecasting. Futures 1 (2), 100–116.

Helmer, O., 1981. Reassessment of cross-impact analysis. Futures 13 (5) (389400).

Honton, E., Stacey, G., Millett, S., 1984. Future scenarios: the BASICS computational method. Economics and policy analysis occasional paper. Battelle Columb. Div.

Ishikawa, M., Toda, M., Mori, S., Kaya, Y., 1980. An application of the extended cross impact method to generating scenarios of social change in Japan. Technol. Forecast. Social. Change 18 (3), 217–233(〈https://doi.org/10.1016/0040-1625(80)90024-4〉.

Jackson, J.E., Lawton, W.H., 1976. Some probability problems associated with cross-impact analysis. Technol. Forecast. Social. Change 8 (3), 263–273(URL 〈https://doi.org/10.1016/0040-1625(76)90004-4〉.

Jeong, G.H., Kim, S.H., 1997. A qualitative cross-impact approach to find the key technology. Technol. Forecast. Social. Change 55 (3), 203–214(URL 〈https://doi.org/10.1016/s0040-1625(96)00209-0〉.

Kaivo-oja, J., Luukkanen, J., Panula-Ontto, J., Vehmas, J., Chen, Y., Mikkonen, S., Auffermann, B., 2014. Are structural change and modernisation leading to convergence in the CO_2 economy? Decomposition analysis of China, EU and USA. Energy 72, 115–125.

Kane, J., 1972. A primer for a new cross-impact language - KSIM. Technol. Forecast. Social. Change 4 (2), 129–142.

Kaya, Y., Ishikawa, M., Mori, S., 1979. A revised cross-impact method and its applications to the forecast of urban transportation technology. Technol. Forecast. Social. Change 14 (3), 243–257(URL 〈https://doi.org/10.1016/0040-1625(79)90080-5〉.

Kirby, P., O'Mahony, T., 2018. Planning future pathways: Implications and outcomes of scenario studies. In: The Political Economy of the Low-Carbon Transition. Springer, pp. 115–141.

Linss, V., Fried, A., 2010. The ADVIAN classification-A new classification approach for the rating of impact factors. Technol. Forecast. Social. Change 77 (1), 110–119.

Lund, P.D., 2007. The link between political decision-making and energy options: assessing future role of renewable energy and energy efficiency in finland. Energy 32 (12), 2271–2281.

Luukkanen, J., 1994. Role of planning philosophy in energy policy formulation. Ph.D. Thesis, Tampere University of Technology, Tampere University of Technology publications # 129.

Luukkanen, J., Panula-Ontto, J., Vehmas, J., Liyong, L., Kaivo-oja, J., Häyhä, L., Auffermann, B., 2015. Structural change in Chinese economy: Impacts on energy use and CO_2 emissions in the period 2013-2030. Technol. Forecast. Social. Change 94, 303–317.

Martino, J.P., Chen, K.-L., 1978. Cluster analysis of cross impact model scenarios. Technol. Forecast. Social. Change 12 (1), 61–71(URL 〈https://doi.org/10.1016/

0040-1625(78)90035-5⟩.
Medina, E., Arce, R.D., Maha, R., 2015. Barriers to the investment in the concentrated solar power sector in Morocco: A foresight approach using the cross impact analysis for a large number of events. Futures 71, 36–56.
Metz, B., 2007. Climate change 2007: mitigation of climate change: contribution of Working Group III to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge University Press.
Mitroff, I.I., Turoff, M., 1976. On the distance between cross-impact models: A set of metric measures for cross-impact analysis. Technol. Forecast. Social. Change 8 (3), 275–283(URL ⟨https://doi.org/10.1016/0040-1625(76)90005-6⟩.
Nakicenovic, N., Alcamo, J., Grubler, A., Riahi, K., Roehrl, R., Rogner, H.-H., Victor, N., 2000. Special Report on Emissions Scenarios (SRES), A Special Report of Working Group III of the Intergovernmental Panel on Climate Change. Cambridge University Press.
Nicolini, M., Tavoni, M., 2017. Are renewable energy subsidies effective? Evidence from europe. Renew. Sustain. Energy Rev. 74, 412–423.
Nováky, E., Lóránt, K., 1978. A method for the analysis of interrelationships between mutually connected events: A cross-impact method. Technol. Forecast. Social. Change 12 (2–3), 201–212(URL ⟨https://doi.org/10.1016/0040-1625(78)90056-2⟩.
Pagani, M., 2009. Roadmapping 3G mobile TV: Strategic thinking and scenario planning through repeated cross-impact handling. Technol. Forecast. Social. Change 76 (3), 382–395(URL ⟨https://doi.org/10.1016/j.techfore.2008.07.003⟩).
Panula-Ontto, J., November 2016a. AXIOM Method for Cross-Impact Modeling and Analysis. Master's thesis, University of Tampere, available online at ⟨http://tampub.uta.fi/handle/10024/100041⟩.
Panula-Ontto, J., 2016b. EXIT Method for Cross-Impact Analysis, available at ⟨https://www.researchgate.net/publication/319679034_EXIT_method_for_cross-impact_analysis⟩.
Panula-Ontto, J., 2017. EXIT: Express Cross Impact Technique. Software available at ⟨https://github.com/jmpaon/EXIT⟩.
Panula-Ontto, J., Luukkanen, J., Kaivo-oja, J., Majanne, Y., Vehmas, J., 2016. Complex energy futures. the use of Express Cross-Impact Technique (EXIT) with participatory expert workshops to analyse complex systems and interactions. In: Proceedings of International Conference on Advances on Clean Energy Research, ICACER 2016, at Bangkok, Thailand. ICACER.
Panula-Ontto, J., Piirainen, K., 2017. EXIT method for cross-impact analysis, unpublished.
Ritchey, T., 2006. Problem structuring using computer-aided morphological analysis. J. Oper. Res. Soc. 57 (7), 792–801(URL ⟨http://dx.doi.org/10.1057/palgrave.jors.2602177⟩).
Sathaye, J., Najam, A., Cocklin, C., Heller, T., Lecocq, F., Llanes-Regueiro, J., Pan, J., Petschel-Held, G., Rayner, S., Robinson, J., et al., 2007. Sustainable development and mitigation. In: Climate Change 2007: Mitigation of Climate Change. Cambridge University Press, pp. 691–743.
Statistics Finland, 2017. Statistics finland database. URL ⟨http://www.tilastokeskus.fi/tup/statfin/index.html⟩.
Steen, M.V.D., Twist, M.V., 2013. Foresight and long-term policy-making: An analysis of anticipatoryanticipatory boundary work in policy organizations in the Netherlands. Futures 54 (3342).
Thorleuchter, D., den Poel, D.V., Prinzie, A., 2010. A compared R&D-based and patent-based cross impact analysis for identifying relationships between technologies. Technol. Forecast. Social. Change 77 (7), 1037–1050(URL ⟨https://doi.org/10.1016/j.techfore.2010.03.002⟩).
Thorleuchter, D., Poel, D.V.D., 2014. Quantitative cross impact analysis with latent semantic indexing. Exp. Syst. Appl. 41 (2) (406411).
Turoff, M., 1971. An alternative approach to cross impact analysis. Technol. Forecast. Social. Change 3, 309–339(URL ⟨https://doi.org/10.1016/s0040-1625(71)80021-5⟩.
Van den Bergh, J.C., Bruinsma, F.R., 2008. Managing the transition to renewable energy: theory and practice from local, regional and macro perspectives. Edward Elgar Publishing.
Vehmas, J., Kaivo-oja, J., Vehmas, J., et al., 2016. Sustainability cycles in China India, and the world? East. Eur. Bus. Econ. J. 2 (2), 139–164.
Vögele, S., Hansen, P., Poganietz, W.-R., Prehofer, S., Weimer-Jehle, W., 2017. Building scenarios for energy consumption of private households in Germany using a multi-level cross-impact balance approach. Energy 120, 937–946.
Weimer-Jehle, W., 2006. Cross-impact balances: a system-theoretical approach to cross-impact analysis. Technol. Forecast. Social. Change 73 (4), 334–361(URL ⟨https://doi.org/10.1016/j.techfore.2005.06.005⟩).