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Constructing Consistent Energy Scenarios using Cross Impact Matrices

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Abstract

The ongoing transformation process towards a low or even zero emission energy system is facing a steadily increasing complexity, notably through variable renewable energies and sector coupling. At the same time, the necessity for long-term decisions associated with high capital costs remains.

Hence methods are desirable that help decision makers to manage the broad range of possible futures without overly simplifying the interplay of multiple developments in many societal, technological, and economic fields. This requires the inclusion of expert knowledge from different domains without putting an excessive workload on these experts.

The paper at hand proposes an efficient two-stage approach to derive a limited set of scenarios. In the first step, the focus is on establishing the key causal relationships and derive the key exogenous drivers for future developments. In the second step, their interdependency is then assessed in more detail and consistent scenarios are derived. The approach builds on two existing methods, the "ADVanced Impact ANalysis (ADVIAN)" and the "Cross-impact balances analysis" (CIB), yet these are refined and tailored both in terms of improved computation approaches and advanced assessment indicators.

The newly developed approach is applied to the case of network extension planning as this is characterized by both significant complexity increases and long-term investment decisions under high uncertainty. Starting with many potential driving factors, just a few key exogenous drivers are identified and four consistent scenarios up to the year 2050 are derived with a limited amount of expert assessment workload.

The methodology enables thus the development of consistent socio-techno-economic scenarios that may also serve as framework for more detailed model-based assessments of energy-system developments.

Keywords: energy scenarios, cross impact matrix, indirect and direct impacts, exogenous drivers and endogenous factors, cross impact balances, scenario-reduction, consistent scenarios, consistency analysis, network expansion scenarios

JEL-Classification :

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Content

1 Introduction

For the energy system of many countries around the world, a deep transformation process from fossil towards renewable energies is envisaged in order to fulfil the Paris climate agreement, which aims at keeping the global temperature rise well below 2 degrees Celsius (UNFCCC 12/12/2015). Especially in the electricity sector, an important potential exists to reduce CO_2-emissions by replacing fossil-fuelled power plants by variable renewable energy sources (VRE) and Germany is one of the countries in the world that has achieved the highest share of "new" renewables (especially wind and solar) in the electricity generation mix. Yet this transformation poses also various challenges, one of them being to ensure a secure and stable supply. Notably, this requires electricity grids to be extended both at the distribution and the transmission level to cope with shifting generation patterns and technical challenges like voltage control while taking social, ecological and economical aspects into account (ENTSOG/ENTSO-E 2019; Übertragungsnetzbetreiber 2019). As the aforementioned transformation process of the energy system is dominated by VRE extensions and at least partial electrification of the heat and transportation sector, the distribution grids (DG) require particular attention. The legacy of a historically grown DG is not sufficient to meet the resulting requirements, given that a large share of VRE are and will be installed at DG level (Schuster and Büchner 2016; Greenblatt et al. 2017). These decentralized VRE imply that the previously unidirectional power flow (from generators connected to high-voltage grids to consumers in lower-voltage grids) is changing to a bidirectional power flow pattern. Hence, DGs do no longer work solely as a sink but also as a source of power. Consequently, power flows in transmission grids are changing, too. The resulting need for network extension measures (in DGs) yet highly depends on the expected consumption patterns and VRE infeeds (and the distribution grid operators' possibilities to adjust them e.g. through curtailment). These loads and infeeds are in turn driven by several uncertain developments of other external[1] factors among which are e.g. energy and environmental policy, fuel and carbon prices, economic growth or the level of flexibilization of novel loads like electric vehicles.

Interdependencies between the named and further factors are not only possible but rather very likely – e.g. between energy policy and penetration of electrical vehicles. This complicates the derivation of general statements about the previously mentioned load and infeed situation. Thus, in view of enabling good decisions, it is crucial to structure these multiple uncertain factors and their interdependencies.

[1] External in the sense of Gausemeier et al. 1998; Höjer et al. 2008.

Otherwise the decision maker(s) may either be confused by the multitude of relevant issues and corresponding uncertainties or they may restrict their world view on one single “expected future” which does not reflect uncertainties at all.

Scenarios are a frequently used tool to describe these interdependent uncertainties and to make them more manageable by focusing on a limited number of possible alternative developments (Gausemeier et al. 1998; Börjeson et al. 2006; Höjer et al. 2008). Following (Schoemaker 1991), scenarios are particularly useful for managerial decision making in a context, where costly surprises have been experienced or significant change and uncertainty are ahead. Correspondingly, Climate Change and Energy have been an important field for the use of scenarios all throughout the last decades (Bentham 2014; Rogelj et al. 2018; Übertragungsnetzbetreiber 2019; ENTSOG/ENTSO-E 2019).

Although a broad variety of scenario classifications have been developed in literature (e.g. (Ducot and Lubben 1980; van Notten et al. 2003; Börjeson et al. 2006), the distinction between normative and descriptive scenarios (cf. (Ducot and Lubben 1980; van Notten et al. 2003) is particularly relevant when it comes to grid expansion planning.

Normative scenarios serve to investigate a predefined future, where specified targets are met and they allow to explore possible ways to achieve these predefined targets, e.g. a greenhouse gas emission reduction target. These scenarios are also called “what should happen” scenarios where the focus is on the pathway to achieve the predefined desired goal (Börjeson et al. 2006; Weimer-Jehle et al. 2016). They stand out by the fact that, independently from external influences, the predefined targets are always met. These scenarios are utilized to foster debates about necessary decisions or to strengthen political views in order to achieve the predetermined targets (Kopiske and Gerhardt 2018) and are very widely used in the energy and climate policy debates to advocate for stringent energy policy decision making (International Energy Agency 2017; Rogelj et al. 2018; Kopiske and Gerhardt 2018).

Alternatively, descriptive scenarios may be used, which are in contrast to normative scenarios not purposeful and describe futures without imposing certain future states (Poncelet 2018). Hence, the outcome of these future worlds is unknown. Here, the question “what may happen” (cf. (Weimer-Jehle et al. 2016)) or “what will happen, on the condition of some specified event” (cf. (Höjer et al. 2008)) is asked. The main purpose of descriptive scenarios is not predicting the future, but to define several and plausible evolutions whereby the development of uncertain factors and their interdependencies is considered (Chermack 2004; van der Heijden 2005; Gough and Shackley 2006).

Network extension planning is a genuine task for network companies, yet those are frequently state-owned enterprises or their planning is strongly embedded in a public planning process e.g. the “Netzentwicklungsplan” in Germany or the TYNDP at a European level (Bundesnetzagentur 2018; Übertragungsnetzbetreiber 2019; ENTSOG/ENTSO-E 2019). Therefore, the reliance on normative scenarios which are aligned with the energy and climate goals of the respective governments seems “natural”. Yet such a choice may induce several shortcomings. First, uncertainties in external factors such as economic growth or technological development tend to be neglected in normative scenarios. Second, normative targets like decarbonization goals may translate in several ways into concrete demand and supply patterns (e.g. rooftop solar vs. offshore wind). Third the multiple interdependencies between external factors are hardly addressed and fourth the same is true for the multiple interplays between different levels of decision making from Global and European agreements down to municipal and individual decisions on infrastructure or equipment (Rotmans et al. 2000; van Notten et al. 2003; Schoemaker 1991; Vögele et al. 2017).

Hence, we subsequently propose an approach for developing consistent, descriptive scenarios in view of long-term network extension planning. This will help decision makers to identify good decisions (i.e. welfare-maximising decisions in an economic framing) for network investments taking into account a broad range of uncertain external factors and their interdependencies.

Generally, such descriptive scenarios may be derived using workshops, expert judgements or desk research (Weimer-Jehle et al. 2016). Therefore, constructing scenarios is time-consuming and the outcome also partly depends on the world view of the contributors or the constructor. In order to reduce the complexity and the required time resources for the scenario creation process, it is beneficial to focus on a few thoughtfully selected uncertain factors and combine them in a way that the resulting scenarios are consistent. In particular, these selected factors should influence other factors (considerably) more than vice versa. This leads to a set of uncertain factors that in fact mainly drives the overall future development. Subsequently we call these uncertain factors, influencing other factors more than they are being influenced conversely “exogenous drivers”. Beyond the identification of these exogenous drivers, the construction of descriptive scenarios also requires the characterization of these scenarios by specific realizations[2] of all relevant exogenous drivers. Again, this process is resource-intensive if multiple contributors are involved – but involving multiple contributors is a prerequisite to limit the impact of subjective world views and personal idiosyncrasies.

Subsequently we present a novel two-step approach which builds on the combination of two established methods – yet adapting and extending them to improve both resource-efficiency and interpretability of results. Identifying the relevant exogenous drivers is done by using an adjusted version

[2] A “specific realization” of a factor is a qualitative or quantitative characterization of the development of this factor. E.g. for e-mobility this could be a certain number of existing battery electric vehicles in a given year.

of the “ADVanced Impact Analysis” (ADVIAN) (Linss and Fried 2009), where direct and indirect impacts are appropriately weighted and an improved evaluation metric is used. Afterwards, specific realizations of these drivers are described and consistent scenarios are derived by using the cross-impact balances (CIB) approach (Weimer-Jehle 2006). Thereby we make use of a novel and fast analysis approach to analyse the degree of consistency for the identified scenarios – in occurrence scenarios for network expansion planning.

The remainder of the paper starts with some general considerations about constructing scenarios and an overview of the developed approach in section 2. Later in that section, both the adjusted ADVIAN and the CIB approaches are explained shortly both verbally and in formal notation. In section 3, the results of the application study on electricity system transformation scenarios are presented. Specifically, the effects of the adjusted impact-weighting are analysed for the adjusted ADVIAN approach and the resulting relevant exogenous drivers are presented. Also, the derived scenarios are discussed including an evaluation using the newly developed consistency metrics. Finally, section 4 provides a brief conclusion and outlook on further research directions.

2 Methodology

As stated in the introduction, constructing scenarios is both time-consuming and challenging. By using workshops or expert surveys together with additional desk research, we aim at deriving plausible and broadly applicable scenarios. Here, a major challenge is to obtain a limited number of scenarios that consistently depict diverging routes for the development of the (energy) system and allow to handle appropriately the high complexity and strong interdependencies between the multiple uncertain factors. Or put differently: a first important step in scenario construction is in our opinion to reduce the multiple interdependencies to a limited number of key exogenous drivers. In a second step consistent scenarios may be constructed for these key drivers and subsequently spelled out for other factors.

2.1 General considerations

2.1.1 Cross-impact analysis and scenario construction

A frequently used approach to deal with multiple interdependent factors in prospect studies is cross-impact analysis (CIA). The origins of this method may be traced back to the 1960s with the first approach being developed by (Gordon and Hayward H. 1968). A main motivation for early approaches to cross-impact analysis has been to complement Delphi studies using also expert judgements but focusing on interdependencies between different developments. In fact there is not one single methodology for CIA, rather a broad number of different varieties have been developed over the years, cf. notably (Turoff 1971; Enzer 1971; Duperrin and Godet 1973; Duperrin and Godet 1975; Edward Jackson and Lawton 1976; Kaya et al. 1979; Brauers and Weber 1988; Weimer-Jehle 2006, 2008; Linss and Fried 2009; Bañuls et al. 2013; Thorleuchter and van den Poel 2014; Ceric 2016; Lee and Geum 2017; Panula-Ontto and Piirainen 2018). Also several classification schemes have been proposed to categorize the different methods (cf. e.g. (Weimer-Jehle 2006; Panula-Ontto and Piirainen 2018). A common point in many of these categorizations is the distinction between (mostly) older methods for CIA which focus on discrete events and their probabilities of occurrence (e.g. availability of a certain new technology) and more recent methods which aim at identifying interdependencies between rather continuous developments (e.g. cost of battery technologies or deployment of solar rooftop systems)[3]. For the former approaches, the estimation of probabilities of oc-

[3] Note that a further category could be identified that considers combinations of several methods, e.g. CIA and Delphi (Enzer 1971; Bañuls et al. 2013) CIA and semantic analysis (Thorleuchter and van den Poel 2014) , CIA and Analytical Hierarchy Process (AHP), (Lee and Geum 2017.)

currence for different events and their interdependencies is characteristic. Therefore, they are frequently labelled as "probabilistic" or "probability-focused" CIA. The latter approaches have been by contrast labelled as "deterministic" (Weimer-Jehle 2006) or "structure-focused" (Panula-Ontto and Piirainen 2018). The label "deterministic" is somewhat misleading in the context of scenario construction. It refers basically to the type of judgement that the involved experts provide.

Our focus is on "structure-focused" approaches since we do not see major discrete events that may (or may not) change profoundly the future energy system developments. Rather the big driving forces like decarbonization, decentralization and digitization consist of multiple activities undertaken by numerous stakeholders and they are better described through continuous variables such as the share of electric vehicles. Different methods like the *paper computer* (Vester 1988) *,* the *MIC-MAC* method (Duperrin and Godet 1973) or approaches using fuzzy logic (Parashar et al. 1997; Asan et al. 2004) are already used in different studies which are able to determine the impact of factors on a considered system. However, the approaches "MICMAC" (Duperrin and Godet 1973), "AD-Vanced Impact Analysis (ADVIAN)" (Linss and Fried 2009), and "EXIT" (Panula-Ontto and Piirainen 2018) stand out because they include indirect influences. Thus, instead of only considering the direct influence, the overall influence from one factor can be determined. The difference between the multiple approaches lies in the way of computing these influences and their quantitative valuation of the impacts.

The MICMAC and the ADVIAN methods are based on matrix multiplication. While MICMAC uses the distinction of 0 *(has no impact)* and 1 *(has impact),* the ADVIAN method uses impacts from 0 *(no impact)* to 3 *(strong impact).* In the MICMAC approach, direct multiplications of the incidence matrix are used and the end result is achieved when the ranking of all factors is stable after a certain number of multiplications (Götze 1993). This criterion is yet not always reached. In contrast to MICMAC, the ADVIAN method uses matrix multiplications applied to its column and row sums. For the ADVIAN method, indirect effects are computed up to order n-1, with n being the number of impact factors considered. Thus, ADVIAN considers indirect influences and enables analyzing the impacts of factors on a whole system

The EXIT method values impacts either positive when one hypothesis strengthens another or negative in the opposite case. Hypotheses describe thereby the state of the analysed system, the occurrence of an event or a driving force. They have an (ex ante unknown) Boolean value. For system states and also driving forces, a hypothesis ideally already includes an expected numerical value, e.g. a share of electric vehicles. Additionally, the values assigned on each direct relationship then have an interpretation as "probability-changing influence". The indirect impacts are computed based on acyclic graphs instead of using a matrix multiplication approach. Comparing the total (or summed) impacts and the direct impacts, the interlinkages between hypotheses are categorized. This may not directly be used for constructing consistent scenarios.

Therefore, we subsequently rely in the first step of our approach on an adjusted version of the ADVIAN approach that allows us to preselect key drivers and characterize their general influence on the system by identifying their degree of exogeneity. In the second step, the involved experts then only are required to assess cross-impacts for specific realizations (value attributes, cf. page 3) within the reduced set of exogenous drivers. These are then used as inputs for a cross-impact balance analysis (cf. Weimer-Jehle 2006, 2008). The cross-impact balance primarily aims at identifying consistent scenarios, so its use requires detailed expert judgements on the possible co-existence of realizations for uncertain factors. This approach has proven to be very useful (e.g. Weimer-Jehle et al. 2016), yet is rather time-consuming when applied to multiple uncertain factors. Applying the approach to a limited number of exogenous drivers and using improved evaluation techniques allows us to identify consistent scenarios while values for endogenous factors may be derived subsequently based either on the outcomes of the first step or using numerical simulation models (cf. Blumberg et al. 2020).

Before providing an overview of the steps of the proposed approach, we summarize in the next subsection several working hypotheses that have guided us in the development of the methodology.

2.1.2 Underlying working hypotheses

From the context where this research is placed – i.e. the transition to sustainable energy systems as well from the existing literature on scenario building – we have conscientiously selected working hypotheses which provide an underpinning for the developed methodology. They do not provide a full axiomatic foundation in any decision-theoretical, mathematical sense to the proposed method. Yet they make more explicit why cross-impact analysis and scenario construction are used, which prerequisites must be considered and what are the expected benefits of a systematic multi-stage approach to scenario construction. The working hypotheses are neither empirically tested so far nor is a full-fledged method for empirical testing proposed – this would be beyond the scope of the present paper. Yet we believe them useful to identify the boundaries of applicability of the developed approach beyond the specific application case dealt with in section 3.

- Scenario construction as practiced here aims to support corporate (or also political) decision making by providing a structured way of dealing with the multiple uncertainties in the environment of the firm (or the public body)[4].
- Both the complexity of the firm's environment and the firm's internal decision-making structures require the involvement of multiple persons both in decision making and in scenario construction, given that the tasks encompass a high degree of disciplinary heterogeneity and reliance on "soft" system knowledge (Weimer-Jehle 2006).
- Scenario construction has therefore an important procedural component (cf. Gausemeier et al. 1998) helping to build a shared understanding of the firm's environment – in parallel to structuring and aggregating the multiple uncertainties to a limited number of discrete states of the environment that may be used in formal and quantitative decision-support models.
- Building a shared understanding of the interplay between different external factors becomes easier when focusing first on the general causal relationships and strength of effects, including indirect effects and (positive and negative) feedback loops. Looking at specific outcomes and how they consistently fit together may be dealt with at a second stage.
- Although there are multifold interdependencies between the multiple uncertain factors in the firm's environment, some factors may be extracted that influence others strongly while being less influenced by others. Those might be called "exogenous drivers" and form a subset of all external factors.
- A major aim of scenario construction should be consistency (Rotmans et al. 2000), especially when descriptive scenarios are designed.
- Focusing on exogenous drivers in scenario construction and using one or several modelling approaches to identify suitable outcomes for the non-exogenous factors in the different scenarios contributes to complexity reduction and effective use of resources.
- Model-based derivation of scenario outcomes strengthens consistency and reduces uncertainties. Yet numerical simulation results are dependent on the model input data (Weimer-Jehle et al. 2016), which should be derived using a dedicated scenario construction process.

[4] Subsequently we drop for the ease of reading the additional reference to the political and public realm. This does not mean that we believe that the methodology is of no use there, quite the contrary. Yet we acknowledge that the multi-stakeholder and multi-objective context of decision-making is even more complex in this field.

2.1.3 Overview of the proposed approach

As discussed so far, multiple uncertain factors as well as their interdependencies need to be considered in the construction process for (energy) scenarios. Notably the following questions have to be addressed:

1. What are key **interdependencies** between **uncertain factors**?
2. Is there a subset of factors, called **exogenous drivers,** that is sufficient to characterize scenarios?
3. What are coherent sets of realizations for these factors, i.e. **consistent scenarios**?

Hence key drivers need to be identified, which describe the development of the energy system and have a great impact on this system, even though they are not necessarily part of the particular energy system (e.g. social, economic or political aspects). Therefore, a classification of uncertain factors in exogenous drivers and endogenous factors is needed. Exogenous drivers are then forces from outside the system and (predominantly) immutable from inside of the considered system. This means that their future development and thus, their specification could be set as a scenario assumption more reasonably, as these exogenous drivers influence the other factors (significantly) more than vice versa; i.e. they constitute a rather stable set of context factors which mainly drives the systems development. Consequently, they (strongly) influence this specific system and are less likely to be influenced by the development of the other (endogenous) factors. Moreover, interdependencies between exogenous drivers need to be considered, even though these interdependencies may be weaker than those between endogenous factors. In contrast to exogenous drivers, endogenous factors are (almost) not able to influence the exogenous drivers although they may be strongly interrelated among themselves. Besides this verbal description, a formal description of exogenous drivers (and “truly” exogenous drivers and endogenous factors) is given in chapter 2.2.3.

The method developed and applied in this paper is summarized in Figure 1. The objective thereby is to describe the multiple uncertainties affecting network extension planning through a limited number of consistent scenarios. Thereby multiple potentially relevant factors are to be considered and their interdependencies are to be taken into account comprehensively.

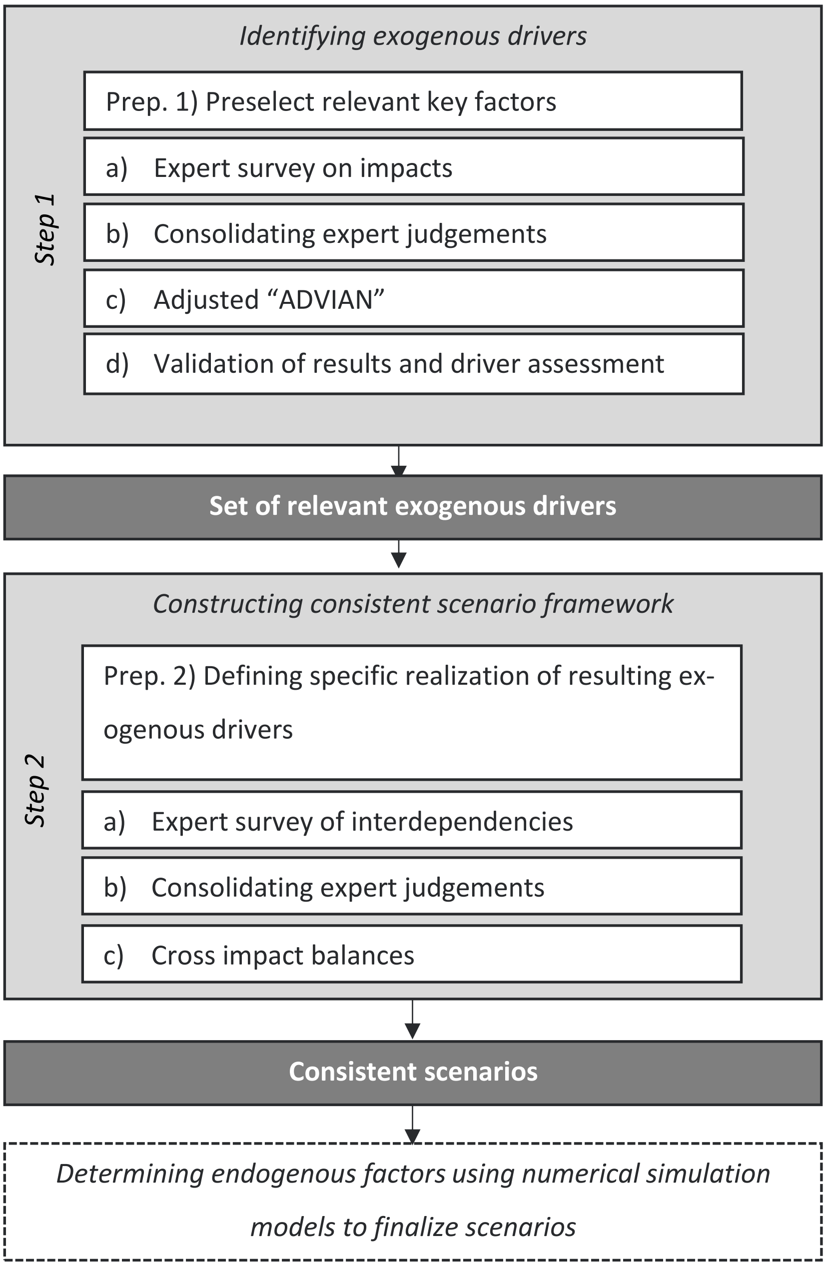

Figure 1 Main steps of the proposed scenario construction approach

The developed approach comprises three major steps. Using a modified version of the cross-impact approach ADVIAN allows to identify the exogenous drivers. Thereby, expert judgements about the influences from one factor onto others are combined. Using these quantitative judgements, the interdependencies among factors are analysed in order to determine the full impact of one factor on the whole system and to derive the key exogenous drivers. The details of this step are discussed in section 2.2.

The second major step is to identify scenarios, i.e. a consistent set of specific realizations of all exogenous drivers. Fundamental considerations about this step as well as a description of the cross-impact balance approach used here are given in section 2.3 along with a discussion of newly defined consistency parameters.

As a third step, values for endogenous factors may be determined using numerical simulation tools [5]. This step is not further detailed in the present paper and the interested reader is referred to Blumberg et al. (2020).

2.2 Determining key elements and drivers for the energy system transformation

The exogenous drivers (cf. 2.1.3) are derived here from a set of considered key factors using expert judgements and a structural cross-impact approach. Typically, such cross-impact approaches are used to evaluate the degree of influence of factors and enable system analyses (see (Duperrin and Godet 1973; Vester 1988; Linss and Fried 2009; Panula-Ontto and Piirainen 2018; Panula-Ontto et al. 2018). However, the consideration of indirect impacts raises a number of issues. The EXIT approach developed by (Panula-Ontto and Piirainen 2018) aims at avoiding excessive indirect effects by considering only acyclic impacts. In approaches based on matrix multiplication, either convergence may not be guaranteed – this is the case for MICMAC (cf. (Götze 1993)). Or the indirect impacts may be overestimated, as discussed for the ADVIAN approach in section 2.2.1 and Appendix 1. Therefore, we present a new approach adjusting the ADVIAN method such that indirect influences are weighted more appropriately in higher orders (cf. section 2.2.2). This is complemented by a newly developed approach to rank the factors according to their degree of exogeneity (cf. section 2.2.3) while ensuring convergence. Thereby, for each factor the summed impact values on the system are compared to the summed values of induced influence from the system. This allows then to define a threshold to identify the truly exogenous drivers.

2.2.1 ADVIAN approach

The ADVIAN approach developed by (Linss and Fried 2009) uses a classification scheme for impact analysis while considering indirect influences of factors by using a cross-impact matrix. Here, every impact of each factor on the whole system needs to be evaluated. Since it is very difficult to quantify the impact of one factor onto the whole system, cross-impact matrices are used as a reasonable tool to reduce the complexity of the expert judgements. In a cross-impact matrix, experts quantify consecutively (only) the impact of one factor (listed in row i) onto one other factor (listed in column j). Thus, each time only two factors are compared bilaterally. The impacts are thereby valued on a scale from 0 to 3 *(no impact to strong impact)*. Hence it is only evaluated whether an impact from

[5] Also optimization tools may be used if either central planning is playing a predominant role in the unfolding of the endogenous factors or they result from a welfare-maximizing market-based interplay between various actors.

one factor onto the other one exists, the direction of the impact - *promoting* or hindering - is ignored. Therefore, the only information recorded in element a_{ij} is the strength of the influence of factor i on factor j.

The impact of one factor onto the others is obtained row-wise. Looking at the column indicates how a factor is influenced by the system. From the experts' assessments the driver with the biggest impact on the whole system can be derived using following approach (Linss and Fried 2009). Grouping the elements $a_{ij}^{(k)}$ for each expert *k* yields a matrix

$$A^{(k)} = \left(a_{ij}^{(k)}\right) \in R^{N \times N}. \tag{1}$$

From these expert judgements, the average is taken in order to obtain a more reliable estimate of the actual patterns of interdependencies[6].

$$A = \frac{1}{K} \sum_{k=1}^{K} A^{(k)} = \left(a_{ij}\right) \in R^{N \times N} \tag{2}$$

The row sum $a_{i.} = \sum_{j=1}^{N} a_{ij}$ is then called active sum and corresponds to the total direct influence, or influence of first order. Correspondingly, the column sum $a_{.j} = \sum_{i=1}^{N} a_{ij}$ is the passive sum for factor j and summarizes to what extent that factor is influenced directly (first order) by others (Vester 1988).

Using matrix multiplication with matrix *A* on the active and passive values, the impacts and induced influences are determined as illustrated in Table 1.

Table 1 Impact matrix

						active values		
	Factor	F1	F2	F3		direct sum	2nd order	**indirect sum**
	F1	0	1	0		1	2	**3**
	F2	0	0	2		2	6	**8**
	F3	3	0	0		3	3	**6**
					sum	6	11	17
passive Values	direct sum	3	1	2	6	det(A) = 6 > 1 → exponential growth of impact of higher orders, cf. Appendix 2		
	2nd order	6	3	2	11			
	indirect sum	**9**	**4**	**4**	17			

[6] Note that outliers may be eliminated when averaging the single elements in order to obtain more robust results.

The single indirect impact of the second order from factor F1 on factor F3 is obtained by multiplying influence factors along all possible paths (in this case F1->F2->F3). In Table 1 a small example is given that shows the difference between only considering the direct influence compared to the indirect influence (which according to the definition in (Linss and Fried 2009) also includes the direct impact). The influence of factor F1 on F3 is computed in this example as $a_{12} \cdot a_{23} = as_1^{(2)}$ or $1 \cdot 2 = 2$, where a_{12} is the influence of F1 on F2 which influences F3 with a_{23}. The value $as_i^{(n)}$ represents the influence of the *n*-th order, which describes the indirect influence in the example of Table 1 from F1 over F2 to F3.

Formally, the individual active as well as passive values of the *n*-th order $as_i^{(n)}$ and $ps_i^{(n)}$ are obtained through:

$$as_i^{(n)} = \begin{cases} \sum_{j=1}^{N} a_{ij} & \text{for } n = 1 \\ \sum_{j=1}^{N} a_{ij} \cdot as_j^{(n-1)} & \text{for } 2 \le n \le N-1 \end{cases} \quad (3)$$

$$ps_i^{(n)} = \begin{cases} \sum_{i=1}^{N} a_{ij} & \text{for } n = 1 \\ \sum_{i=1}^{N} a_{ij} \cdot ps_i^{(n-1)} & \text{for } 2 \le n \le N-1 \end{cases} \quad (4)$$

The total active and passive values are computed then as:

$$As_i = \sum_{n=1}^{N-1} as_i^{(n)} \quad (5)$$

$$Ps_i = \sum_{n=1}^{N-1} ps_i^{(n)} \quad (6)$$

They describe whether a factor is more likely to influence the system, i.e. has an impact on other factors rather than being impacted by them. Conversely a factor is more likely to be a dependent variable if it is more influenced by other factors than having an impact on them.

2.2.2 Adjusted approach for cumulative active and passive values

Taking a closer look shows that the classical ADVIAN approach as presented so far tends to put a very high weight on the influences of higher order. Given the ratings that exceed 1 in many cases, the indirect impact typically raises steadily with higher orders. The example in Table 1 illustrates this as the sum of the second order of impacts (11) is almost twice as large as the active or passive sum of the first order. Through the matrix multiplication, the active as well as the passive values increase exponentially with the order N. If a large matrix is evaluated, the matrix multiplication leads to $as_i^{N-1} \gg \sum_{n=1}^{N-2} as_i^n$ and $ps_i^{N-1} \gg \sum_{n=1}^{N-2} ps_i^n$. A more detailed analysis including a small example and a mathematical condition for exponential growth is provided in the Appendix 2.

Consequently, the indirect value of the last order may affect the outcome in a way that all previous influences are negligible. Therefore, the equations (5) and (6) are superfluous (in the case of larger N and abs(det(A))>1), because the comparison of the last order alone would result in the same outcome. To reduce this overly strong influence of the last order, the previously described classification method of impact factors which considers indirect influences is adjusted to rebalance the impact of the different orders of active and passive values. Generally, it seems rather plausible that the indirect impact would decrease with increasing order *n*[7]. Because of the exponential growth characteristic of the original approach, a mere division by the order is insufficient to obtain declining impact strength. In addition to the division, the active and passive values are hence normalized in each calculation step. This approach is described formally in equation (7) and (8). Consequently, the active and passive values of *n*-th order are weighted and normalized.

$$\overline{as}_i^{(n)} = \begin{cases} \dfrac{as_i^{(1)}}{\sum_{j=1}^{N} as_j^{(1)}} & \text{for } n = 1 \\ \dfrac{\widetilde{as}_i^{(n)}}{n \cdot \sum_{j=1}^{N} \widetilde{as}_j^{(n)}} & \text{for } 2 \leq n \leq N-1 \end{cases} \qquad \textbf{(7)}$$

and

$$\overline{ps}_j^{(n)} = \begin{cases} \dfrac{ps_j^{(1)}}{\sum_{i=1}^{N} ps_i^{(1)}} & \text{for } n = 1 \\ \dfrac{\widetilde{ps}_j^{(n)}}{n \cdot \sum_{i=1}^{N} \widetilde{ps}_i^{(n)}} & \text{for } 2 \leq n \leq N-1 \end{cases} \qquad \textbf{(8)}$$

The order-weighted normalization is carried out at each step. Therefore, the auxiliary variables $\widetilde{as}_i^{(n)}$ and $\widetilde{ps}_j^{(n)}$ are specified according to the equations (9) and (10) as follows:

[7] Only in the presence of strong positive (self-reinforcing) feedback loops, the impacts of higher orders will exceed the direct impacts.

$$\widetilde{as}_i^{(n)} = \sum_{j=1}^{N} a_{ij} \cdot \overline{as}_j^{(n-1)} \quad \text{for } 2 \leq n \leq N-1 \tag{9}$$

$$\widetilde{ps}_j^{(n)} = \sum_{i=1}^{N} a_{ij} \cdot \overline{ps}_i^{(n-1)} \quad \text{for } 2 \leq n \leq N-1 \tag{10}$$

The auxiliary variables $\widetilde{as}_i^{(n)}$ and $\widetilde{ps}_j^{(n)}$ must be computed after determining the active and passive values of the previous order and are not normalized and weighted.

With the adjusted active and passive values of *n*-th order $\overline{as}_i{}^{(n)}$ and $\overline{ps}_i{}^{(n)}$, the adjusted active and passive scores may be computed analogously to equations (5) and (6):

$$\overline{As}_i = \sum\nolimits_{n=1}^{N-1} \overline{as}_i^{(n)} \tag{11}$$

$$\overline{Ps}_i = \sum\nolimits_{n=1}^{N-1} \overline{ps}_i^{(n)} \tag{12}$$

2.2.3 Determining exogenous drivers

A cardinal measure of the degree of exogeneity Ex_i respectively the degree of endogeneity En_i may be computed by taking the difference of the active and passive values for each factor:

$$Ex_i = \overline{As}_i - \overline{Ps}_i \tag{13}$$

$$En_i = \overline{Ps}_i - \overline{As}_i \tag{14}$$

The determined value Ex_i is then used for the classification of the factors. The greater the value Ex_i, the more impact the factor i has on the whole system while being weakly impacted from the system at the same time. A value near zero means that the considered factor is neither strongly exogenous nor endogenous. These factors are either characterized by having a great influence on the other factors while being simultaneously strongly influenced by other factors or they have only few interdependencies and thus, they have a small impact on the whole system while being also themselves (mostly) unchangeable.

We label exogenous drivers those factors with a positive exogeneity score. In order to identify the most important ("truly") exogenous factors, we then proceed as follows:

1. We define as exogenous drivers those factors with $Ex_i > 0$. The corresponding set of all exogenous drivers E is then given by $E = \{i|Ex_i > 0\}$.
2. We order the exogenous drivers by decreasing exogeneity score Ex_i and relabel them using the index e. Hence for the resorted exogenous drivers e we have $Ex_e \geq Ex_{e+1}$.
3. We compute the total exogeneity score TEx as the sum of the scores of the exogenous drivers e: $TEx = \sum_e Ex_e$.
4. Additionally, we define the cumulative exogeneity score CEx_e as the sum of the exogeneity scores of all factors preceding driver e in the sorting order: $CEx_e = \sum_{e'=1}^{e} Ex_{e'}$.

In order to reduce the complexity of the subsequent analysis steps, we may select a subset of relevant exogenous drivers based on the cumulative exogeneity scores. The idea is to select the most important drivers that in sum explain at least a share α (e.g. 80%) of the total exogeneity score TEx. Hence, the subset of exogenous drivers represents a trade-off between considering a sufficient amount of factors really driving the system while being rather stable and ensuring a reasonable effort for the second step of our method (cf. section 2.3) since this effort increases exponentially with the amount of considered exogenous drivers (assuming a similar effort for each pairwise comparison). This leads to the following step:

5. Determine the subset $E_\alpha \subset E$ of relevant exogenous drivers, i. e. formally $E_\alpha = \{e|e \leq l\ with\ CEx_l \geq \alpha \cdot TEx\ and\ CEx_{l-1} < \alpha \cdot TEx; 0 \leq \alpha \leq 1\}$.

Alternatively one may also select the relevant exogenous drivers e' by simply requiring that the exogeneity score $Ex_{e'}$ to exceed a certain fraction β (e.g. 5 %) of the total exogeneity score TEx, i.e. $Ex_{e'} \geq \beta \cdot TEx$. Yet the rule based on the cumulative exogeneity scores has the advantage that a certain coverage of all exogenous scores is reached.

2.3 Deriving consistent scenarios

In order to derive consistent scenarios, the exogenous drivers determined in step 1 are scrutinized in view of possible interdependencies. To this end, to each specific realization (cf. page 3) of these drivers' appropriate parameter values are assigned based on expert knowledge, forecasts of possible developments and general literature. E.g. for oil price developments, the forecasts and scenarios issued by the International Energy Agency (International Energy Agency 2017) or the US Energy Information Administration (U.S. Energy Information Administration) may serve as basis. On the other hand, national renewable deployment may be parametrized based on government objectives, agency forecasts and/or recent market dynamics. The parametrization should describe a range that is sufficiently large to cover a broad range of possible scenarios and on the other hand no very unlikely developments are included.

Subsequently, three discrete specific realizations are distinguished for each driver in order to enable an expert survey, where experts provide judgements on consistent driver combinations within a reasonable amount of time. Specifying the levels of the drivers corresponding to either strong, moderate or weak developments provides an intuitive, user-friendly representation and also simplifies the layout of the survey. Besides the standardized characterization as "high, moderate, low", a detailed qualitative description or a numerical characterization of drivers having a quantitative nature (Weimer-Jehle 2006) is prepared for the experts.

To determine consistent scenarios, i.e. a consistent set with all exogenous drivers in certain specifications, the cross-impact balance approach developed by ENERGY-TRANS (Weimer-Jehle 2006) or the approach presented by Gausemeier in (Gausemeier et al. 1998) are suitable. Theoretically, the EXIT approach presented in section 2.1.2 could be used here, too. However, this method is predominantly developed to investigate the impacts of a certain driver specification (hypothesis) on the system instead of deriving a consistent sets (bundles) of all drivers in certain specification. The approach from Gausemeier determines the consistency of scenarios in a similar way to the cross-impact balances method. A consistency matrix is constructed where specified drivers are compared with each other. Experts rate these specified drivers quantitative between 1 to 5, if they are consistent or inconsistent to each other. Afterwards, inconsistent bundles are eliminated and with the help of clustering aggregated. Unfortunately, in this process there is an information loss and scenarios are simplified (Gausemeier et al. 1998). Therefore, using the cross-impact balances approach is more suitable which is explained briefly in the following section.

2.3.1 Cross Impact Balances

The cross-impact balances approach is characterized by using a simple logical structure with high transparency for participating experts. Furthermore, experts need only to compare and rate the interrelationships of two driver's specifications. In contrast to the common applications in literature, in this paper only exogenous driver's specifications are set in relation to each other to derive consistent scenarios.

Contrary to the approach in step 1, the experts assess impacts between specific realizations of the exogenous drivers according to their direction and strength. Any combination of a specific realization z_1 of driver 1 and a realization z_2 of driver 2 is ranked between -5 *(strongly hindering)* and +5 *(strongly promoting)*; i.e. this combination is valuated regarding the pairwise consistency of these two specific realizations with $c_{12}(z_i, z_j)$[8] . These specific realizations are often probable developments including a

[8] A pairwise valuation of two specific realizations of the same driver is pointless since each driver can only be realized in one way and thus, a valuation of the consistency c_{ij} is only defined for $i \neq j$

short description. In Table 2 a small example with three different drivers and three specific realizations of each exogenous driver is given. Here, z_i describes a realization of driver i. Z_i is the set of possible realizations of driver i, in the example for all drivers $Z_i = \{1,2,3\}$. A scenario is then a combination of one specific realization of each driver. Mathematically this is written as the tuple $\boldsymbol{z} = (z_1, \dots, z_n)$. A consistent scenario is characterized by the inequality

$$\sum_i c_{ij}(z_i, z_j) \geq \sum_i c_{ij}\,(z_i, l)\;\forall\, j \in \{1, \dots, n\}, \forall\, l \in Z_j \tag{15}$$

In our example, a consistent scenario $\boldsymbol{z} = \{3,2,2\}$ is marked in light grey in Table 2. The consistency check of equation (15) then reads for driver 2 in Table 2: $c_{12}(3,2) + c_{32}(2,2) \geq c_{12}(3,1) + c_{32}(2,1)$ and $c_{12}(3,2) + c_{32}(2,2) \geq\; c_{12}(2,3) + c_{32}(3,3)$ must be true.

In general, the indices i and j run over all drivers and z_i and z_j designate their specific realizations in one scenario, whereas l runs over all possible realizations Z_j of driver j. A combination of specific realizations for all drivers is consistent, if for each selected specific realization, the column sum is greater or equal than the column sum for not selected specific realizations (Weimer-Jehle 2008). A more detailed explanation of the method can be found in (Weimer-Jehle 2006, 2008; Weimer-Jehle et al. 2016) where typically 10 to 20 drivers are compared, with 2 to 4 specific realization each. The approach foresees factors to be determined through workshops or desk research.

In contrast, the approach presented in this paper stand out from other works as not all system relevant factors need to be set. Furthermore, these drivers are preselected systematically in the previous step using expert judgement. The advantage of this approach is the reduced effort for evaluating the matrix through expert judgements, as explained in more detail in chapter 3.

Table 2 CIB-Approach Example

		Driver 1			Driver 2			Driver 3		
		$z_1 = 1$	$z_1 = 2$	$z_1 = 3$	$z_2 = 1$	$z_2 = 2$	$z_2 = 3$	$z_3 = 1$	$z_3 = 2$	$z_3 = 3$
Driver 1	$z_1 = 1$				$c_{12}(1,1)$	$c_{12}(1,2)$	$c_{12}(1,3)$	$c_{13}(1,1)$	$c_{13}(1,2)$	$c_{13}(1,3)$
	$z_1 = 2$				$c_{12}(2,1)$	$c_{12}(2,2)$	$c_{12}(2,3)$	$c_{13}(2,1)$	$c_{13}(2,2)$	$c_{13}(2,3)$
	$z_1 = 3$				$c_{12}(3,1)$	$c_{12}(3,2)$	$c_{12}(3,3)$	$c_{13}(3,1)$	$c_{13}(3,2)$	$c_{13}(3,3)$
Driver 2	$z_2 = 1$	$c_{21}(1,1)$	$c_{21}(1,2)$	$c_{21}(1,3)$				$c_{23}(1,1)$	$c_{23}(1,2)$	$c_{23}(1,3)$
	$z_2 = 2$	$c_{21}(2,1)$	$c_{21}(2,2)$	$c_{21}(2,3)$				$c_{23}(2,1)$	$c_{23}(2,2)$	$c_{23}(2,3)$
	$z_2 = 3$	$c_{21}(3,1)$	$c_{21}(3,2)$	$c_{21}(3,3)$				$c_{23}(3,1)$	$c_{23}(3,2)$	$c_{23}(3,3)$
Driver 3	$z_3 = 1$	$c_{31}(1,1)$	$c_{31}(1,2)$	$c_{31}(1,3)$	$c_{32}(1,1)$	$c_{32}(1,2)$	$c_{32}(1,3)$			
	$z_3 = 2$	$c_{31}(2,1)$	$c_{31}(2,2)$	$c_{31}(2,3)$	$c_{32}(2,1)$	$c_{32}(2,2)$	$c_{32}(2,3)$			
	$z_3 = 3$	$c_{31}(3,1)$	$c_{31}(3,2)$	$c_{31}(3,3)$	$c_{32}(3,1)$	$c_{32}(3,2)$	$c_{32}(3,3)$			
		C_1^1	C_1^2	$\boldsymbol{C_1^3}$	C_2^1	$\boldsymbol{C_2^2}$	C_2^3	C_3^1	$\boldsymbol{C_3^2}$	C_3^3

2.3.2 Consistency and stability indicators

As explained in the last subchapter, a larger valuation $c_{ij}(z_i, z_j)$ indicates that a certain driver specification z_j is strongly promoted by the other driver's scenario-specific realization z_i; i.e. this development is likely if the other driver develops corresponding to its selected realization. In this paper, the column sums of the valuations of one specific realization l of driver j are defined as *consistency value* $C_j^l = \sum_i c_{ij}(z_i, l)$ (where $l \in Z_j$). In a consistent scenario, the consistency value of each driver's specific realization is always larger than or equal to the consistency value of the other realizations for the same driver.

Consequently, a large overall sum of all consistency values $C_j^{z_j}$ of the chosen realizations z_j within a scenario $\boldsymbol{z}$ indicates that the scenario's driver realizations promote each other and vice versa a small sum indicates that they are not strongly supportive. Thus, we define this value as ***consistency indicator***, which is formally defined in the following equation:

$$\hat{C}^{\boldsymbol{z}} = \sum_j C_j^{z_j} \quad \textit{for a specific scenario } \boldsymbol{z} = (z_1, \ldots, z_n) \tag{16}$$

Furthermore, one can assess the valuations $c_{ij}(z_i, z_j)$ of a specific driver's realization and another's driver specific realization. Comparing the valuation $c_{ij}(z_i, z_j)$ of the two specific realizations of two drivers of the scenario **z** with the overall highest valuation $c_{ij}(l_i, z_j)$ of one specific realization z_j of **z** and all possible realizations l_i of the other driver i (where $z_i \neq l_i$), a delta is computable for each comparison. This delta indicates how strong these two developments promote each other in comparison to the most promoting development l_i for driver i which is not part of the scenario.

$$\Delta C_j^{z_j} = C_j^{z_j} - \sum_i \max_{l_i | l_i \neq z_i} c_{ij}(l_i, z_j) \qquad \textbf{(17)}$$

By summing up all these deltas a value is calculated which allows an indication of the stability of **z**. We define this sum as ***stability indicator*** $\hat{S}^{\mathbf{z}}$. Formally the stability indicator is then given by:

$$\hat{S}^{\mathbf{z}} = \sum_j \Delta C_j^{z_j} = \sum_j \left(C_j^{z_j} - \sum_i \max_{l_i | l_i \neq z_i} c_{ij}(l_i, z_j) \right) \qquad \textbf{(18)}$$

For a consistent scenario, this value is larger than or equal to zero. If each delta is large this means that the scenarios combination of specific realizations is promoting each other best and thus, a large stability indicator reveals a set of specific developments which enforce each other making other specific developments more unlikely. In chapter 3.3.2 both the stability and the consistency indicator are shown in Table 7 for the following presented scenarios.

3 Results and discussion: Constructing consistent energy scenarios for distribution grid expansion planning

In this chapter we discuss the application of the proposed scenario construction method to the construction of energy scenarios which serve as input for network expansion planning. A particular focus is thereby laid on factors relevant for distribution grids. For this application case, the outcomes of the adjusted ADVIAN approach and the derived scenarios using the CIB are presented.

First, the inputs to the approach, notably the initial choice of key factors for the energy transformation process are introduced in chapter 3.1. Also, further information about the setup of the application case and the survey are briefly given.

Hereafter, chapter 3.2 sheds light on the results of the adjusted ADVIAN approach as first major step of our methodology. The identified exogenous drivers are therefore presented and critically discussed. Additionally, the impact of the methodological improvements introduced in chapters 2.2.2 and 2.2.3 are highlighted based on our application case; in particular, it is shown

- why weighting the preselected key factors like described in section 2.2.2 is appropriate;
- and that our approach leads to a reasonable selection of exogenous drivers representing a beneficial trade-off between the depiction of the entire exogeneity and a feasible number of inputs for the CIB (i.e. exogenous drivers for the second step of the method).

Chapter 3.3 presents the results of the second major step of our methodology by illustrating the obtained scenarios. Again, results are briefly presented and critically discussed. In addition, chapter 3.3.2 validates qualitatively the derived scenarios by calculating and assessing the indicators derived in chapter 2.3.2.

In chapter 3.4, the efficiency of the proposed approach in terms of resource use is briefly discussed to highlight the benefits of the proposed two-step approach.

3.1 Preselected key factors for adjusted ADVIAN approach and survey conduction

The key factors considered as starting points in this case study have been derived by both a combination of desk research, literature review and intense discussions between the authors of this paper as well as a preselection process described in more detail in Appendix 1.

The preselected 39 key factors (corresponding to Prep. 1 in Figure 1) used in our application case are presented in Table 3. Some of these factors may seem closely related, but they do have a different main focus. For example, the factors 18 to 20 are rather interconnected, yet factor 20 is related to the infeed structure whereas factors 18 and 19 describe generation deployment.

Table 3 (preselected) Key factors and their ID

Driver	Driver
1 Global price development for fossil fuels	21 Civil opinion towards energy transition
2 Economic Growth in Europe/ Germany	22 Individual energy consumption patterns
3 Divergence of European to German energy policy	23 Final energy consumption for heat
4 Political intervention in the conventional power plant fleet	24 Final energy consumption electricity
5 Regulatory level of legislation for the energy sector	25 Number of electric vehicles in Germany
6 Political targets regarding CO_2 emissions	26 Investment in charging infrastructures (e-mobility)
7 Political targets regarding the share of renewable energy	27 Usage of local/ regional electricity prices
8 Structuring/designation/arrangement of grid charges/levies	28 Sector coupling
9 Demand for fossil fuels	29 Distribution of smart energy management systems
10 Development of the electricity price for the industry	30 Expansion of electrical storage
11 Development of prices for CO_2 certificates	31 Battery production/manufacturing costs
12 Efficiency development industry	32 Technological progress of electrical energy storage
13 Efficiency development in the transport sector	33 Expansion of ”Power to X” technologies
14 Possibilities for cross-border electricity transport	34 Share of flexible loads in households
15 Grid expansion in the transmission grid	35 Share of flexible loads by electric vehicles
16 Grid expansion int he distribution grid	36 Share of flexible loads in industry
17 Grid expansion in the low-voltage grid	37 Share of flexible loads in GHD
18 Installed capacity of wind energy	38 Number of connected plants to virtual power plants
19 Installed capacity of photovoltaic systems	39 Expansion of thermal storage
20 Volatility level of electricity generation	

These key factors are used as starting point for the application of the methodology presented in chapters 2.2 and 2.3 (cf. notably also the overview in Figure 1). First, 16 experts in electricity network expansion planning and related fields with a focus on distribution grids were recruited within the Agent.GridPlan[9] consortium. They participated in the survey of the first step of our methodology, i.e. they filled out the matrix of expert ratings of the adjusted ADVIAN approach (pairwise comparison of key factors). In the subsequent evaluation, the two highest and lowest values are neglected for each pairwise comparison in order to avoid distortions by extreme views[10] and the arithmetic

[9] Cf. Acknowledgements. The project focused on Germany that is why factors are partly preselected with a focus on Germany.
[10] Since the first step aims to identify whether a factor has an impact on the other factors or not it seems reasonable to discard extreme views. By ignoring extreme views, a higher homogeneity is generated.

average of the remaining 14 values is used (we hereinafter refer to this as “processed output from step 1”) to identify the exogenous drivers (cf. chapter 3.2).

For the second major step, three specifications (“high”, ”mid” and ”low” development) as explained in chapter 2.3 are derived for each exogenous driver. Then 17 experts participated in the second survey, i.e. they filled out the matrix for the CIB (pairwise comparison of exogenous drivers in different specific realizations). These results are merged by using the rounded arithmetic average for each cell of the matrix[11] (we hereinafter refer to this as “processed output from step 2”). Finally, the method established by (Weimer-Jehle 2006) is applied in order to derive the consistent scenarios (cf. chapter 3.3) which are then evaluated using the indicators presented in chapter 2.3.2. The methods have thereby been explained in detail to all experts in advance and they were highly encouraged to provide their assessments in line with scientific best practice.

3.2 Exogenous drivers

3.2.1 Identified exogenous drivers

The application of the adjusted ADVIAN approach to the processed output from step 1 (cf. chapters 2.1.3 and 3.1) reveals that 17 of the 39 preselected key factors are exogenous. As discussed in section 2.2.3, the set of truly exogenous drivers is then determined based on a prespecified exogeneity threshold. In Figure 2 the exogeneity score for the factors is shown with factors ordered by decreasing exogeneity score. Furthermore, the cumulative exogeneity score is shown that is used to identify the truly exogenous drivers.

[11] As the CIB approach allows positive and negative ratings filtering extreme values is not reasonable here. Rounding was done to ensure input for the CIB as described in Weimer-Jehle 2006.

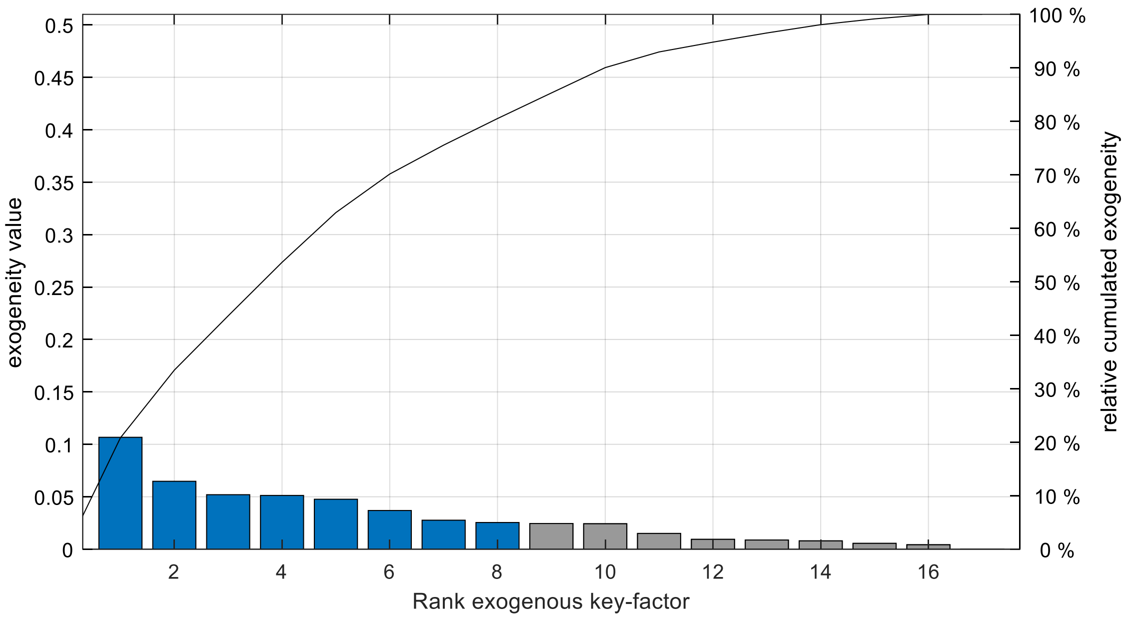

Figure 2 Pareto chart of estimated exogeneity of key-factors

Accordingly, the eighth driver is the last one with an exogeneity share β greater than 5% and cumulatively more than 80% of the total exogeneity α is described through these eight most exogenous drivers, i.e. the sum of the degree of exogeneity of the eight most exogenous drivers (named in Figure 3) corresponds to 80% of the total exogeneity score (cf. 2.2.3). By focusing on the relevant exogenous drivers hence both the number of factors is reduced and those with a low degree of exogeneity are eliminated. These factors could either be strongly influenced by others (in a similar range like they influence others) and are hence not truly exogenous, in the sense of being not influenceable. Or they have neither a significant impact on other key factors nor they are influenced by them which makes them quite irrelevant for the construction of a scenario family. Additionally, this obviously also contributes to reduce the number of exogenous drivers to be considered in the following steps.

In Figure 3, the obtained exogenous drivers and the eight most endogenous factors are shown. On the left-hand side, the exogenous drivers and on the right-hand side the endogenous factors are shown. Light grey bars represent the passive value of each key-element and dark grey bars the active value. The black bar then represents the degree of exogeneity. Taking a closer look, most of the exogenous drivers are either political, regulatory or economic factors. The development of electro mobility is the only driver which does not belong to the previously mentioned categories.

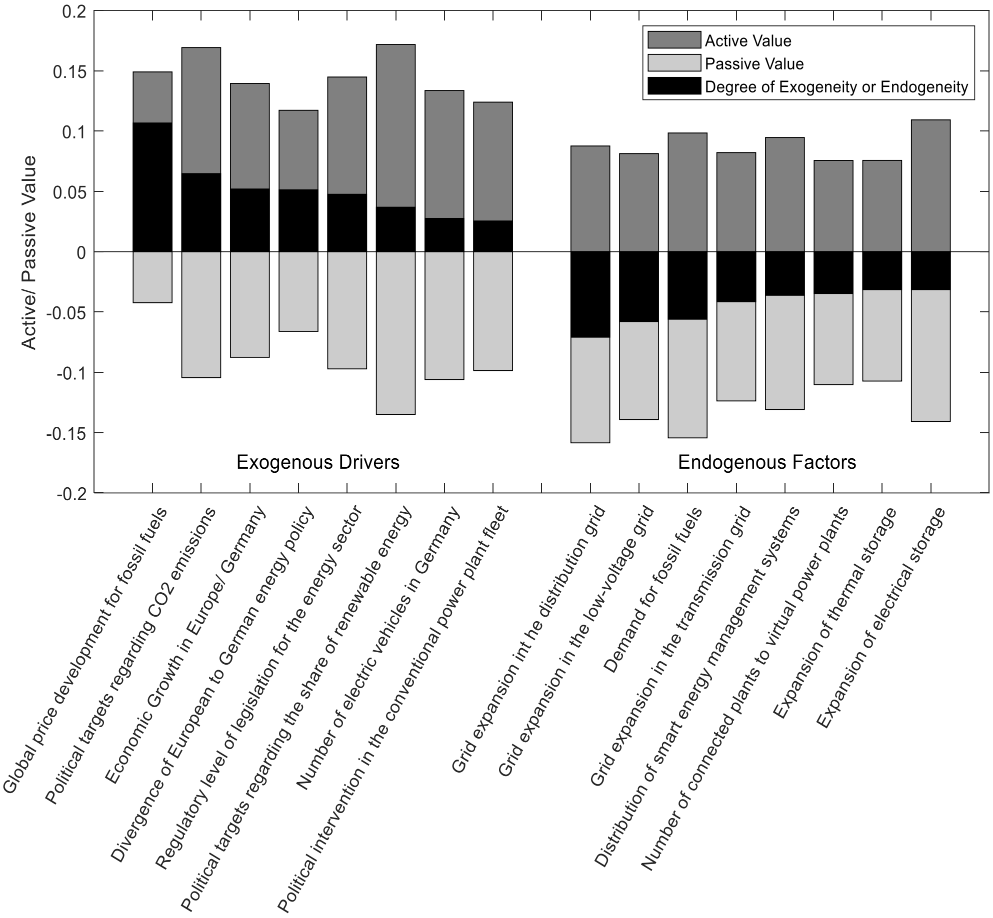

Figure 3 Obtained exogenous drivers and endogenous factors

All drivers are strongly influencing the considered system but are conversely not strongly impacted by other factors. However, no statement is made at this point whether these drivers promote or hinder the energy transformation process. Furthermore, the active value of each exogenous driver exceeds the active value of all endogenous factors.

Among the endogenous factors, different aspects of network development are found. In particular, distribution grid expansion is qualified as even more endogenous (and passive) than transmission grid expansion. The market penetration of thermal and electric storage systems is also found to be endogenous. This may be related back to the fact that electric storage systems require investments which are in turn influenced by multiple political, regulatory and economic framework conditions.

This contrasts somewhat with the rating obtained for the development of electro mobility, which is found to be an exogenous driver. Also, the penetration of electric vehicles is dependent on investments. Yet the current German policies regarding electro mobility have shown limited impact and the target of one million vehicles in 2020 is not met. Consequently, referring to electro mobility as an exogenous driver (i.e. not much influenced by other drivers) seems adequate. Notably the development of electro mobility in Germany or generally in Europe is also driven from outside the considered system, e.g. through the developments in large mobility markets like China or the US. Moreover, the impact of electric vehicles (e.g. on the distribution grid or on the energy consumption of electricity) is rather important if a high market share is achieved.

3.2.2 Impact of the weighting approach

As discussed in chapter 2.2.2, the original ADVIAN approach has been modified by using weighting as well as normalization. This notably weakens the indirect impacts of the predefined factors. This becomes obvious in Figure 4, where the influence of each term is shown for the different approaches. The left part of the graph illustrates that the impact is monotonously decreasing for higher order terms when the adjusted ADVIAN approach is used. The highest impact can be found in the first term which is approximately 37 times higher than the influence of the last terms. In the middle part, the impact of the orders in the original approach is shown. Here the last order has much more weight than the sum of all previous terms. Even though according to the original approach, the total influence is the sum of all influences from each order, the results are (virtually) only determined by the influence of the last order. On the right side, an alternative approach is analyzed where only weighting is applied, i.e. for each term the influence is divided by the order of the term. Because of the close to exponential increase in the factors between the 11th and the 31st order, this method still leads to a domination of high order indirect impacts.

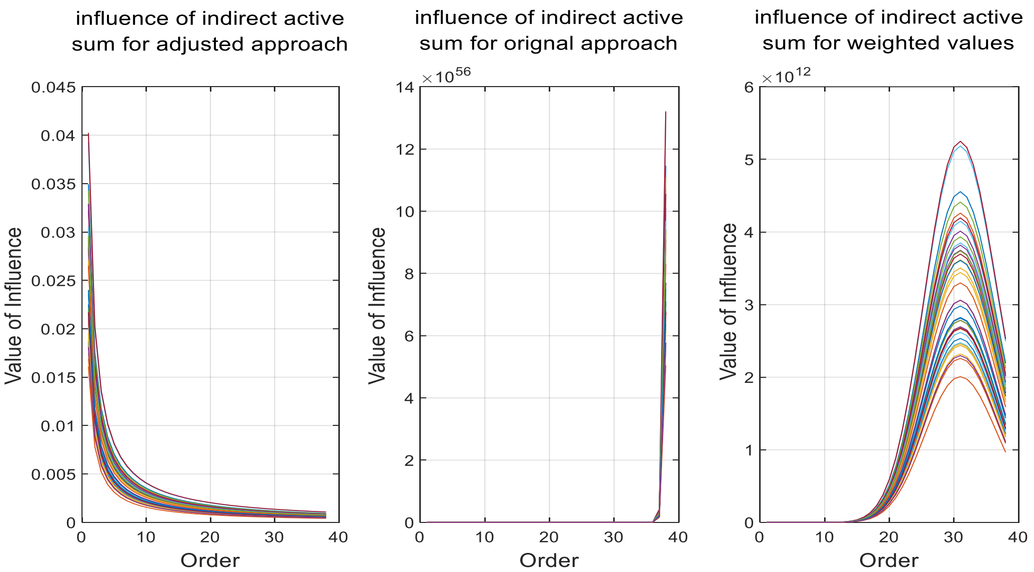

Figure 4 Differences of indirect influence of different orders

The difference in scale between the values of the original and the adjusted method is highlighted in Table 4 for some exemplary cases. Notably, the values for the highest order terms show extraordinarily large differences in comparison to the values from other orders.

This again illustrates that the value of the term of order 38 in the original approach is many times larger than the cumulated sum of terms 1 to 37. For the passive values, the same characteristic may be observed. Using the adjusted approach, this anomality can be avoided. In contrast to the original approach, the range of values spans less than two magnitudes.

Table 4 Strength of influence (1st order equals direct sum)

indirect influences according to the original approach

	1st order	2nd order	$\cdots$	19th order	$\cdots$	37th order	38th order
Factor 1	42.454	1347.975	$\cdots$	$3.960 \cdot 10^{28}$	$\cdots$	$3.6420 \cdot 10^{55}$	$1.1463 \cdot 10^{57}$
Factor 2	39.818	1260.752	$\cdots$	$3.704 \cdot 10^{28}$	$\cdots$	$3.4055 \cdot 10^{55}$	$1.0719 \cdot 10^{57}$
$\vdots$	$\vdots$	$\vdots$	$\vdots$	$\vdots$	$\vdots$	$\vdots$	$\vdots$
Factor 39	22	686.429	$\cdots$	$1.997 \cdot 10^{28}$	$\cdots$	$1.8361 \cdot 10^{55}$	$5.7794 \cdot 10^{28}$

indirect influences according to the adjusted approach

	1st order	2nd order	$\cdots$	19th order	$\cdots$	37th order	38th order
Factor 1	0.03492372	0.01758994	$\cdots$	0.00186294	$\cdots$	0.00095664	0.00093147
Factor 2	0.03275501	0.01645175	$\cdots$	0.00174196	$\cdots$	0.00089452	0.00087098
$\vdots$	$\vdots$	$\vdots$	$\vdots$	$\vdots$	$\vdots$	$\vdots$	$\vdots$
Factor 39	0.01809752	0.00895733	$\cdots$	0.00093922	$\cdots$	0.00048230	0.00046961

For an in-depth comparison of the impact of the chosen approach, we compare the results from the different approaches in Figure 5. Here the active and passive values are shown for each driver, thereby the drivers are normalized to a mean value of 1 for each approach in order to facilitate the comparison. The diagonal solid line then indicates the border between endogeneity and exogeneity (which we refer to as iso-impact line) whereas the dotted lines in Figure 5 are isoquants for the degree of exogeneity (or endogeneity). The circles represent the results of the original approach whereas the stars show the results of the adjusted approach. Blue marked circles or stars represent endogenous factors whereas the red colored circles and stars represent exogenous drivers. At first view, the results are rather similar (in our specific application case). The mean distance to the iso-impact line is almost identical (0.1713 to 0.1678) and the variance does also not differ, at least within the first three significant digits. Nevertheless, the ranking of the resulting values is different and one driver changes from the endogenous to the exogenous class (cf. black ellipsoid in the graph).

Figure 5 Comparison of active and passive values from the original and the adjusted approach

It is also noteworthy that many factors are located close to the iso-impact line, where active as well as passive values are very similar. These factors are hence depending on others and simultaneously impact further factors which reflects the strong interdependencies mentioned in chapter 1.

In Table 5, the rank of each factor regarding its active as well as its passive value is shown. For comparison purposes, the original ADVIAN approach is also included in this table. Furthermore, the rank is shown for each factor based only on the first term, i.e. the so-called direct sum. The difference between the direct sum and the results of the two presented approaches is rather significant, with differences up to 6 ranks showing up. In comparison to the original approach, the adjusted approach yet leads to changes in the rank only for a few factors, these factors gain or lose up to two ranks. Moreover, it turns out that a change in the active rank does not automatically also corresponds to a change in the passive rank.

Overall, the results suggest that a modification of the weighting approach does not strongly impact the outcomes, at least in out exemplary application. Nevertheless, we believe that the proposed adjusted approach is preferable since its weighting does not use astronomic numbers and the decline in weight for higher-order impacts seems more appropriate for most practical applications, at least in the energy sector where various counter-forces dampen indirect impacts. Put differently, one may also argue that our identification of exogenous drivers is rather robust against various weighting schemes which reflect different beliefs about the importance of higher-order indirect effects.

Table 5 Overview of ranking regarding active and passive values for the two different approaches.

Differences between the two approaches are highlighted in **bold**

	Rank Active			Rank Passive		
ID. Factor	direct sum (1st order)	indirect sum original	indirect sum adjusted	direct sum (1st order)	indirect sum original	indirect sum adjusted
1	3	3	3	39	39	39
2	7	5	5	30	**32**	**30**
3	17	**15**	**16**	37	37	37
4	14	11	11	26	26	26
5	4	4	4	27	27	27
6	2	2	2	22	25	25
7	1	1	1	7	7	7
8	13	**16**	**15**	5	4	4
9	25	21	21	1	2	2
10	18	17	17	9	**12**	**10**
11	24	20	20	34	36	36
12	30	**28**	**29**	29	29	29
13	35	**33**	**34**	33	**35**	**34**
14	29	**25**	**26**	31	31	31
15	34	32	32	14	13	13
16	31	30	30	2	1	1
17	32	**34**	**33**	6	**5**	**6**
18	15	**12**	**14**	17	**18**	**17**
19	9	9	9	11	11	11
20	6	7	7	12	**10**	**12**
21	8	6	6	3	3	3
22	22	**23**	**24**	19	**17**	**18**
23	38	38	38	35	33	33
24	16	18	18	15	16	16
25	5	8	8	18	**24**	**22**
26	23	**26**	**25**	28	28	28
27	10	10	10	16	15	15
28	12	**14**	**13**	13	14	14
29	20	**24**	**23**	10	9	9
30	19	19	19	4	**6**	**5**
31	33	35	35	38	38	38
32	27	27	27	36	**34**	**35**
33	11	**13**	**12**	8	8	8
34	28	31	31	25	**23**	**24**
35	26	**29**	**28**	20	20	20
36	21	22	22	24	**22**	**23**
37	39	39	39	32	**30**	**32**
38	37	**36**	**37**	21	19	19
39	36	**37**	**36**	23	21	21

3.3 Consistent scenarios

3.3.1 Resulting consistent scenarios

Based on the processed output from step 2 (cf. chapters 2.1.3 and 3.1) the evaluation process of the cross-impact balances matrixes has revealed four different consistent scenarios. In Table 6, these scenarios with their specific realizations for the exogenous drivers are summarized and shortly described in the first row.

Table 6 Identified Scenarios

<table>
<tr><th></th><th>Scenario 1</th><th>Scenario 2</th><th>Scenario 3</th><th>Scenario 4</th></tr>
<tr><td>Exogenous Driver</td><td>Deep decarboniza-tion and low growth</td><td>Deep decarboniza-tion and mod-erate growth</td><td>Policy-focused Energiewende</td><td>Market-ori-ented Energiewende</td></tr>
<tr><td>Global price development for fos-sil fuels</td><td colspan="2">Low</td><td colspan="2">Moderate</td></tr>
<tr><td>Political targets regarding CO2 emissions</td><td colspan="2">High: Targets advanced to 2040, more ambitious targets in 2050</td><td colspan="2">Moderate: Unchanged targets</td></tr>
<tr><td>Economic growth in Europe/ Ger-many</td><td>Low</td><td colspan="3">Moderate</td></tr>
<tr><td>Divergence of European to Ger-man energy policy</td><td colspan="2">High</td><td colspan="2">Moderate</td></tr>
<tr><td>Regulatory level of legislation for the energy sector</td><td colspan="3">High</td><td>Moderate</td></tr>
<tr><td>Political targets regarding the share of renewable energy</td><td colspan="3">High</td><td>Moderate</td></tr>
<tr><td>Number of electric vehicles in Germany</td><td colspan="2">High</td><td colspan="2">Moderate</td></tr>
<tr><td>Political intervention in the con-ventional power plant fleet</td><td colspan="2">High</td><td colspan="2">Moderate</td></tr>
</table>

Two out of four scenarios (scenario 1 and 2) overfulfill the targets set by the government, whereas the other two scenarios are realizing the Energiewende as stipulated in the 2010/2011 energy concept (i.e. reduction of GHG emissions by 80 to 95 % compared to 1990 levels). An interesting outcome of the consistency analysis is that no combination is consistent where the CO_2-emission reduction targets set by the government are not met. Furthermore, it is remarkable that for each driver only two out of three specifications are selected in the consistent scenarios – so that there are considerable commonalities between the scenarios. Since the development of endogenous factors is derived based on model calculations, the remaining differences may nevertheless induce very different futures (see Blumberg et al. 2020).

Taking a closer look, the first scenario shows a future where the German Energiewende is overfulfilled and policy makers are interfering strongly in the transformation process. Two remarkable characteristics are a weak GDP-growth and low fossil fuel prices. The second scenario differs only in one characteristic: the moderate GDP-growth.

In the third and fourth scenario, several drivers have different realizations. The main difference between the two scenarios is that political interventions and the level of regulation are much stronger in the third scenario than in the fourth.

Overall, scenario 4 is closest to a business-as-usual projection whereas scenario 1 may be considered as the most disruptive. Yet even the achievement of the minimum government target for 2050 in scenario 4 would go beyond current trends – before the outbreak of the COVID-19 crisis an achievement of the 2020 intermediate target (– 40 % GHG reduction) was extremely unlikely in Germany. On the other hand, scenario 1 may align with the new realities that have emerged before and during the corona crisis: stronger focus on green investments and a lower economic growth. To get a better understanding of the obtained scenarios, a quantitative assessment using the indicators discussed in chapter 2.3.2 is yet advisable and thus provided in the following section.

3.3.2 Analysis of the consistency of the identified scenarios

In order to get a better understanding of the obtained scenarios and the interdependencies among the exogenous drivers, looking at the consistency and stability indicators for each driver is useful.

Table 7 shows the consistency as well as the stability indicator for each driver with its specific realization in each scenario. Their derivation is explained in chapter 2.3.2.

The consistency analysis shows that scenario 1 has the highest consistency indicator of 66 compared to the other scenarios. Here, the specific realization of political drivers are the ones which strengthen the consistency and this combination of driver developments is generally promoting each other strongly. Moreover, alternative developments of selected drivers do not seem to fit with the other ones since the stability indicator is relatively high.

Here, only the consistency value for the driver GDP growth is indifferent between the mid and the low development, which means that these realizations are equally supported by the other drivers' characteristics. This is also true for scenario 2, where in fact only this driver has a different realization than in scenario 1.

Table 7 Consistency values, consistency and stability indicators for the identified scenarios (realizations of the drivers in each scenario are printed in **bold**)

Exogenous Driver	Realization	Scenario 1		Scenario 2		Scenario 3		Scenario 4	
		C_j^{zj}	ΔC_j^{zj}	C_j^{zj}	ΔC_j^{zj}	C_j^{zj}	ΔC_j^{zj}	C_j^{zj}	ΔC_j^{zj}
Global price development for fossil fuels	High	0		-1		-1		-1	
	Mid	0	3	0	4	2	0	**3**	3
	Low	**3**		**4**		**2**		0	
Political targets regarding CO2 emissions	High	**7**		**4**		6		4	
	Mid	5	2	4	0	**6**	0	**9**	5
	Low	-3		-2		-2		-1	
Economic growth in Europe/ Germany	High	-1		-1		-1		-1	
	Mid	2	0	**2**	0	**5**	3	**5**	4
	Low	**2**		2		2		0	
Divergence of European to German energy policy	High	**11**		**13**		**8**		2	
	Mid	4	7	3	10	6	2	**7**	5
	Low	-6		-7		-4		-1	
Regulatory level of legislation for the energy sector	High	**11**		**11**		**7**		1	
	Mid	5	6	4	7	7	0	**7**	6
	Low	-5		-4		-4		-1	
Political targets regarding the share of renewable energy	High	**12**		**9**		**7**		5	
	Mid	7	5	4	5	7	0	**9**	4
	Low	-6		-5		-3		-2	
Number of electric vehicles in Germany	High	**6**		**3**		3		4	
	Mid	4	2	2	1	**4**	1	**7**	3
	Low	0		2		1		0	
Political intervention in the conventional power plant fleet	High	**14**		**13**		**10**		3	
	Mid	7	7	6	7	9	1	**10**	7
	Low	-6		-6		-4		0	
Consistency indicator $\hat{C}^{\boldsymbol{z}}$: sum of consistency values C_j^{zj} for selected realizations		66		59		49		57	
Stability indicator $\hat{S}^{\boldsymbol{z}}$: sum of ΔC_j^{zj} between consistency values for different realizations			32		34		7		38

Yet this different realization impacts the consistency values for the other drivers and overall scenario 2 obtains a slightly lower consistency indicator for the overall system. At the same time, the rating regarding the stability indicator is somewhat higher.

Similar observations can be made for scenario 4: again, the consistency indicator is slightly lower than for scenario 2 whereas the stability indicator is somewhat higher. This indicates that the various drivers are not as strongly supporting each other than in the previous scenarios yet a change in a single driver would not lead to a rather instable configuration instead of another stable scenario.

The third scenario has the lowest consistency indicator compared to the other scenarios. Also, the stability indicator is small which means that scenario 3 suffers from latent instability. A closer look reveals that the consistency values for prices for fossil fuels, CO_2 –emission-targets, the grade of regulation and the political targets for RES are all zero which indicates that another realization of the same driver would be equally consistent at least locally, regarding this factor.

Obviously, no consistency value in any scenario is negative, which is a prerequisite for a consistent scenario. This implies that each combination of realizations within the scenarios is supporting each other.

3.4 Resource efficiency

At first sight the use of a two-step approach may appear as an increased burden put on the contributing experts. Yet a small calculation illustrates that the proposed approach in fact improves resource efficiency, measured as the time experts spend on the assessments. We thereby compare the proposed two-step approach to a one-step application of the CIB approach.

The sole application of the CIB approach would also lead to a set of consistent scenarios, yet for our case study without the preceding identification of truly exogenous drivers (cf. 2.1.3 and 2.2.3), 39 potentially relevant factors would have to be considered.

For each of these 39 factors, we assume also an average of three possible realizations. This would lead to a matrix with 117 columns and rows. Experts would have to rate a total of 13.338 cells $(3 \cdot 39)^2 - 3^2 \cdot 39$ (i.e. each specification of all drivers against each other minus the cells where specifications of the same driver stand against themselves). Assuming that for each cell an expert needs 20 seconds per cell, the whole survey process would roughly take 74 hours per expert.

In the second stage of our approach, the matrix is reduced to eight drivers. With an average of three specifications the processing time reduces to 2.8 hours, which is relatively high, but correspond to only 3.8 % of the original time.

We yet have to add the time spent on the evaluation for the first stage. Here the full set of 39 drivers has to be considered but without differentiation of realizations. Also, the impacts are rated on a scale between 0 and 3 instead of -5 to 5 which may further speed up the evaluation process. But even disregarding this efficiency gain, the assessment would require ratings for 1444 (=38^2) cells, corresponding to a processing time of 8.0 hours.

So even if the two-stage process is quite time consuming for the experts, as it requires a total processing time of 10.8 hours, the procedure is speeded up by almost a factor seven compared to the single-stage approach. Alternatively, the single-stage approach would need to reduce the number of considered factors, which may be even worse as important aspects and interdependencies may be neglected.

4 Conclusion

In this paper we propose and apply a novel expert-assessment based approach which enables the determination of consistent scenarios in a two-step procedure. Contend-related, we focus on energy system transformation scenarios which aims to support decision making in the field of electrical network expansion planning with a focus on the distribution grid level.

In a first stage, the experts assess the strength of causal relationships between a large set of possible factors driving or constraining future energy system developments. Methodologically, a cross-impact approach is applied, where indirect and direct influences of factors are considered. More in detail, an adjusted approach of "ADVIAN" is used, where direct and indirect impacts are appropriately weighted, and an improved evaluation metric is used. The analysis of the introduced impact-weighting shows that with each indirect order the influence is weakened while in the original approach (almost) only the last order of the impact analysis determines active and passive scores. In order to derive exogenous drivers, an exogeneity score is computed as difference of the obtained active and passive values. For the selection of the most relevant ("truly") exogenous drivers, a method using the cumulative exogeneity score is moreover presented and deployed.

In the second stage, concrete realizations for the identified truly exogenous drivers are specified. These specified drivers are then used to construct consistent scenarios; i.e. several sets containing each exogenous driver in a specific realization. The construction process is carried out based on a second expert survey and applying the cross-impact balance (CIB) approach. Additionally, indicators to assess scenarios quantitatively are presented. Thereby a consistency and a stability indicator are defined, enabling a better understanding and valuation of the quality of scenarios.

The results reveal eight truly exogenous drivers comprising especially political and economic factors while factors belonging to grid expansion are classified as endogenous. This underpins the need of scenarios for the purpose of network expansion planning. As a major result, four consistent (descriptive) scenarios are identified and discussed in detail which may serve as input data for determining system relevant endogenous factors using numerical simulation (or optimization) models.

The proposed two step approach reduces the effort for constructing consistent scenarios and notably the required input by external experts, by preselecting the truly exogenous drivers in step one. Hence, small project groups – with limited resources and little time – are enabled to build their own scenarios instead of relying on scenarios proposed in the literature which may be inappropriate for the considered application case.

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Appendix 1: Preselection process for key factors

The 39 preselected key factors - used as starting point of our application case for the presented methodology in the paper at hand – are themselves a result of both a combination of desk research, literature review and intense discussions between the authors of this paper as well as a preselection process. In particular, desk and literature research led to 48 possible key factor which were then rated anonymously by 16 experts with a value between zero and five where zero is not important at all while five means extraordinarily important in the case of network extension planning scenarios with a special focus on distribution grids. Afterwards, each possible key factor received one point from each expert rating if its rating was above the average of all ratings from this specific expert. In total, each potentially relevant factor could hence obtain a "preselection-value" between 16 and zero.

Similar to the selection of exogenous drivers in chapter 2.2.3, we hereinafter selected the subset of key factors from all potentially relevant factors based on the cumulative preselection values. The target has been to ensure that the retained key factors cover at least 80 percent of the sum of the preselection values from all potentially relevant factors. In particular, the same five steps as in chapter 2.2.3 are conducted but instead of the degree of exogeneity Ex_i the "preselection-value" is used.

However, as the presented methodology in this paper was focusing on different aspects, we concede that this process could surely be improved by further research and/or be replaced by another process. Notably the selection of experts for this step was done uniquely among our colleagues within the House of Energy Markets and finance. Even though these colleagues are addressing a broad variety of fields within the energy sector, a larger group with even more heterogeneous backgrounds would have been desirable.

Appendix 2: Impact of indirect influences

Given the ratings of the ADVIAN approach which exceed 1 in many cases, the indirect impact typically raises steadily with higher orders. A sufficient condition for this "exponential behaviour" is that $as_i^1 \cdot a_{ii} > 1$ is true for at least one i and analogously that $ps_j^1 \cdot a_{jj} > 1$ is true for at least one j. Since the determinant of the matrix is the linear mapping (preserving or reversing the orientation) of the n-dimensional matrix into the n-dimensional space an alternative sufficient criterion is that abs(Det(A))>1 is fulfilled.

A small example is shown in Table 8 where the beforehand explained exponential behaviour is represented using the determinant of each order.

Table 8 Exponential behaviour of indirect influences

				$as_i^{(1)}$	*Determinant*
	0	1	0	**1**	
	1	0	2	**3**	2
	1	0	0	**1**	
$ps_i^{(1)}$	**2**	**1**	**2**	**5**	

				$as_i^{(2)}$	*Determinant*
	1	0	2	**3**	
	2	1	0	**3**	4
	0	1	0	**1**	
$ps_i^{(2)}$	**3**	**2**	**2**	**7**	

				$as_i^{(3)}$	*Determinant*
	2	1	0	**3**	
	1	2	2	**5**	8
	1	0	2	**3**	
$ps_i^{(3)}$	**4**	**3**	**4**	**11**	

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