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Investing in power grid infrastructure as a flexibility option: A DSGE assessment for Germany

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Abstract

This paper provides an approach to incorporate planned investments in power grid infrastructure in Germany, which intend to provide the necessary flexibility to integrate large shares of variable renewable energy sources into the power system, into a dynamic stochastic equilibrium model. Since the investments' economic impact remains unclear, this paper sheds light on two questions: Do power grid infrastructure investments in Germany have the potential to positively impact economic performance, particularly GDP and employment? Is power grid infrastructure investment an efficient way to provide flexibility to the electricity system? We find the potential for negative effects of power grid infrastructure investments on economic outcomes, which can, however, be mitigated by an adequate design of the investments and its framework conditions.

Keywords: DSGE analysis, infrastructure, Germany, electric grid, energy transition, flexibility

JEL Classification Nos.: C68, E61, O13, P18, Q43, Q48, Q56

List of abbreviations

ARegV	Ordinance on Incentive Regulation (*Verordnung über die Anreizregulierung der Energieversorgungsnetze*)
BEV	battery electric vehicles
BMWi	Federal Ministry of Economics and Technology
HH	households
LC	load curve
LDC	load duration curve
MRTS	marginal rate of technical substitution
NAPE	National Action Plan for Energy Efficiency (*Nationaler Aktionsplan Energieeffizienz*)
NK	New Keynesian
OPEX	operational expenditures

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	(*Bundesministerium für Wirtschaft u. Technologie*)	PF	production function
		PPF	production possibility frontier
BNetzA	Federal Network Agency (*Bundesnetzagentur*)	PPP	public private partnerships
		PtX	power-to-X
CAPEX	capital expenditures	RES	renewable energy sources
DSGE	dynamic stochastic general equilibrium	RLC	residual load curve
		RLDC	residual load duration curve
DSM	demand-side management	ROR	rate of return
DSO	distribution system operator	R&D	research and development
		SES	stationary energy storage
EE	energy efficiency	TFP	total factor productivity
EED	economic efficiency determinants	TSO	transmission system operator
		UF	utility function
EUR	Euro	USD	US dollar
FOC	first-order condition	VRES	variable renewable energy sources
GDP	gross domestic product		
GHG	greenhouse gases		

1 Introduction

Extensive investment requirements in power grid infrastructure will be an increasingly discussed issue throughout the decades to come. The International Energy Agency (IEA, 2018) has observed rising investment volumes worldwide over the last few years, amounting to US$ 300 billion (bn) in 2017, and predicts continuingly increasing trends. In Germany, the Federal Ministry of Economics and Technology (BMWi, 2019a,b) has observed investment volumes of nearly € 10 bn in 2017, and cumulated investments in just transmission grid infrastructure during the time periods from 2019 to 2030 respectively 2035 are estimated to amount to approximately € 60 respectively € 70 bn (NDP, 2019a-c).

In some cases, these substantial investments become crucial as the end of life cycles of existing power transmission and distribution infrastructure are reached, and worn-out infrastructure is to be replaced. Often, however, prospectively substantial investment volumes are induced by trends towards an increased valuation of sustainability in political targets, and a consequent wide-ranging transformation and re-design[1] of the current electricity system, of which the power grid is an integral component. Particularly, an aspired large-scale integration of variable renewable energy sources (VRES) into the electricity system and an aspired maintenance of high levels of security of supply entail the need for more flexibility within the system[2] (IEA, 2013; Blazejczak, 2013; TYNDP, 2018a,b; NDP, 2019a-c). Throughout all

[1] Including grid optimization, reinforcement and expansion. Objectives concerning sustainability in power generation have been defined in political processes and laid down statutorily in many economies worldwide, translating the normative shift in the power sector and beyond into concrete political goals.
[2] Renewable energy sources (RES) are integrated into the electricity system centrally and decentrally (definition see Art. 3 EnWG), while significantly reducing fossil fuel and nuclear generation. Fossil generation is to be reduced to

investments, technological progress and innovation enable to implement structural changes throughout the electricity value chain and make it possible to translate the targets into physical and technical reality.

As it is a variety of other than purely economic motives incentivizing the investments, macroeconomic impacts of power grid infrastructure investments remain widely unclear. Often, negative economic effects are suspected to prevail, as investment costs in power grid infrastructure are passed on to electricity consumers, which henceforth face considerably higher electricity prices. Resulting budgetary constraints are for instance conjected to threaten profitability and competitiveness of particularly the private sector economy (cf. Büdenbender, 2003; Monopolkommission, 2007; Britz et al., 2012). As opposed to this view, there are approaches emphasizing the potential to reconcile, or to even create synergies between, a transformation towards an equally reliable and more sustainable electricity system and increased macroeconomic performance. The currently observable main approaches therefore are twofold: Firstly, it is argued that targeted energy efficiency (EE) measures have the potential to at least partially decouple economic performance from energy consumption, and hence mitigate impacts of increased energy system costs (e.g. IEA, 2014b)[3]. Secondly, synergies between power grid infrastructure investments and economic performance are emphasized, i.e. via the role of infrastructure investments stimulating economic growth and its role in setting up a future-oriented energy system, which is able to adequately meet prospective system challenges and hence provides value added (e.g. Treasury, 2011; OECD, 2017a,b). Existing assessments, however, point to various and strong conditionalities under which those synergetic effects can prevail (e.g. Kirschen and Strbac, 2004; Flyvbjerg, 2009, 2013; Ansar et al., 2016). A central conditionality results from the fact that a multitude of potential development paths and target states during an electricity system transformation exists. For instance, power grid infrastructure investments are not the sole option to provide flexibility to the electricity system. Substitutes, which might be able to provide flexibility to a future-oriented electricity system in a more efficient way, especially from a long-term perspective, exist or have the potential to be developed, such as, *inter alia*, storage or power-to-X technologies.

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comply with greenhouse gas (GHG) reduction targets, nuclear power generation due to safety issues, particularly nuclear disasters and final disposal of radioactive material. Generally, the majour share of RES is planned to be generated from VRES, particularly wind and solar power. Due to VRES' generation patterns distinct from those of conventional generation, e.g. concerning time, lead-time and space (cf. Hirth et al., 2016), changed and intensified deviations between generation and load patterns in the power system must be compensated for, if system stability and thus security of supply shall be guaranteed. This requires a corresponding transformation of the power system towards one which is able to provide the flexibility necessary to bridge those deviations.

[3] The prevalence of those positive effects, however, is discussed controversially due to the potential occurrence of rebound effects, which suggest that increased EE ceteris paribus leads to energy price decreases and hence, via different links such as income or substitution effects, to an increased utilization of energy (e.g. Sorrell, 2007; Herring and Sorrell, 2008; Madlener and Alcott, 2009; Friedrichsmeier et al., 2015; Lutz and Breitschopf, 2016).

To create evidence concerning the to-date widely unexplored effects of power grid infrastructure investments on macroeconomic parameters, the analysis presented in this paper evaluates these effects by means of a dynamic stochastic general equilibrium (DSGE) approach and investigates the existence and magnitude of the potential conflicts described above. It further sheds light on determinants for economic efficiency[4] of power grid infrastructure investments. Hence, it provides rationally founded inputs for power grid investment decision-making processes and identifies potential areas and designs of policy interventions. This paper aims at a macroeconomic assessment of investments within the German national economy. As many other economies worldwide face similar challenges, and the transferability of considerations, and results might generate value added, descriptions are kept at the most conceptional level possible and specify them for the German case whenever necessary.

The remainder of the paper is organized as follows: In section 2, the DSGE methodology is introduced. In section 3, a literature review is provided, pointing to the lacuna intended to be addressed with this paper. In section 4, the theoretical foundations via which power grid infrastructure investments are incorporated in the DSGE model are presented. In section 5, the DSGE model is presented, which in section 6 is applied to the case of Germany. Section 7 provides conclusions and discuss the model results.

2 Methodology

In order to understand the dependency between power grid infrastructure investments and their induced macroeconomic effects, a small-scale DSGE model is set up, which allows to test the effects of power grid infrastructure investments on different macroeconomic parameters and under different framework conditions. DSGE models are comprehensive macroeconomic models, whose structure is strongly theory-founded. In the models, the national economy is represented as an economic cycle, subject to resource scarcity and having no internal sinks and sources. The structure of the economy is determined by its constituting actors, of which each can be modeled exhibiting distinct behavioural patterns. Further, the convergence of the economy towards an economic equilibrium state is assumed. Changes in the economy, which are not induced by market mechanisms, such as public sector interventions, appear as exogenous shocks

[4] Economic efficiency within a national economy generally refers to a state under which every scarce resource in this economy is allocated in such a way that overall welfare is maximized. In the case of power grid infrastructure investments, being motivated by sustainability and security of supply aspirations, the criterion of economic efficiency comes down to the target of conducting only those investments which allow for a maximization (minimization) of positive (negative) impacts on macroeconomic outcomes. This has an interesting implication: Economic efficiency is given, if the power grid infrastructure investment at issue impacts economic performance in the most positive way possible compared to its counterfactuals, i.e. its alternatives which equally contribute to sustainability and security of supply aspirations. Following this interpretation, economic efficiency is also given if its impacts on economic performance are the least negative possible.

to the model national economy, causing deviations from the national economy's equilibrium state. In the model presented in this paper, power grid infrastructure investments can be reflected as such an exogenous shock, as investments do not follow market mechanisms, but can in many economies be characterized as quasi-public investments (cf. Schreiner and Madlener, 2019).

The main reasons for choosing a DSGE approach are twofold. Firstly, its strong theory foundation allows to conceptionalize theoretical insights in a transparent way and incorporate them into one joint model. Secondly, the DSGE methodology provides great flexibility concerning the concrete model setup and dynamics. For instance, there is great freedom regarding which agents to incorporate, how to model their respective behaviour and how to design the dynamics of the overall economy.

3 Literature review

In existing literature, there are, to the best of our knowledge, no assessments of effects of power grid infrastructure investments on the overall national economy. Four strands of literature can be identified, indicated by (I) to (IV) in Figure 1, which are related to such an assessment. These approaches differ concerning the scope of the assessed cause for economic effects, and the scope of assessed effects. This paper contributes to the existing literature by explicitly assessing effects of power grid infrastructure investments on the overall national economy.

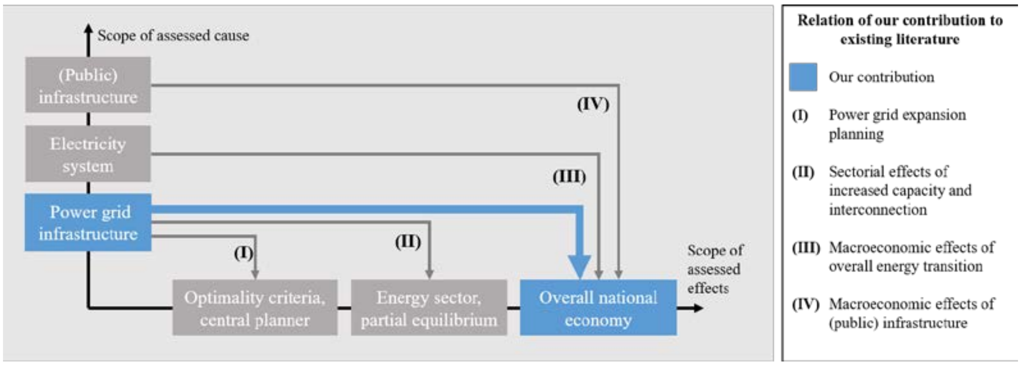

Figure 1: Literature classification based on causal relations assessed

3.1 Power grid expansion planning (I)

The literature on power grid expansion planning assesses effects of power grid infrastructure investments on defined optimality criteria, aiming at answering the question, which power grid infrastructure investments should be undertaken according to the criteria. Often, the assessments are based on optimization models, implying a central planner's approach. Power grid expansion planning provides the basis for power grid infrastructure investment decision-making as one of the key strategic decisions in a power systems context. Due to the intensified practical topicality of such decision-making in view of VRES integration targets and persistently high standards of desired security of supply, contributions consist of both stakeholder reports and studies, contributions from academic literature, which are closely affiliated[5]. Central stakeholder reports and studies on power grid expansion planning in Germany are the network development plans (NDP, 2012-2015, 2017, 2019a-c), which partially translate into statutory expansion plans in German legislation. They are embedded into a European context of the ten-year network development plans, set up by the national system operators and by ENTSO-e, respectively, based on own ratings under stakeholder consultation (TYNDP, 2010, 2012, 2014, 2016, 2018a,b). They are backed by additional reports set up and published by the partially state-owned German Energy Agency dena (dena, 2005, 2010, 2012, 2017c, 2018e) and stakeholders' planning approaches, such as Lumbreras and Ramos (2016). Publications from an academic context dealing with power grid expansion planning mostly provide optimization approaches in view of the target criteria of either overall system cost minimization, such as in Liu et al. (2013), Steinke et al. (2013), Budischak et al. (2013), Egerer et al. (2013, 2016), Henning and Palzer (2014), Palzer and Henning (2014), Rodríguez et al. (2014), Kemfert et al. (2016), Zhang et al. (2017) or Held et al. (2018), or overall maximization of expected objective value of investments, such as in Ecofys (2017), or multiple target criteria, such as in Hongbo and Yu (2000), El-Keib et al. (2006) or Chang et al. (2013).

Macroeconomic effects of power grid infrastructure investments are accounted for in contributions from this strand of literature mostly implicitly and partially, as far as macroeconomic target parameters overlap with the optimization or evaluation criteria deployed in the respective power grid expansion planning approach. Cost-minimizing optimization models for instance, in which future overall system costs are minimized given VRES integration targets and persistently high levels of security of supply, account for macroeconomic effects insofar as they are described by the macroeconomic target parameter of energy provision at the lowest possible cost. However, macroeconomic evaluation criteria are multiple and ambiguous in the sense that their selection and weighing is dependent on the underlying normative framework of the respective national economy considered. Furthermore, even if macroeconomic target criteria are well-represented in an optimization or evaluation criterion, flaws rooted in the rather narrow-sighted central planner's approach might distort optimal accounting for macroeconomic effects due to constraints *inter alia* arising from methodological inadequacy.

[5] Even though reports and studies are not published as academic contributions in the literature, their results are closely intertwined with academia, as results are often generated based on methodological approaches and findings from academic literature. Due to their rather blurry distinction from academic contributions, power grid expansion planning studies and reports are listed in this section.

3.2 Sectorial effects of transmission capacity and interconnection (II)

This strand of literature assesses sectorial effects of increased transmission capacity and interconnection in the electricity market, such as in Borenstein (2000), Bresesti et al. (2009), Valeri et al. (2009), Pozo et al. (2013), Wolak (2015) and Solli (2017). Contributions emphasize the role of power grid infrastructure as an enabler of electricity trade in a liberalized energy market setup. A reduction of congestion and increased market size are argued to lead to increased market efficiency. In an ideal case, the grid would exhibit characteristics of a "copper plate", i.e. a system not imposing any limitations to electricity transport. Those positive effects are traded off against costs induced by investments and operation and maintenance, respectively.

Macroeconomic effects of power grid infrastructure investments are accounted for as welfare effects in a basic economic sense, consisting of the total surplus in the electricity market.

3.3 Macroeconomic effects of the overall electricity system transition (III)

This strand of literature assesses macroeconomic effects of the sustainable energy transition or "*Energiewende*", i.e. all investments and operational expenses induced by the energy transition, particularly for the case of Germany. An explicit accounting for power grid infrastructure investments is not included.

Macroeconomic effects of power grid infrastructure investments as an integral part of the energy transition are implicitly accounted for as far as they are included in overall expenses. In most contributions, however, they are only included as a necessary condition for the realization of *Energiewende* targets, such as in Blazejczak et al. (2010, 2011a,b, 2013), Breitschopf and Held (2014), Fraunhofer ISI et al. (2014), DG Energy et al. (2014), IRENA and CEM (2014), GWS et al. (2014), Lehr et al. (2015), IRENA (2016) and Lehr et al. (2017). Literature contributions systemizing macroeconomic effects, such as Fraunhofer ISI et al. (2010), Lutz and Breitschopf (2016), Kreuz and Muesgens (2017) can be consulted to identify potential analogous macroeconomic causal relationships of power grid infrastructure investments.

3.4 Macroeconomic effects of (public) infrastructure investments (IV)

This body of literature investigates macroeconomic effects of (public) infrastructure investment, and particularly growth effects. Different types of infrastructure are considered jointly and at rather high aggregation levels, including for instance water, transport, information and communication technologies, waste and energy infrastructure. This body of literature establishes a link between general infrastructure and macroeconomic parameters, such as in Woodford, (2010a,b), Bom and Ligthart (2011), Flyvbjerg (2014), Younis (2014), Ansar et al. (2016), Gianelli and Tervala (2016), Stupak (2017) and Thacker et al. (2019), or between energy infrastructure and macroeconomic parameters, such as in Diffney et al. (2009), Payne (2010), Lindenberger and Kümmel (2011), Warr and Ayres (2012), Ayres et al. (2013), Carlsson et al. (2013), Ayres and Voudouris (2014), Bigerna (2015), Kümmel et al. (2015), Voudouris et al. (2015), Cust and Zhang (2016), Karakatsanis (2016), Best and Burke (2018) and Santos et al. (2018), and is widely based on micro-founded macroeconomic theories and particularly theories of growth. Various conditionalities are assessed, which determine the magnitude and nature of the relationship between infrastructure and growth, such as characteristics of the institutional regime, forms of financing and ownership structures, and particularities in the economic nature of infrastructure and related project commissioning, for instance in Pereira (2011), Arezki et al. (2016), Buffie et al. (2016) or Yoshino and Taghizadeh-Hesary (2018).

Macroeconomic effects of power grid infrastructure investments are included as one type of infrastructure amongst others. As aggregately assessed different types of infrastructure still exhibit considerable degrees of heterogeneity in their nature and concerning the investments' framework conditions, however, the assessment of macroeconomic effects is only significant as far as characteristics and framework conditions overlap with those of the representative aggregated infrastructure considered.

4 Theoretical foundations

In the following, four macroeconomic theory approaches are presented, which allow to create links between power grid infrastructure investments and macroeconomic parameters, such as business cycles, economic growth and employment. These links form the basis to set up the small-scale DSGE model for assessing macroeconomic effects of power grid infrastructure investments.

The four different theoretical links – Keynesian theories, neoclassical theories, energy economics theories and endogenous growth theories – allow to incorporate power grid infrastructure investments in distinct ways ("levers"), and also point to respective determinants for economic efficiency. Figure 2 provides an overview of the four different theoretical links, the respective incorporation of power grid infrastructure investments, as well as the respective economic efficiency determinants (EED), and points to the incumbency of the levers and EED, i.e. if they are more or less established in literature.

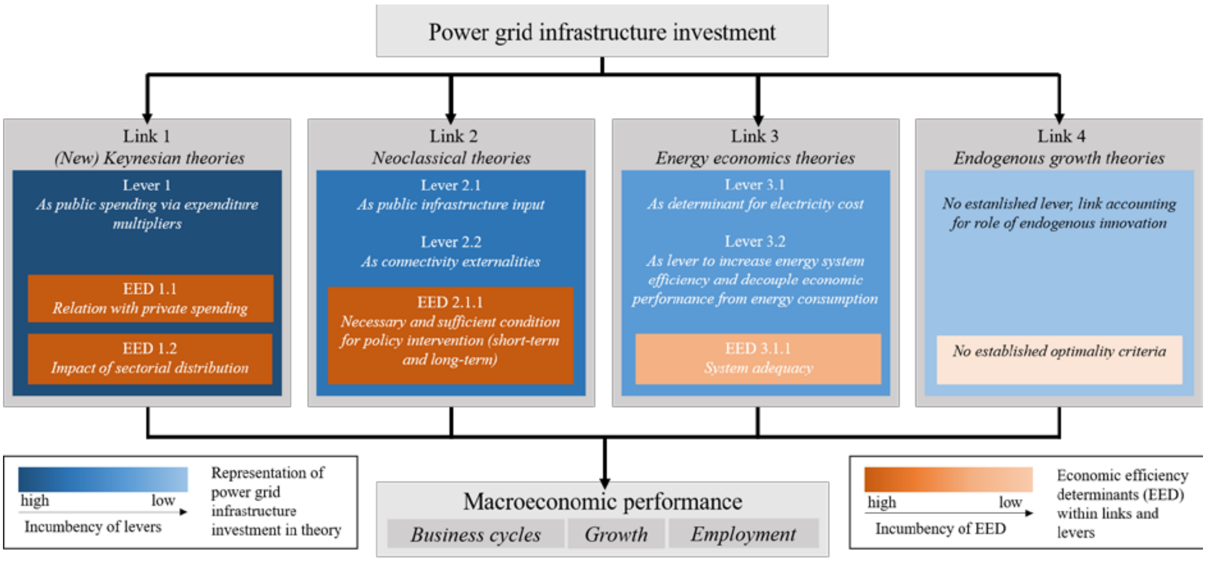

Figure 2: Theory foundations relating power grid infrastructure investments to macroeconomic outcomes

4.1 Power grid infrastructure investments in Keynesian theories (Link 1)

Keynesian theories[6], rooted in the seminal work of John Maynard Keynes (e.g. Keynes, 1936), in their initial school of thought are macroeconomic theories giving insights to causes for short-term business cycles. Central causes for those short-term fluctuations are different forms of changes in aggregated demand. Increasing demands lead to increases in economic activity or booms while depressions occur when demand decreases (Commendatore et al., 2003: 100). Due to the assumption that market failures prevail and no self-sustaining equilibrium exists[7], Keynesian theorists postulate – opposing a laissez-faire economic policy approach – that an economic policy[8] must intervene in an adequate way to channel short-term fluctuations in a way that economic performance can oscillate around a long-term equilibrium growth path and long-term recessions are avoided (cf. Harrod, 1939; Romer, 2012). In DSGE models, Keynesian theory can be reflected via sticky prices and imperfect competition (cf. Bergholdt, 2012).

4.1.1 Power grid infrastructure investments as public spending (Lever 1)

Quasi-public power grid infrastructure investment is represented in Keynesian or new Keynesian (NK) theory as a form of public spending. As such, it is a means of fiscal intervention with the goal to stimulate economic activity and increase employment by publicly compensating for a lack in private demand (cf. Woodford, 2010a,b).

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[6] Further developed to New Keynesian (NK) theories, adding microeconomic foundations to the macroeconomic constructs (e.g. Harrod, 1939, 1948, 1964, 1973; Kaldor, 1956, 1958, 1961; Steedman, 1972; Robinson, 1956, 1962; Kalecki, 1971) and to Neo Keynesian theories, bringing together Keynesian theory with the neoclassical equilibrium thought.

[7] This is especially the case as households (HH) show adverse preferences in view of spending during economic recessions.

[8] Generally, two types of market interventions exist: Firstly, governments can intervene with their fiscal policy, secondly, central banks with their monetary policy.

4.1.2 EED in Keynesian theory (EED 1)

Public demand, i.e. public spending, is adduced as the central means of policy intervention. It is irrelevant, whether this spending occurs in the form of consumption or investment. What is relevant, however, is the mode of financing of public spending. Put simply, increased public spending can be either financed by means of taxes or by public debt. Hence, in order to optimally exploit positive effects, it must be assessed to which degree public spending should be debt-financed. As stated by the Ricardian Equivalence (cf., e.g., Barro, 1974), aggregated public expenditures must sooner or later be financed by means of taxes as – given interests on debt larger than zero – they cannot indefinitely be debt-financed as otherwise the no-ponzi condition[9] would be violated (Costa Junior, 2016). Hence, cumulated over time, the amount of taxes levied for financing public expenditures reduces the budget for private spending. It is the basic idea that government spending should occur in an anti-cyclical mode: Whenever there is a recession during which private demand is low, the government should compensate. Whenever there is a boom and private spending and demand are high, the government should save and recover its expenses, i.e. should reduce its debt (Abiad et al., 2015).

4.2 Power grid infrastructure investments in neoclassical theories (Link 2)

While Keynesian theories typically focus on short-term economic activity, neoclassical theories assessing macroeconomic outcomes, introduced by the seminal work of Solow and Swan (1956), make an attempt to explain and model long-term growth. According to neoclassical economics theory, national economies are assumed to converge to the economy's steady state. Growth is caused by factors exogenous to the model[10], and must eventually cease in the absence of exogenous shocks. In micro-founded exogenous growth models, actors' behavior is conceptionalized by means of neoclassical production functions (PF) and utility functions (UF) (Barro and Sala-i-Martin, 2004: 27f). An approach to establish a link between power grid infrastructure investment as a subset of public infrastructure[11] and growth is the inclusion of public infrastructure as an additional factor into the neoclassical HH and firms' behavioural functions (Barro and Sala-i-Martin, 2004: 27f), here in the Cobb-Douglas form

$$Y_t = A_t K_t^{\alpha} L_t^{\beta} \tag{1}$$

[9] The no-ponzi condition gives the constraint to fiscal policies that public debt interests cannot be financed by means of the issuance of new debt, as otherwise the government's intertemporal budget constraint would be violated (Costa Junior, 2016: 187ff).

[10] Population growth or exogenous technological shocks.

[11] Public infrastructure is defined here in a very broad sense, including all forms of physical and, depending on the respective underlying definition, also non-physical infrastructure such as *inter alia* transport, water, waste, energy or information and communication infrastructure.

where Y_t denotes the aggregated total output of the national economy's private sector firms, K_t the input factor private capital, L_t the input factor private labour, α and β the substitution elasticities; A_t is the national economy's total factor productivity (TFP) expressing the level of technological efficiency, and the index t denoting the time period considered. The inclusion can follow two distinct approaches: As an additional input factor to private sector behavioural equations, or as connectivity externalities.

4.2.1 Additional input factor to private sector behavioural equation (Lever 2.1)

Power grid infrastructure as one type of public infrastructure can be included as an additional input factor to private sector firms' PF or, alternatively, in the HH UF, and power grid infrastructure investment accordingly as an increase in the amount of public infrastructure provision (cf. Bom and Ligthard, 2014: 892; Costa Junior, 2016). The approach to account for public infrastructure capital by means of its inclusion in the private sector firms' PF of the form with public capital G_t can be specified as

$$Y_t = A_t K_t^{\alpha} L_t^{\beta} G_t^{\gamma} \; . \tag{2}$$

The influence of the private sector's output has been introduced in seminal theoretical works by Aschauer (1987, 1989a,b). Barro (1990) and Barro and Sala-I-Martin (1992) similarly. The latter, more generally, establish a macroeconomic link between public services and private sector output by the inclusion of public services in the private sector PF. Both approaches argue that the provision of public infrastructure capital or services alters the factor productivity within private sector firms' production functions and hence the overall economy's TFP. A similar link between the provision of public services and HH utility by an inclusion of consumption of public services in the HH utility function is established by Barro (1981), Aschauer (1985) and Aiyagari et al. (1992), respectively. Based on these seminal works, a body of literature has developed refining the exact dependency relations and conditionalities of these macroeconomic links, as summarized e.g. in El Makhloufi (2011), Palei (2015) and Ansar et al. (2016).

4.2.2 Connectivity externalities (Lever 2.2)

Power grid infrastructure can be further conceptionalized as exhibiting positive connectivity externalities, impacting private sector firms' production functions, as formulated via the inclusion of a connectivity parameter (Braess, 1968; Sutherland et al., 2009; Lakshmanan, 2011). The PF then includes a connectivity parameter Φ, and the according PF is

$$Y_t = A_t \Phi K_t^{\alpha} L_t^{\beta} . \tag{3}$$

Connectivity is defined as the potential of economic agents to exchange goods and services across space and physically allows for trade. Economic agents can hence exploit their comparative advantages and extend their production possibility frontier (PPF) to larger production volumes given constant inputs of their production factors (cf. Carlsson et al. 2013). Even though this line of argument has been predominantly used for transport infrastructure such as roads and railways, interpreting power grid infrastructure as transport infrastructure for electricity, the argumentation of this theoretical foundation can be applied in an analogous way.

4.2.3 EED in neoclassical theory

Determinants for economic efficiency of power grid infrastructure investments are predominantly related to the optimal interplay of private sector action based on market mechanisms and interventions of the public sector. Generally, neoclassical, and particularly institutional theory suggest that the interplay is efficient, if the public sector intervenes only, if necessary and sufficient condition for a public sector intervention[12] are fulfilled.

Related to these conditions for economically efficient policy intervention, a theory strand has evolved, which investigates the productivity of public infrastructure capital, as on a macro level represented by G_t in the aggregate private sector PF in Eq. (2) (cf. Pritchett, 2000; Durlauf and Aghion, 2005; Ansar et al., 2016). Essentially, it investigates conditions under which a public provision of infrastructure is economically efficient instead of its provision by the private sector. Put differently, potential market failure and potential regulatory failure have to be jointly minimized in order to achieve an efficient setup. Therefore, EED are twofold.

Potential market failure in (quasi-)public infrastructure provision (EED 2.1)

Power grid infrastructure exhibits a variety of special characteristics deviating from those of a perfect good in economic theory. Those special characteristics can lead to various potential distortions of perfect competition and hence induce market failure. Economic particularities of power grid infrastructure are subject to the broader theoretical fields of network economics and particularly of power system economics. Rooted in these theory strands, the prevalence of two main groups of market failure can be identified, being natural monopoly characteristics of the power grid and its connectivity externalities (cf. e.g. Kirschen and Strbac, 2004; Shy, 2011).

Potential regulatory failure in (quasi-)public infrastructure provision (EED 2.2)

Policy interventions and the design of an institutional regime including the regulatory design can be by itself a source of various economic inefficiencies. Main sources of inefficiencies are an inefficient regulation or market design[13], the so-called investment coordination problem in

[12] As well known, the necessary condition is fulfilled if market failure prevails, the sufficient condition if market failure exceeds the regulatory failure which comes along with the policy intervention (cf. e.g. Varian, 2011).

[13] The Averch-Johnson effect (Averch and Johnson, 1962) describes the lack of incentives for efficiency increases for regulated power grid providers, which often face considerable costs in the case of congestion. Incentives for over-investment are described e.g. in Kirschen and Strbac, (2004) or Goetz et al. (2014). Improvement approaches for regulatory design can be for instance found in Fuhr (1990), Cambini and Rondi (2010), Evans and Guthrie (2012) Haucap and Pagel (2014) or Poudineh (2017). Efficient market designs are discussed for instance in Pollitt and Anaya (2015) and Cramton (2017).

partially liberalized electricity sectors[14], inefficient investment project execution of public investments (cf. Flyvbjerg et al, 2003; Flyvbjerg, 2009, 2013), the impact of time-inconsistent policies (cf. Pollitt, 2012; Brendon and Ellison, 2017; Baldwin, 2018), and the issue of investment finance of public investments[15].

4.3 Theories of growth related to energy economics (Link 3)

Theories of growth related to energy economics are partly based on neoclassical growth models and utilize that theoretical framework as the basis of this line of argument. In distinction to the theoretical approaches presented above, they explicitly account for the role of energy and the energy system as a determinant for macroeconomic outcome. In times, they implicitly neglect the assumption of the validity of the first welfare theorem, in a sense that they often focus on technical instead of economic drivers for growth.

In neoclassical theories of growth related to energy economics, energy or useful energy[16] E_t is included in the private sector firms' production function as a third input factor with a certain substitution potential with regard to labour and capital (cf. Allen, 2009; Millard, 2011; Wrigley, 2010), i.e.

$$Y_t = A_t K_t^{\alpha} L_t^{\beta} E_t^{\delta}. \tag{4}$$

Energy, or useful energy, is argued to contribute to economic growth via two distinct levers: The first lever points to the importance of the affordability, i.e. of the provision at low prices, of energy as an important input factor to private sector production (cf. Ayres et al., 2013). The second lever is argued to be the role of energy systems as "technology incubators" with the role of decoupling economic growth from energy consumption, i.e. via energy efficiency (cf. Ayres and Voudouris, 2014).

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[14] The coordination problem is underpinned by New Institutional Economics, i.e. the Theory of the Firm (Coase, 1937). It discusses, to which extent coordination is efficient to take place amongst private sector firms based on market mechanisms, and to which extent it is efficient to be centralized. The locational spread between generation and load strongly determines the need for power grid infrastructure provision and determines the magnitude of investment requirements. Efficient investment can therefore only be achieved if investments into generation and power grid infrastructure are jointly optimized under consideration of the loads' locations. The introduction of market structures to formerly integrated and state-owned utilities entails a separation of organizational and informational structures (cf. Bonanno, 1988; Höffler, 2011; Meyer, 2012a,b; Borenstein and Bushnell, 2015; Heim, 2018). If the necessary decentralized coordination via market mechanisms, particularly efficient prices indicating scarcity, is flawed and the possibility of cheap talk is inhibited, inefficient investment decisions in both generation and power grid infrastructure will result (cf. Aumann, 2003; Brunekreeft, 2015).

[15] The impact of different modes of finance plays a crucial role in power grid infrastructure investment as a quasi-public infrastructure. For instance, efficient capital availability and cost, risk allocation as well as the timely distribution of investments are subject to investigation (cf., e.g., Flyvbjerg et al., 2014; Mayer et al., 2018).

[16] Instead of simply including energy as a third input factor into the private sector firms' PF, it is argued that, accounting for laws of thermodynamics, only those shares of total energy can be productive which exhibit sufficiently low levels of thermodynamic entropy. Hence, total energy must be divided into "waste energy", whose levels of thermodynamic entropy are so high that it cannot be used to perform physical work, and "useful energy", or "exergy", exhibiting sufficiently low levels of thermodynamic entropy and hence having the potential of being economically productive (cf. also Sorrell, 2007; Karakatsanis, 2016).

4.3.1 Power grid infrastructure investment decreasing electricity cost (Lever 3.1)

The specific role of power grid infrastructure provision and investment is not subject to the theory strand introduced above. However, the economically efficient power grid infrastructure provision and investment has the potential to lead to optimal electricity prices (c.f. Kirschen and Strbac, 2004; Diffney et al., 2015) and hence can impact economic performance via the lever of incorporating energy as an important input factor to private sector production (Lever 2.1).

4.3.2 Power grid infrastructure as a lever for energy efficiency increases (Lever 3.2)

Again, the specific role of power grid infrastructure provision and investment has not been subject to the theory strand introduced above. However, power grid infrastructure is a core component of the electricity and hence the energy system. Further, it is considered that theories of growth related to energy economics suggest that technological progress and innovation towards increased levels of energy efficiency have the potential to decouple economic performance from energy consumption (cf. Deutch, 2017). Following the same argumentation, it can hence be assumed that investment in more efficient power grid infrastructure has the potential to contribute to economic performance.

4.3.3 EED in energy economics

While neoclassical theories postulate the first welfare theorem, enabled by efficient interventions and institutional regimes (as postulated by the second welfare theorem), there are doubts if this theoretical assumption is applicable to the real-world case of energy, and if it was, whether a state of efficient markets could ever be reached. These doubts especially have arisen due to very particular physical and technical constraints rooted in the nature of energy and the electricity system and its particular role in enabling economic activity (cf. Böhmer et al., 2015; Lutz and Breitschopf, 2016).

The theory strand of energy economics therefore *inter alia* investigates these particularities, with regard to the entirety of the electricity system including the ways in which market mechanisms are impacted by the physical nature of electricity, how it generates value and which purpose it fulfils, and how it affects the environment in which economic activity takes place. At least in those strands within energy economics closely intertwined with environmental economics, energy economics on the theoretical level thus accounts for the more or less recent normative shift towards an increased valuation of sustainability. The theory strand of energy economics hence strives for the same normative target of efficient provision of the good and service electricity. However, it investigates the question of optimality and system adequacy through a different theoretical lens.

Power grid infrastructure investment as a flexibility option (EED 3.1)

Investment optimality in power grid infrastructure in energy economics theory is investigated in view of its optimal contribution to electricity system adequacy in order to provide electricity in a sense that it creates optimum value for its users[17]. Due to the particular physical characteristics of electricity, in an adequate electricity system, power supply and demand must match. Approaches to conceptualize the nature of the match of supply and demand include the residual load duration curve (RLDC), which indicates the cumulated mismatch between supply and demand within a defined time frame (cf. Ueckert et al., 2011, 2013, 2015). In this conceptualization, the nature of the mismatch is not further specified. Approaches to do so exist for instance in Hirth et al. (2016), who further identify three dimensions along which the matching between supply and demand can be indicated: A timely dimension, which is also prominently depicted in the RLDC conceptualization, a lead-time dimension, particularly taking into account the dynamics of timely delays between flexibility requirements and provision[18], and, finally, a spatial dimension, indicating locational deviations between supply and demand.

Flexibility options hence denote those measures, which can be taken to decrease the mismatch between supply and demand. In the RLDC conceptualization, the deployment of flexibility options decreases the deviation between the supply and demand patterns. In the three-dimensional conceptualization, the deployment of flexibility options increases the match between supply and demand in each of the dimensions. The magnitude of influence in each dimension is strongly determined by the exact nature of the flexibility option deployed.

To characterize the value of power grid infrastructure in the electricity supply system, the physical nature of electricity and its impacts on the role of power grid infrastructure in guaranteeing security of supply and trading electricity as a commodity are crucial to understand. The physical nature of electricity can be brought down to two core characteristics impacting the role of the power grid: Firstly, electrical energy can only be stored to a very limited extent, concerning the storable amount, the storage duration and the injection and withdrawal patterns. Also, storage of electrical energy is associated with poor degrees of efficiency and hence with high losses. Therefore, electricity supply and demand are required to match to a great extent in a timely dimension. Secondly, as locations of supply and demand are seldomly congruent and the divergence is reinforced by the requirement for congruency in a timely dimension, the transportation of electricity between locations of supply and demand becomes necessary in order to guarantee security of supply at any time. The transportation of electricity requires a very

[17] The final consumer value created by the electricity sector is electricity provision at the desired time and location, which is further defined as the good “electricity supply”.

[18] For instance, power plants often take long ramp-up times until they can generate and provide electricity.

physical system with very specific features, which functions much faster than any market and in which voltage and frequency of power – and, depending on the concrete technological design, reactive power – are balanced at any moment in time (cf. Kirschen and Strbac, 2004; Goetz et al., 2014).

Hence, power grid infrastructure to a certain extent can be interpreted as a prerequisite or at least as a means to match power supply and demand. In this sense, it can be conceptualized as one potential flexibility option which can be deployed to contribute to re-match supply and demand in view of intensified VRES integration. A determinant of optimality of power grid infrastructure investment is hence whether power grid infrastructure is the most economically efficient flexibility option, compared to its potential substitutes.

Power grid infrastructure investment and energy efficiency (EED 3.2)

Depending on the theory strand of energy economics, the normative target criterion of economic efficiency is at least partially substituted by the normative target criterion of energy efficiency in a physical sense, accounting for adverse environmental effects imposed by energy generation and consumption (cf. Ayres et al., 2018). The two target criteria differ from each other in the following way: While economic efficiency is reached if overall (economic) welfare is maximized, energy efficiency in a physical sense aims at a maximization of the technical degree of efficiency of the electricity system. The discussion in how far such a target criterion is expedient as a determinant for investment optimality is rooted in the discussions about rebound effects, according to which reducing effects of technical energy efficiency on overall energy consumption are, at least partially, cannibalized by economic reactions to the changes in energy efficiency, and due the costs associated with the implementation of energy efficient technologies.

4.4 Theories of endogenous growth (Link 4)

Endogenous growth theories incorporate model-endogenous mechanisms inducing economic growth. The rate of growth is sensitive to the rate of factor accumulation (cf. e.g. Romer, 1986; Lucas, 1988; Rebelo, 1991)[19], and technological progress is modeled as caused by economic innovation activity, undertaken by agents and thus based on – more or less – rational decision-making (cf. Benassy, 2011). Endogenous growth models, following seminal work of Schumpeter (1942), incorporate economic innovation activity into the growth model. Initially, this theoretical approach opposes the neoclassical approach assuming the convergence of national economies towards an equilibrium steady state. Instead, it assumes a process of creative destruction, in which existing economic structures are destroyed and re-emerge in a different form recurringly.

[19] The rate of factor accumulation can be modeled as a growth determinant under the assumption of constant returns to scale of the accumulated factors. This assumption, however, seems not to withstand empirical examinations which reveal total returns to traditional accumulated factors of less than unity (Benassy, 2011: 183)

Later theory and modelling approaches merge this approach with the neoclassical equilibrium theory, assuming a long-term stable growth pass and hence the convergence towards a constant trend. “Detrending” the model allows to finally receive a steady state within the model (cf. Roszypal, 2016; Harada, 2018). The basic idea behind the incentive for economic agents from the private sector to undertake innovation is the following: In addition to the final goods sector acting under perfect competition, an intermediate goods sector is conceptionalized that produces goods and services which the final goods sector deploys as input factors to its production. It is assumed that the intermediate goods sector faces monopolistic competition and is hence not a price taker but a price setter. It can therefore make profits in the long term. With this potential for profits, all firms in the intermediate goods sector decide whether they perform innovation activities dependent on their potential future profits.

Two distinct mechanisms can be found in theoretical approaches to explain the dependency relations during the innovation process within the intermediate goods sector (cf. Grossman and Helpman, 1994; Xie, 2000). Both mechanisms follow the rationale that innovation, which is exclusively applied by a firm as protected with patents, can generate competitive advantages. In the first mechanism, competitive advantage results from diversification of the firm’s production portfolio, in the second case from productivity increases within the existing firm’s production[20]. On the macro level, aggregating all intermediate sector firms’ activities, both types of innovation processes lead to increases in the overall TFP, as represented by the factor A_t in the private sector production function presented in Eq. (4). They hence make an approach to endogenously explain the variable, which in neoclassical economic theories of growth could only be altered via exogenous shocks. Based on these initial ideas, many theory strands have developed, further investigating the way and the particularities of innovation as a determinant of macroeconomic performance (cf. Xie, 2000).

4.4.1 Power grid infrastructure in endogenous growth theory (Lever 4)

The role of quasi-public power grid infrastructure investment on private sector innovation activity is not subject to a theory strand yet. However, this theory foundation can be incorporated

[20] The first mechanism, based on diversification, is based on models related to the seminal work of Romer (e.g. 1987, 1990), intermediate goods firms have the incentive to buy the knowledge on how to produce in a technologically superior way, i.e. innovative goods in the form of patents from an also monopolistically competitive innovation sector. Patents give their owners the exclusive right to produce and sell the respective innovative good and hence make profits and outperform their competitors. On a macro level, innovation activity, i.e. the invention of new products, leads to increases in the overall product variety within the national economy, causing growth based on increased “returns to diversification”. The second mechanism, based on productivity increases, is based on work of *inter alia* Aghion and Howitt (1992), Grossmann and Helpman (1991a,b) and Young (1998), who in an analogous sector setup assume that monopolistically competitive intermediate goods firms have the potential to increase their individual competitiveness by buying patents for innovative production technologies from the innovation sector. They thus can increase their production efficiency and hence generate competitive advantages compared to other intermediate goods producers and make profits.

in a macroeconomic assessment of power grid infrastructure investment to assess the role of innovation in a more sophisticated way, as further laid out in Section 5.

4.4.2 EED in endogenous growth theories (EED 4)

As laid out, innovation activities in endogenous growth theories are part of private sector business activities and as such connected to cost-benefit considerations of the respective company and dependent on prospective related profits. Furthermore, lock-in effects and path dependencies may play a considerable role for optimality (cf., e.g., Shy, 2011).

Due to this dependency relation, an interaction between power grid infrastructure investments impacting private sector profits with private sector innovation activities might occur. The question of optimality hence arises from considerations of the way in which innovation activities are efficiently allocated and if crowding-out or crowding-in effects of regulated investments prevail. This optimality determinant has not yet been established in the literature.

5 The DSGE model

5.1 Model structure

The model's fundamental structure incorporates five sectors: A HH sector, a private sector producing final goods and an electricity supply sector, which aggregates inputs from a private electricity sector and a regulated electricity sector, as depicted in grey colour in Figure 3. A closed national economy is modeled, assuming there is no international trade[21]. Power grid infrastructure investments are incorporated in the model as quasi-public infrastructure investments, undertaken by the regulated electricity sector. Investments are financed by means of quasi-taxes in the form of network charges, i.e. quasi-taxes, or debt capital. Potential extensions to the model are depicted in green colour. They include sectors enabling the incorporation of endogenous innovation into the model on the one side, and the incorporation of international trade on the other side.

Also, note the following regarding the model's applicability to different national economies: As it is our goal to apply the model to assess power grid infrastructure investments in Germany, the general structure of our model is tailored to the German national economy, as much as necessary and as little as still expedient. Therefore, especially structural features describing the electricity sector and power grid infrastructure investments specifically are based on the German case. As our model exhibits a rather high level of abstraction, the model has the potential to be transferable to other national economies with similar structural features.

[21] The purpose of this paper is to establish a first quantitative estimation of the different macroeconomic effects of power grid infrastructure investments in Germany. Investigating international effects and the impact of cross-border grind linkages might prove to be fruitful in future analyses building on the approach presented in this paper.

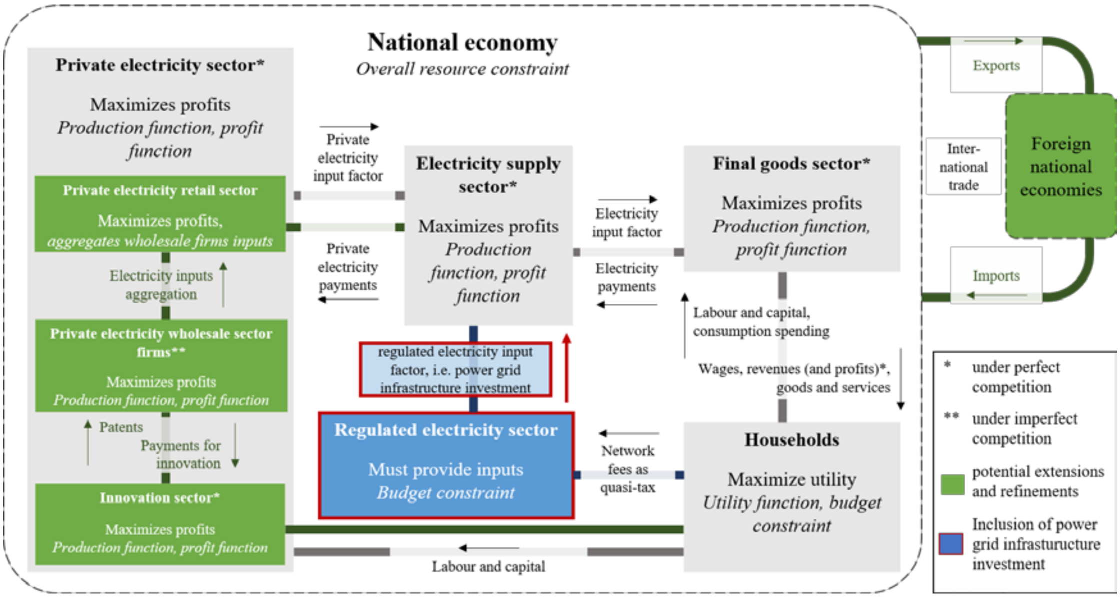

Figure 3: Overall DSGE model structure including potential extensions

5.2 Constituting equations

The model's constituting equations describe the behaviour of each sector included. The way in which power grid infrastructure investment is incorporated in the equations is based on the theoretical foundations presented in Section 4, see Appendix A for details. Table 1 provides an overview of the model's constituting equations[22] for each sector and the way in which power grid infrastructure investment is incorporated in the model structure. The model's steady state (SS) equations as well as their corresponding solutions are shown in Table B.5 and Table B.6 Appendix B.

Table 1: DSGE model's constituting equations and theory incorporations

Sector	Definition	No.	Equation	Power grid inc.
Household	Total labour provision	(5)	$L_t = L_t^G + L_t^{EP}$	n.a.
	Law of motion of private capital	(6)	$K_{t+1} = (1-\delta)K_t + I_t$	
	Total private capital provision	(7)	$K_t = K_t^G + K_t^{EP}$	
	Labour supply function	(8)	$C_t(L_t)^\eta = W_t$	
	Euler equation private capital	(9)	$\frac{C_{t+1}}{C_t} = \beta[(1-\delta) + R_{t+1}]$	
	Euler equation bonds	(10)	$\frac{C_{t+1}}{C_t} = \beta R_t^B$	
Final goods sector	Final goods sector production function	(11)	$Y_t = A_t^G (K_t^G)^\alpha * (A_t^E E_t)^\xi * (L_t^G)^{1-\alpha-\xi}$	***Link 3*** *Levers 3.1 and 3.2*
	Private capital deployment	(12)	$K_t^G = \alpha \frac{Y_t}{R_t}$	
	Electricity supply deployment	(13)	$E_t = \xi \frac{Y_t}{P_t^E}$	***Link 1****

[22] Concerning the variables, three types can be distinguished: Parameters, which are deep structural variables of the considered economy and which remain constant in the long run, or at least during the considered time period. Endogenous variables, whose values are determined within the model by the model dynamics and exogenous variables, which can be altered, i.e. "shocked", and are determined exogenously.

	Private labour deployment	(14)	$L_t^G = (1-\alpha-\xi)\frac{Y_t}{W_t}$	
	Price level relation	(15)	$1 = \frac{R_t}{\alpha A_t^G}\left(A_t^E \frac{\alpha P_t^E}{\xi R_t}\right)^{\xi} * \left(\frac{\alpha W_t}{R_t(1-\alpha-\xi)}\right)^{1-\alpha-\xi}$	
Electricity supply sector	Electricity supply sector production function	(16)	$E_t = V_t * \Phi_t * (U_t S_t^{EG} EG_t)^{\varepsilon} * EP_t$	***Link 2*** *Lever 2.1* *Lever 2.2*
	Electricity services sector private electricity FOC	(17)	$P_t^E = \frac{P_t^{EP} EP_t}{E_t}$	***Link 3*** *Lever 3.1*
	Inputs from regulated electricity sector	(18)	$EG_t = EG_t^A + EG_t^{TD}$	
	Law of motion of power grid infrastructure capital	(19)	$EG_{t+1}^{TD} = (1-\delta^{TD})EG_t^{TD} + I_t^{TD}$	
Private electricity sector	Private electricity sector production function	(20)	$EP_t = S_t^{EP} K_t^{EP\,\vartheta} L_t^{EP\,1-\vartheta}$	***Link 4****
	Private capital deployment in the private electricity sector	(21)	$K_t^{EP} = \vartheta EP_t \frac{P_t^{EP}}{R_t^{EP}}$	
	Labour deployment in the private electricity sector	(22)	$L_t^{EP} = (1-\vartheta) EP_t \frac{P_t^{EP}}{W_t}$	
	Price level in the private electricity sector	(23)	$P_t^{EP} = \frac{1}{S_t^{EP}}\left(\frac{W_t}{(1-\vartheta)}\right)^{1-\vartheta}\left(\frac{R_t^{EP}}{\vartheta}\right)^{\vartheta}$	
Regulated electricity sector	Regulated electricity sector's budget constraint	(24)	$\frac{B_{t+1}}{R_t^B} - B_t + N_t = P_t^A EG_t^A + P_t^{TD} I_t^{TD} + P_t^D D_t$	***Link 2***
	Innovation efficiency	(25)	$S_{t+1}^{EG} = S_t^{EG} + \mu D_t$	
	Share of network fee over debt finance	(26)	$\Psi_{NB} = \frac{N_t}{B_t}$	
Overall resource constraint	Final goods market equilibrium	(27)	$Y_t = C_t + I_t + EG_t^A + I_t^{TD} + D_t$	n.a.

* Link can be implemented in future work.

6 Model application to the case of Germany

6.1 Model parametrization

In the following, the model parametrization for the case of Germany is presented. Therefore, a distinction is made between two types of parameters: General parameters, describing the German national economy on a generic level, are included in existing models for the German economy and can hence be extracted from pertinent literature. Specific parameters are explicitly related to power grid infrastructure investment and are not included in general models of the German national economy. They are estimated based on literature explicitly dealing with relevant considerations within the electricity sector. The determination of specific parameters is discussed in more detail in Appendix C. Table 2 provides a summary of our model's parametrization.

Table 2: Model parametrization for the case of Germany

Parameter	Type	Description	Value min	Value max	Model value	Source
α	General	Output elasticity of capital in the final goods sector	0.38		0.38	Lindenberger and Kümmel (2011)
β	General	Discount factor	0.995	0.998	0.9965	Iwata (2013), Hristov (2016)

δ	General	Depreciation rate of private capital	0.025	0.25	0.1375	Hristov (2016)
δ^{TD}	Specific	Depreciation rate of power grid infrastructure capital	0.0167		0.0167	See Appendix C
ε	Specific	Output elasticity of quasi-public power grid infrastructure	0.001		0.001	See Appendix C
η	General	Marginal disutility with respect to labour supply (reciprocal value of Frisch elasticity of labour supply)	1.4286		1.4286	Keane and Rogerson (2012), Chetty et al. (2013), Gianelli and Tervala (2016)
ϑ	Specific	Output elasticity of capital in the private electricity sector	0.41		0.41	Fan et al. (2016)
μ	Specific	Efficiency of R&D activities of the regulated electricity sector	0.025		0.025	Harada (2018)
ξ	Specific	Output elasticity of electricity supply in the final goods sector	0.47		0.47	Lindenberger and Kümmel (2011)
p^A	Specific	Relative price level (cost) for ancillary services	1		1	See Appendix C
p^{TD}	Specific	Relative price level (cost) for power grid infrastructure investment (transmission and distribution)	1		1	See Appendix C
p^D	Specific	Relative price level (cost) for regulated electricity sector's R&D activities	1		1	See Appendix C
$1-\alpha-\xi$	General	Output elasticity of labour in the final goods sector	0.15		0.15	Lindenberger and Kümmel (2011)

6.2 The shocks

In the following, the shocks applied to the model as deviations from the SS are specified, expressed as shares of SS output Y_t, in order to determine effects of power grid infrastructure investments under different side conditions. Table 3 provides an overview of the deviations of the exogenous variables from the SS in the Scenarios A to D, specifications for Scenarios E to H can be found in Table D.6 in Appendix D. Concerning the notation of timing, the simulated time periods are indicated with $t \in [0, T]$ and the time periods during which the respective shock occurs with $\tau \in [t+\tau, t+T=T]$. Detailed descriptions concerning the derivation of the deviation values can be found in Appendix D.

Table 3: Shocks specification, Scenarios A to D

Var	Description	Shock specific.	Scenario A	Scenario B	Scenario C	Scenario D
I_τ^{TD}	Investment in transmission and distribution grid infrastructure	M* [*10^{-3}]	4.58058	4.58058	4.58058	4.58058
		D** [T]	τ^{ITD}; 64	τ^{ITD}; 64	τ^{ITD}; 64	τ^{ITD}; 64
Φ_τ	Externalities of connectivity and market size	M* [*10^{-3}]	0.159297	0.159297	0.159297	0.159297
		D** [T]	τ^{ITD}; $\tau^{ITD} = 0 \dots T$	τ^{ITD}; $\tau^{ITD} = 0 \dots T$	τ^{ITD}; $\tau^{ITD} = 0 \dots T$	τ^{ITD}; $\tau^{ITD} = 0 \dots T$
EG_τ^A	Ancillary services	M* [*10^{-3}]	1.05003	1.05003	1.05003	1.05003
		D** [T]	$t = 0$; $0 \dots \tau^{ITD}$	$t = 0$; $0 \dots \tau^{ITD}$	$t = 0$; $0 \dots \tau^{ITD}$	$t = 0$; $0 \dots \tau^{ITD}$

D_τ	Power grid operator R&D activities	$M*$ [$*10^{-3}$]	n.a.	n.a.	1.374174	n.a.
		$D**$ [T]	n.a.	n.a.	τ^{ITD}; $\tau^{ITD} = 0 \ldots T$	n.a.
V_τ	Mismatch between power supply and demand, due to VRES integration	$M*$ [%]	-0.01	-0.01	-0.01	-0.01
		$D**$ [T]	t; T	t; T	t; T	t; T
A_τ^G	Factor productivity in final goods sector	$M*$ [%]	n.a.	n.a.	n.a.	n.a.
		$D**$ [T]	n.a.	n.a.	n.a.	n.a.
A_τ^E	Energy efficiency in final goods sector	$M*$ [%]	n.a.	16.7415	n.a.	n.a.
		$D**$ [T]	n.a.	τ^{ITD}; T	n.a.	n.a.
S_τ^{EP}	Factor productivity in private electricity sector	$M*$ [%]	n.a.	n.a.	n.a.	n.a.
		$D**$ [T]	n.a.	n.a.	n.a.	n.a.
U_τ	Regulatory inefficiencies	$M*$ [%]	n.a.	n.a.	n.a.	10.00
		$D**$ [T]	n.a.	n.a.	n.a.	τ^{ITD}; $\tau^{ITD} = 0 \ldots T$
Ψ_{NB}	Share of fee over debt finance	$M*$ [%]	n.a.	n.a.	n.a.	n.a.
		$D**$ [T]	n.a.	n.a.	n.a.	n.a.

* Magnitude, [%] are % of SS values.
** Start period; Duration. One time period t equates 3 months. $\tau^{ITD} = 0$ designates the first period of investment in power grid infrastructure.

6.2.1 Scenario A: Investments as planned

In Scenario A, VRES integration levels are realized as planned in the German national targets. Also, all power grid infrastructure investments are implemented as planned in the NDP (2019b,c) for transmission grid and the IAEW D2 2035 (2014) Scenario for the distribution grid, see Appendix D. Connectivity externalities increase with increasing power grid infrastructure. Note that the VRES-induced mismatch between supply and demand is not fully compensated for by power grid infrastructure investments, however, and ancillary services increase to medium levels. All other exogenous variables remain unaltered.

6.2.2 Scenario B: Energy efficiency

In Scenario B, Scenario A is modified in order to test the impact of increased energy efficiency in the overall economy, i.e. the final goods sector in our model. Other model variables remain unaltered compared to Scenario A.

6.2.3 Scenario C: Innovative power grid system operators

With Scenario C, the impact of TSOs’ and DSOs’ innovation activities is tested, which play a pivotal role in future developments. All other model variables remain unaltered compared to Scenario A.

6.2.4 Scenario D: Efficient regulation

With Scenario D, the impact of increases in regulatory efficiency is tested, for instance improvements in the current incentive regulation or modifications of the institutional regime. Also, improvements in project execution or a better match between required and installed infrastructure assets is depicted via this parameter. As in the previously described scenarios, in Scenario D, all other model variables remain unaltered compared to Scenario A.

6.2.5 Scenario E: Quasi-tax vs. debt finance

The impact of delays in the financing of investments is tested by altering the share of the quasi-tax over debt finance, all other variables unaltered compared to Scenario A.

6.2.6 Scenario F: Innovative private electricity sector

In Scenario F, the effects of exogenous innovation in the private electricity sector is assessed, with all other variables unaltered compared to Scenario A. However, as costs of R&D activities are neglected in this approach and causes for innovation remain unexplained, not impacting the model economy, this approach is rather parsimonious. It can be refined in future research as explained in Appendix A.

6.2.7 Scenario G: Decentral electricity system

In Scenario G, the impact of a more decentralized electricity system is evaluated, in which only 75% of the planned transmission grid investments and 125% of the distribution grid investments of Scenario A are realized. Variable Φ_τ is altered accordingly. Scenario G, hence accounts for a potential development towards a more decentralized electricity system. Such a decentralized electricity system aspires to exploit advantages from decentral RES generation by individual "prosumers", which both consume and produce electricity, and are connected via distribution grids. For instance, so-called "*Quartierskonzepte*" are thought through and tested here, which, depending on their concrete design, may run in complete autarchy detached from the transmission grid[23]. All other variables remain unaltered compared to Scenario A.

6.2.8 Scenario H: Investment project delays and cancellations

With Scenario H, the impacts of investment project delays and cancellations are tested. Acceptance issues and delays in project execution are a considerable issue in power grid infrastructure investments in Germany. This can be seen when comparing planned and actually implemented power grid infrastructure investments throughout the NDPs from 2010 to 2019. For Scenario G hence, it is assumed that only 50% of the planned power grid investments are realized. Φ_τ changes accordingly, the level of EG_τ^A is increased in order to compensate for lacking system adequacy. All other variables remain unaltered compared to Scenario A.

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[23] For instance, in Northern Germany, a decentralized electricity supply system has been tested recently, in which a small number of prosumers, which generate electricity from RES, are connected via a distribution grid system which can be decoupled from the main grid. To mitigate deviations between power supply and demand, the decentral system is backed by a battery storage (for more information see: https://www.wemag.com/mission/oekostrategie/batteriespeicher, accessed on July 20, 2019). Also, for instance blockchain-based approaches exist, comparable to the US Brooklyn Micro Grid (see https://www.brooklyn.energy/ and https://www.zfk.de/energie/strom/artikel/vier-stadtwerke-kooperieren-auf-blockchain-basis-2019-02-05/, accessed on July 20, 2019).

6.3 DSGE model results

Scenarios A to H displayed in Table 3 and Table D.6 were simulated with Dynare, a preprocessor for Matlab, and obtain the results displayed in Figure 3 and Figure E.7 (Appendix E). The software allows to process the model based on its constituting equations listed in Table 1 and its solved SS equations (see Table B.6, Appendix B). To solve and simulate the model, the Dynare software deploys several applied mathematics and computer science techniques, for instance multivariate nonlinear solving and optimization, matrix factorizations, local functional approximation, Kalman filters and smoothers or optimal control (Adjemian et al., 2011). As a result from the simulation, time series about the development of the model's endogenous variables are obtained. When discussing the results, the focus is on long-term impacts for two reasons. Firstly, in a deterministic model, agents have perfect knowledge about future events. Hence, short-term dynamics are not necessarily highly accurate. Secondly, impacts on business cycles are modeled in a more detailed way in Schreiner and Madlener (2019), which is complemented with insights to a more long-term perspective with the present analysis.

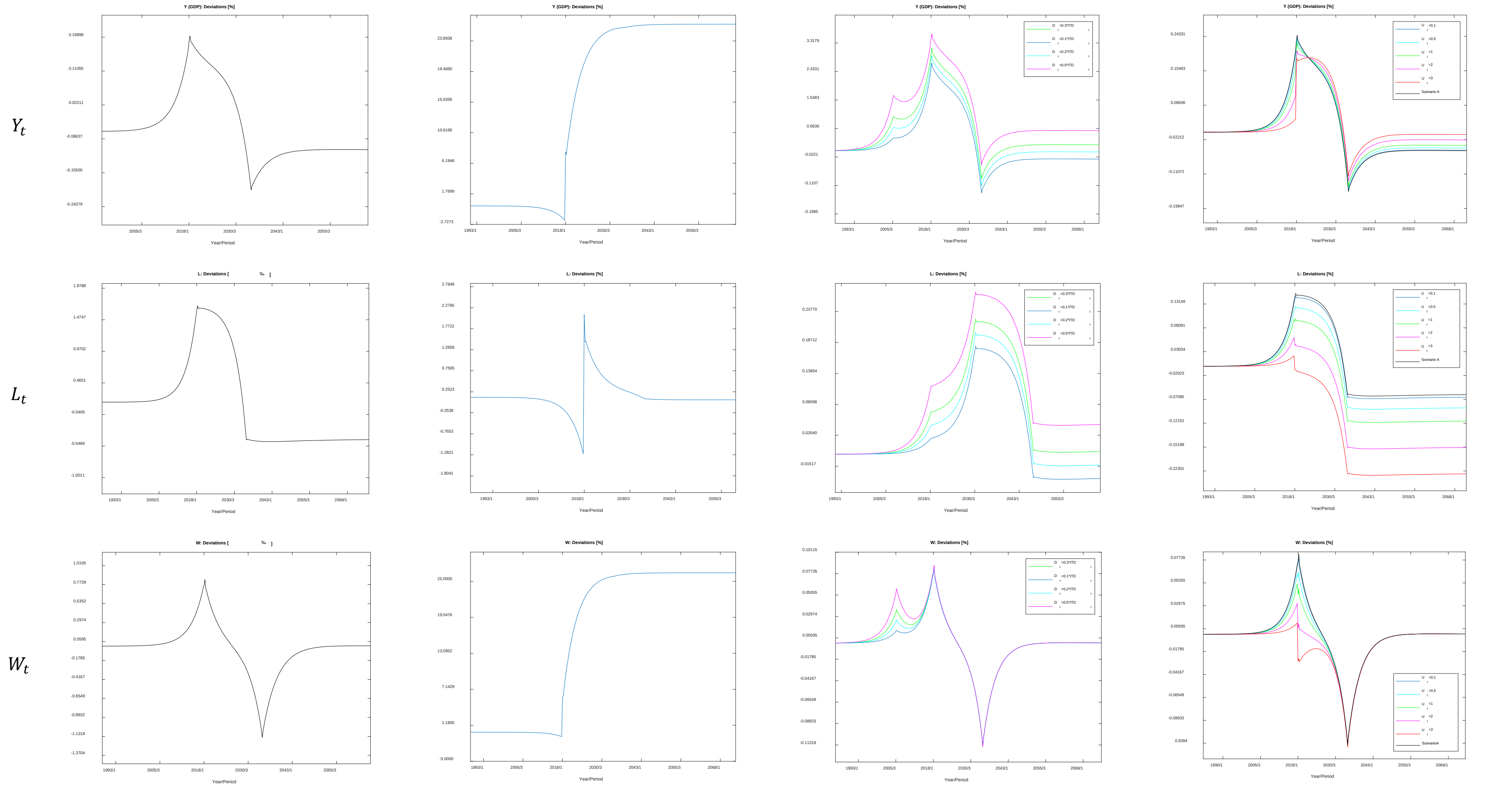
6.3.1 Scenario A: Investments as planned

To obtain absolute values from the Scenario A outputs, the respective 2018 values are multiplied with the deviation from the baseline levels (see Figure 3). With a 2018 nominal GDP of € 3,388.2 bn (destatis, 2019) and a long-term deviation from the SS levels of -0.0961%, a long-term decrease in the GDP level of € 3,254.24 million results. Analogously, from absolute employment of 32.716 million jobs in January 2018 (Arbeitsagentur, 2019) with a modeled deviation of -0.0607%, a long-term decrease in employment levels of 19,866.14 jobs is obtained. Similar considerations apply to the other endogenous variables displayed. These DSGE model outputs can be compared with the results obtained in Schreiner and Madlener (2019), i.e. deviations of Y, representing the German national GDP, and deviations L, representing employment. With a national gross power consumption in 2018 of 598.9 TWh (statista, 2019) and a long-term deviation of -0.3978%, a long-term decrease in power consumption of 238.60 GWh is observed.

6.3.2 Scenario B: Energy efficiency

In Scenario B, the impact of EE increases via A_τ^E in the final goods sector's production is assessed. As A_τ^E is an exogenous variable, EE increases do not require any upfront investment cost, for instance in the form of R&D expenditures. Therefore, the obtained values are likely to deviate from realistic values. Interesting in this scenario, however, is the consideration of the development of electricity consumption E_t . Rebound effects of increased EE are found, suggesting that a sole promotion and subsidization of EE might lead to adverse effects, and the appliance of more targeted policy instruments might be necessary.

Scenario A: Investments as planned | **Scenario B: Energy efficiency** | **Scenario C: Innovative grid operators** | **Scenario D: Efficient regulation**



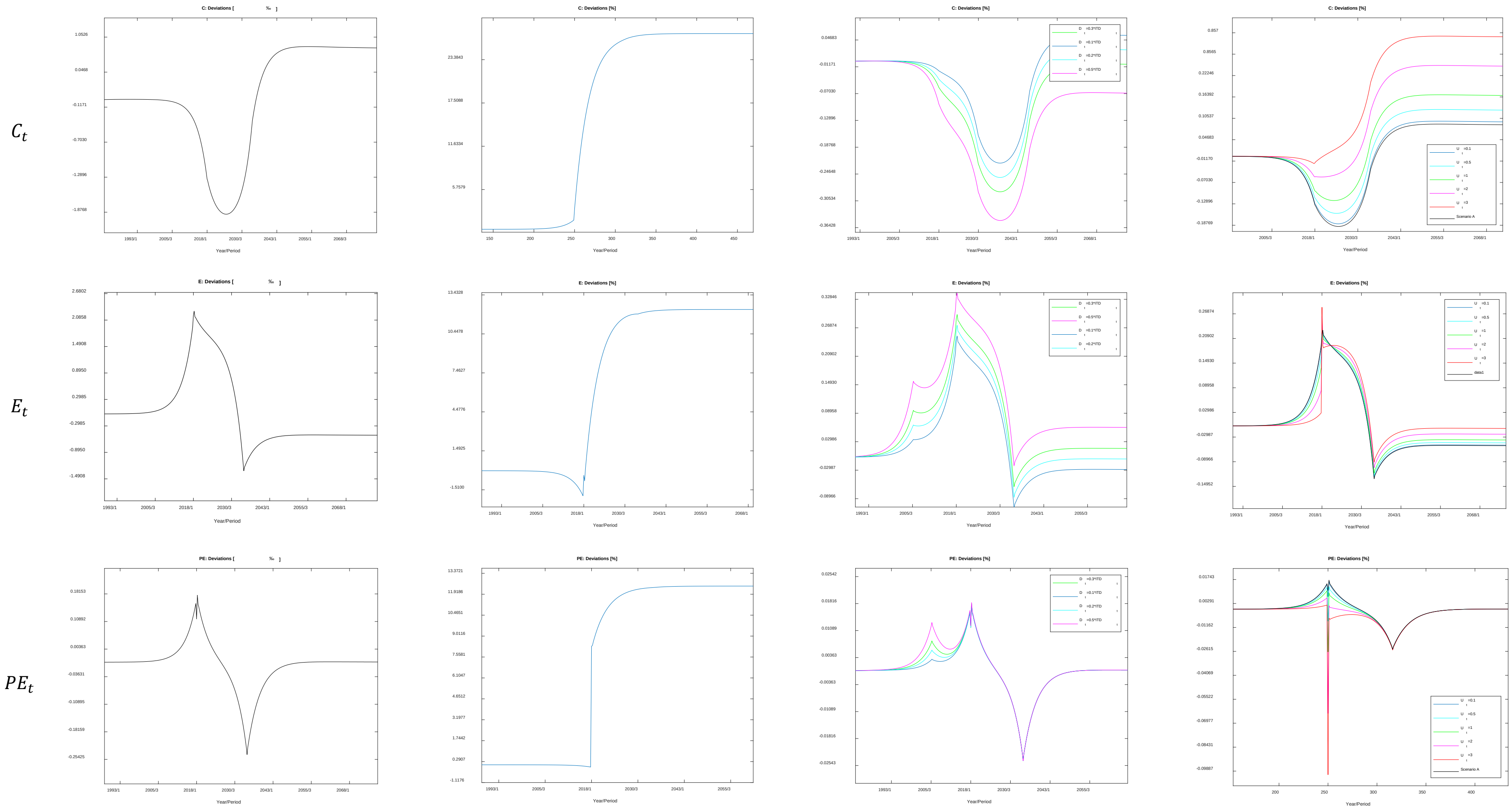


Figure 4: DSGE model results for Scenarios A to D

6.3.3 Scenario C: Innovative power grid system operators

With Scenario C, the impact of the regulated electricity sector undertaking R&D activities is assessed, which partially lead to innovation. Other than in Scenario B, innovation is not exogenous and hence associated with costs, which are recovered via the regulated electricity sector's quasi-tax. The graphs in Figure 20 show that concomitant innovation in the regulated electricity sector, if related expenditures are high enough, has the potential to increase both long-term levels of GDP and employment in absolute terms. For instance, R&D expenses amounting to 30% of power grid infrastructure investment volumes per period lead to percentual deviations of the GDP of 0.0221% and hence to an absolute long-term increase in the GDP level of € 749.44 million. Also, negative employment effects can be mitigated. For R&D expenses amounting to 30% of power grid infrastructure investment volumes per period, long-term employment levels remain constant. For higher R&D expenses, even increases in long-term employment levels of 0.0506% or 16,5451 jobs can be observed. However, increased R&D spending is also associated with higher levels of electricity consumption.

6.3.4 Scenario D: Efficient institutional regime

Results from modelling Scenario D suggest that efficiency increases in the institutional regime lead to rather small impacts, unless considerably high increases occur. Increases of up to 300% compared to baseline levels[24] have been tested. To correctly interpret this result, the very basic model structure is considered, which remains constant while regulatory efficiency increases. As the impact potential of regulatory efficiency within the given structure is small, a potentially superior lever to be tested would be a restructuring of the electricity sector.

6.3.5 Scenario E: Quasi-tax vs. debt finance

Increasing the parameter as depicted in the graphs in Figure 4 generally smoothens the impact of power grid infrastructure investments. However, as previously described, it is expedient to refine the model at this point.

6.3.6 Scenario F: Innovative private electricity sector

In an analogous way to Scenario B, the impact of exogenous innovations in the private electricity sector is tested and compared with impacts of regulated innovation. As in Scenario B, however, exogenous innovation is not associated with any R&D costs. Strong long-term increases in GDP and a decrease in the long-term employment levels are found. Like in Scenario B, innovation in the private electricity sector is found to cause significant increases in electricity

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[24] Testing these high efficiency increases does not suggest that those levels are assumed to be realistic. However, the model's behaviour is informative to observe.

consumption, which the decreasing effect of power grid infrastructure investments does not mitigate. Remarkable here is a strong decrease in the electricity price ratio P_t^E/P_t.

Even though these results give some first insights on the impact of private electricity sector innovation, an endogenization of private electricity innovation has the potential to generate great value added for at least two reasons. Firstly, costs for R&D activities are accounted for. Secondly, and even more importantly, an endogenization of private electricity sector innovation in the way presented in Appendix A, allows to test impacts of power grid infrastructure investment on private electricity sector R&D activities. Only then, potential crowding-out or crowding-in effects can be scrutinized.

6.3.7 Scenario G: Decentralized electricity system

Testing the impact of more decentral power grid infrastructure investments reveals that the long-term impact on GDP levels is the same as in Scenario A, when incorporating a case of higher transmission grid infrastructure investment shares. During the construction period, however, Scenario A investments exhibit higher temporary GDP increases. As employment is concerned, negative impacts are slightly less in the decentral Scenario G, amounting to long-term decreases in levels of employment of 0.0506% or 16,553.4 jobs. Overall electricity consumption in the long term equals the one found in Scenario A, during the construction process, electricity consumption in Scenario A reaches higher levels than in the decentralized electricity system Scenario G.

6.3.8 Scenario H: Investment project delays and cancellations

Testing the macroeconomic impact of project delays and cancellations, less negative long-term deviations in the GDP level from the SS are found. However, during the construction period in the short term, less positive deviations from SS levels are generated. The same findings apply for long-term and short-term employment levels. Electricity consumption remains at higher levels in the long term compared to Scenario A.

7 Conclusion

Findings of this paper's analysis shed light on the existence and magnitude of the potential conflicts between power grid infrastructure investments and macroeconomic outcomes, and on determinants for economic efficiency of power grid infrastructure investments.

As the existence and magnitude of potential conflicts between power grid infrastructure investments and macroeconomic outcomes is concerned, results point to potentially negative effects of power grid infrastructure investments on economic performance in the long term, and hence to the potential for the existence of a conflict. The existence of *per se* synergetic effects can not be verified. In the short term, i.e. during construction times, temporarily positive effects of power grid infrastructure investment on economic performance are found. However, in an aggregated consideration, they are offset by negative effects in the short term which follow periods of positive effects. Also, when considering findings from Schreiner and Madlener (2019), in which multiplier effects accounting for overall effects not limited to the own national economy take on positive values, these short-term findings would have to be investigated in an open DSGE model in order to deliver robust findings.

As the determinants for economic efficiency are concerned, the analysis' results point to four main determinants for investment optimality and conditions under which the conflict can potentially be transformed into synergetic effects, as well as influencing factors potentially increasing the magnitude of the conflict. Firstly, from modelling Scenarios B, C and F the potential of innovation and increases in factor productivity to mitigate negative effects of power grid infrastructure investments on economic performance can be observed. In regulated electricity sector innovation, ceteris paribus, expenses in R&D activities of 30% of the planned infrastructure investment volumes can mitigate negative effects on both GDP and employment. Innovation in the private sectors bears even greater potential to offset negative effects. However, innovation both in the regulated and in the private sectors has the potential to cause significant rebound effects, which increase electricity consumption in the case of their occurrence relative to zero rebound. Secondly, it is found that delays and cancellations in power grid infrastructure investment projects modeled in Scenario H lead to lower negative effects than their implementation as planned. This finding is quite intuitive considering the revealed long-term negative effects of power grid infrastructure investments on economic outcomes. However, in Scenario H, electricity consumption remains at higher levels than in Scenario A. Thirdly, the lower connectivity externalities when setting up a decentralized electricity system reduce increases in GDP and employment in the shorter term. Their impact is, however, negligible in the longer term. Finally, rather low impacts of increasing regulatory efficiency within the status quo structural setup of the electricity sector can be observed. The impact of restructuring the electricity sector, for instance by partially liberalizing and introducing competitive mechanisms to the now regulated transmission and distribution sectors can be investigated in a potential future refined version of the model.

The presented model is a first attempt to incorporate power grid infrastructure investments via different existing theory links into one joint macroeconomic model. There is plenty of scope for future research, as indicated particularly in sections 4 and 5, to extend and refine the analysis based on the introduced approach.

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Appendices

Appendix A: Theory foundations incorporation

This section describes how the power grid infrastructure investments are included in our model, based on the theory links, levers and EED. In the following, the incorporation via neoclassical theory (Link 2) and energy economics theory (Link 3), put into practice in our DSGE model is described, and how the model can be extended and refined by further incorporating insights from Keynesian theory (Links 1) and endogenous growth theory (Link 4) respectively.

A.1 Link 2: Neoclassical theory

Neoclassical theory allows to incorporate power grid infrastructure investments via two distinct levers: Firstly, as public infrastructure input to a private sector PF and, secondly, as connectivity externalities.

A.1.1 Lever 2.1: Public input to a private sector firm's PF

We use Lever 2.1 to model quasi-public power grid infrastructure as an input to a partially liberalized electricity supply sector[25]. The electricity supply sector amalgamates regulated and liberalized components of the overall electricity sector value chain by deploying the corresponding input factors provided by the regulated and liberalised electricity sectors. Being one part of the regulated electricity input factor, see Eq. (20), power grid infrastructure EG_t^{TD} is incorporated as a quasi-public input factor to the overall electricity supply sector's PF, depicted in Eq. (12) as EG_t. The way the public input factor is included is based on Basu and Kollmann (2013).

A.1.2 Lever 2.2: Connectivity externalities

In the same electricity supply sector PF, Eq. (12), an externalities parameter Φ_t is included, which reflects the contribution of power grid infrastructure to an increased market size. The magnitude of Φ_t is *inter alia* dependent on the type of power grid infrastructure investment, i.e. transmission or distribution grid, and of the particularities of the markets it connects.

A.1.3 EED 2.1: Efficient institutional regime

As laid out in Section 4, economic efficiency, and particularly regulatory efficiency in the sense of an optimal institutional regime play a key role in determining the contribution quasi-public power grid infrastructure makes to private production. A variable U_t is hence included into the electricity supply sector's PF, Eq. (12), depicting economic efficiency of quasi-public

[25] The model structure is transferable to economies exhibiting similar structures and institutional regimes of their electricity sectors as the German one.

infrastructure provision. The variable U_t reflects three main influencing factors on the efficiency of the institutional regime.

A.1.3.1 Regulatory framework

The quality and appropriateness of the regulatory framework to compensate for market failure is depicted, in the sense of its potential to contribute to short-term and long-term efficiency in the regulated sector embedded in the overall economy. Hence, U_t *inter alia* reflects the economic efficiency of power grid infrastructure investment incentives. Particularly, the mode of regulation is accounted for, which can take the form of, for instance, price-cap regulation, rate-of-return (ROR) regulation or incentive regulation. Impactful here is also the very concrete design of the mode of regulation and the way in which it interacts with the respective overall institutional regime. A body of related literature investigates the way in which different regulatory designs impact short- and long-term efficiency in the electricity sector and beyond (cf. e.g. Guthrie, 2006; von Hirschhausen, 2008; Oliver, 2018). Furthermore, different approaches to increase economic efficiency and particularly regulatory efficiency in partially deregulated electricity sectors are proposed. Here, different suggestions concerning the institutional setup itself or its regulation are made (cf., e.g., Poudineh and Jamasb, 2014; Esmat et al., 2018a,b).

A.1.3.2 Liberalization and market design

U_t reflects changes in economic efficiency within the regulated electricity sector which are linked to de-regulation and liberalization and the related market design of the liberalized sectorial components. U_t increases, if the introduction of market mechanisms to the provision of outputs from the regulated electricity sector, amongst which power grid infrastructure, increases economic efficiency in its provision. A body of literature investigates the potential of the introduction of different market mechanisms, for instance the introduction of flexibility markets (cf. e.g. Bertsch et al., 2013; Esmat et al., 2018a,b) and its potential impact on power grid infrastructure investment (cf. e.g. Oliver, 2018).

A.1.3.3 Mode of financing

U_t reflects economic efficiency in the way in which regulated power grid infrastructure investments are financed. The mode of financing hereby describes different characteristics of power grid infrastructure finance: *Inter alia*, it includes the timing of finance, i.e. if the investment costs are passed on to consumers via a quasi-tax in the time period of the investment or if it is transferred to a later time by increasing the share of debt finance. Furthermore, it accounts for the source of capital and its related capital cost (for instance reflected by the WACC), different ownership structures and risk allocation.

A strand of literature and also current political initiatives investigate distinct ways in which infrastructure can best be financed and in which way capital can be efficiently provided (cf. e.g. Barro, 1990; Flyvberg, 2003; IMF, 2016; OECD, 2017a,b, 2018; Baldwin et al., 2018; Mayer et al. 2018). A politically very topical example is the discussion of public private partnerships (PPP) in infrastructure financing, whose main advantage is stated to be shorter construction periods due to superior technical expertise, greater implementation capacity and fewer agency problems (IMF, 2016).

A.1.4 Link 3: Energy economics

As seen, power grid infrastructure is deployed as an input factor to generate electricity supply E_t according to Eq. (12). Underpinned by the theoretical approach within energy economics, in which energy is represented as a third input factor besides labour and capital, electricity supply E_t is incorporated as an input factor into the final goods sector PF, Eq. (7).

A.1.4.1 Lever 3.1: Determinant for electricity cost

Power grid infrastructure provision EG_t^{TD} and its economic efficiency U_t as well as its connectivity externalities Φ_t in Eq. (12) determine the requirement within the electricity supply sector for inputs from the private electricity sector EP_t. As such, power grid infrastructure is a determinant for the price level P_t^E, see Eq. (13), at which the final goods sector can purchase electricity supply, al. the final goods sector's electricity cost. Analogously to the argumentation before, it is assumed that private sector firms consume electricity, and deploy it to produce goods for HH consumption. Via this lever, electricity inputs are indirectly also included in HH consumption[26].

A.1.4.2 Lever 3.2: Efficiency in the electricity sectors and overall energy efficiency

We depict Lever 3.2 in our model by means of different types of efficiency parameters indicating factor productivity within the relevant sectors.

Firstly, efficiency of inputs from the regulated electricity sector to the electricity supply sector are expressed as variable S_t^{EG}, which determines the productivity of the deployment EG_t and hence of EG_t^{TD} as modeled in Eq. (12). S_t^{EG} is endogenously determined by R&D activities which the regulated electricity sector undertakes, and develops according to (IV.47*). The decision to allocate expenses to R&D activities is modeled exogenously as an alternative for spending for ancillary services EG_t^A and power grid infrastructure investments I_t^{TD}, subject to the regulated electricity sector's budget constraint, see Eq. (20). Secondly, the efficiency of

[26] It is abstracted from including electricity consumption directly into the HH UF based on argumentations in Barro (1990) and Costa Junior (2016), which show the analytical equivalence of including public inputs in a production function or in the UF. The argumentation can analogously be consulted for the IF electricity.

inputs from the private electricity sector to the electricity supply sector's PF is modeled as the exogenous variable S_t^{EG}.

While the two presented efficiency parameters directly or indirectly represent efficiency within the production of the input factor electricity E_t, the third and fourth efficiency-related parameters A_t^G and A_t^E enable the modelling of its efficient deployment in the final goods sector PF, Eq. (7). While A_t^G represents TFP in the final goods sector and its increase leads to a more efficient deployment of all input factors electricity, capital and labour, A_t^E stands for the efficiency of electricity deployment only, and hence represents energy efficiency within the final goods sector in a narrow sense.

A.1.4.3 EED 3.1: Electricity system adequacy

Electricity system adequacy indicates the degree to which electricity supply and demand match. The parameter $V_t \in [0,1]$ is hence included into the electricity supply sector's PF, indicating the degree of mismatch induced by VRES integration along all dimensions, with 1 representing no impact and 0 a very severe impact with an induced mismatch so high that the electricity supply sector cannot produce any usable output. Hence, system adequacy for power grid infrastructure investment indicates to which extent it contributes to (re-)match supply and demand in the electricity sector and hence is a strong determinant for the desirability of a potential electricity system's target state.

Alternative flexibility options: Defining the counterfactual

When looking into optimality from a system adequacy perspective and in view of the overall target criterion of economic efficiency, there are two optimality determinants for a flexibility option: Firstly, it must exhibit the technological potential to provide flexibility of the required dimension, and secondly, it must be able to do so at the lowest cost compared to its alternatives.

Two categories of flexibility options are represented in the model, based on the actor within the economy they are provided by, as displayed in Figure A.6 and described in the following.

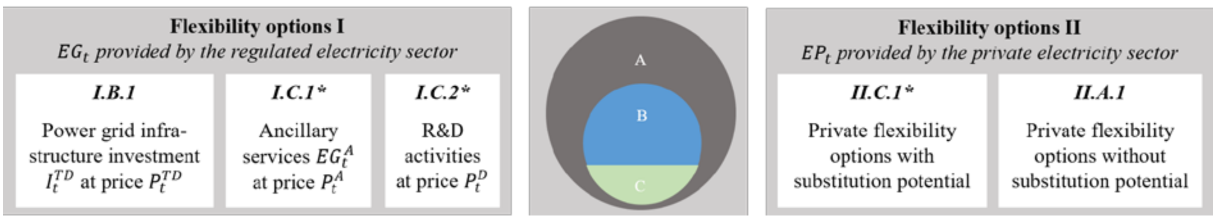

Figure A.5: Categories of flexibility options in the DSGE model setup
* imperfect substitutes

Flexibility options from the first category (I) are provided by the regulated electricity sector and represent its distinct options for action to achieve system stability. These options are, firstly, to invest into power grid infrastructure[27] (I.B.1) and, secondly, to compensate for system inadequacies by providing ancillary services including e.g. congestion management (I.C.1*), which can partially be deployed as substitutes for power grid infrastructure investments (cf. e.g. Kemfert et al., 2016). Thirdly, they serve to perform R&D activities to increase the efficiency of the deployment of the former two options (I.C.2*). Options (I.C.1*) and (I.C.2*) can be interpreted as imperfect substitutes, which are able to replace (I.B.1) to a certain extent, which must be determined for the specific application case. A parameter for substitutability between the different flexibility options is not included, as the deployment intensity of each option is determined exogenously.

Flexibility options from the second category (II) subsume all flexibility options which can be provided by actors from the liberalized, electricity sector. Flexibility options from this category are further grouped into private flexibility options with substitution potential (II.C.1) and without (II.A.1). Flexibility options (II) are reflected in EP_t in the electricity supply sector's PF, Eq. (12).

The substitution potential between flexibility options from categories (I) and (II) is modeled as the output elasticity ε of the input factor from the regulated electricity sector. It accounts for technological substitutability, and is related to the marginal rate of substitution (MRTS) between EG_t and EP_t via

$$MRTS_{EG_t,EP_t} = \varepsilon \frac{EP_t}{U_t S_t^{EG} EG_t} \tag{A.1}$$

Literature here points to the requirement of further investigation of substitution potentials between different flexibility options (cf. e.g. Goetz et al., 2014; Zöphel et al., 2018)

A.1.5 Link 4: Endogenous innovation*

A.1.5.1 Relevance of private sector endogenous innovation

As depicted in Figure 3 (marked in green colour), a potential step towards a model extension is to include endogenous innovation in the private electricity sector. The introduction of endogenous innovation allows to incorporate theory Link 4 in the model and hence enables to test the impact of power grid infrastructure investments on private sector innovation. The value added of this extension mainly results from the very considerable requirements for innovation in order to make particularly high shares of VRES in power systems realizable, and from the aspiration to realize these innovations in an economically efficient way. The question of

[27] Investments in power grid infrastructure can also include interconnections with electricity systems of foreign national economies.

optimality in innovation activities, an avoidance of crowding out, and a fostering of crowding in effects of private sector innovation hence becomes a very relevant one.

A.1.5.2 Potential model extensions

Endogenous innovation can be incorporated in the model, as depicted in Figure 2, by splitting the current private electricity sector into three distinct interacting sectors: A private electricity wholesale sector, a private electricity retail sector and an innovation sector. To model incentives for innovation activities, first, imperfect competition in the private electricity sector must be introduced via the interplay of electricity wholesale and retail sectors, as for instance in Costa Junior (2016). Imperfect competition allows the private electricity firms to set prices and hence realize profits. The link with innovation activities can hence be established as private sector electricity firms can increase their prospective profits by demanding innovation patents from the innovation sector. As the success of R&D activities, i.e. the outcome of innovation from these activities, is inherently uncertain, in a deterministic version of the model a parameter can be included depicting R&D efficiency comparable to the one included to describe the behaviour of the impact of R&D activities undertaken by the regulated electricity sector. In a stochastic version, one could include a likelihood of successful innovation outcomes from R&D activities, such as in Roszypal (2016) and Harada (2018). The decision of the private electricity sector to demand in R&D activities and hence the magnitude of private sector innovation, as mentioned above, are highly dependent on realizable profits in the private electricity sector, i.e. the demand for private electricity sector outputs.

We can further model an impact of R&D activities on the marginal rate of technical substitution between power grid infrastructure investments and alternative flexibility options. This relation accounts for innovation activities in the private sector which improve technologies such as storage or power-to-X (PtX) technologies, whose current substitution potential is rather low, but in which it is likely that innovation can lead to increases in the latter. By establishing these relations, the impacts of regulated power grid infrastructure on private sector R&D activities and innovation can be tested.

A.1.6 Link 1: Keynesian theory*

Constructs from (new, neo-) Keynesian theories can be incorporated into the model via refinements including for instance sticky prices and wages into the model behaviour. These refinements are of rather general nature and the way in which they can be included in the model can be found in existing DSGE models. An inclusion of these refinements can provide further insights to impacts of regulated power grid infrastructure investments on business cycles.

Appendix B: The steady state

Table B.4: The DSGE model's constituting SS equations

No.	Constituting equation	No.	Steady state equation
(5)	$L_t = L_t^G + L_t^{EP}$	(S.5)	$L_{SS} = L_{SS}^G + L_{SS}^{EP}$
(6)	$K_{t+1} = (1-\delta)K_t + I_t$	(S.6)	$\delta K_{SS} = I_{SS}$
(7)	$K_t = K_t^G + K_t^{EP}$	(S.7)	$K_{SS} = K_{SS}^G + K_{SS}^{EP}$
(8)	$C_t(L_t)^\eta = W_t$	(S.8)	$C_{SS}(L_{SS})^\eta = W_{SS}$
(9)	$\frac{C_{t+1}}{C_t} = \beta[(1-\delta) + R_{t+1}]$	(S.9)	$R_{SS} = \frac{1}{\beta} - (1-\delta)$
(10)	$\frac{C_{t+1}}{C_t} = \beta R_t^B$	(S.10)	$R_{SS}^B = \frac{1}{\beta}$
(11)	$Y_t = A_t^G (K_t^G)^\alpha * (A_t^E E_t)^\xi * (L_t^G)^{1-\alpha-\xi}$	(S.11)	$Y_{SS} = (K_{SS}^G)^\alpha * (A_{SS}^E E_{SS})^\xi * (L_{SS}^G)^{1-\alpha-\xi}$
(12)	$K_t^G = \alpha \frac{Y_t}{R_t}$	(S.12)	$K_{SS}^G = \alpha \frac{Y_{SS}}{R_{SS}}$
(13)	$E_t = \xi \frac{Y_t}{P_t^E}$	(S.13)	$E_{SS} = \xi \frac{Y_{SS}}{P_{SS}^E}$
(14)	$L_t^G = (1-\alpha-\xi)\frac{Y_t}{W_t}$	(S.14)	$L_{SS}^G = (1-\alpha-\xi)\frac{Y_{SS}}{W_{SS}}$
(15)	$1 = \frac{R_t}{\alpha A_t^G}\left(A_t^E \frac{\alpha P_t^E}{\xi R_t}\right)^\xi * \left(\frac{\alpha W_t}{R_t(1-\alpha-\xi)}\right)^{1-\alpha-\xi}$	(S.15)	$1 = \frac{R_{SS}}{\alpha A_{SS}^G}\left(A_{SS}^E \frac{\alpha}{\xi R_{SS}}\right)^\xi \left(\frac{\alpha W_t}{R_{SS}(1-\alpha-\xi)}\right)^{1-\alpha-\xi} {P_{SS}^E}^\xi$
(16)	$E_t = V_t * \Phi_t * (U_t S_t^{EG} EG_t)^\varepsilon * EP_t$	(S.16)	$E_{SS} = V_{SS} * \Phi_{SS} * \left(U_{SS} S_{SS}^{EG} EG_{SS}\right)^\varepsilon * EP_{SS}$
(17)	$P_t^E = \frac{P_t^{EP} EP_t}{E_t}$	(S.17)	$P_{SS}^E = \frac{P_{SS}^{EP} EP_{SS}}{E_{SS}}$
(18)	$EG_t = EG_t^A + EG_t^{TD}$	(S.18)	$EG_{SS} = EG_{SS}^A + EG_{SS}^{TD}$
(19)	$EG_{t+1}^{TD} = (1-\delta^{TD})EG_t^{TD} + I_t^{TD}$	(S.19)	$\delta^{TD} EG_{SS}^{TD} = I_{SS}^{TD}$
(20)	$EP_t = S_t^{EP} {K_t^{EP}}^\vartheta {L_t^{EP}}^{1-\vartheta}$	(S.20)	$EP_{SS} = S_{SS}^{EP} {K_{SS}^{EP}}^\vartheta {L_{SS}^{EP}}^{1-\vartheta}$
(21)	$K_t^{EP} = \vartheta EP_t \frac{P_t^{EP}}{R_t^{EP}}$	(S.21)	$K_{SS}^{EP} = \vartheta EP_{SS} \frac{P_{SS}^{EP}}{R_{SS}^{EP}}$
(22)	$L_t^{EP} = (1-\vartheta)EP_t \frac{P_t^{EP}}{W_t}$	(S.22)	$L_{SS}^{EP} = (1-\vartheta)EP_{SS} \frac{P_{SS}^{EP}}{W_{SS}}$
(23)	$P_t^{EP} = \frac{1}{S_t^{EP}}\left(\frac{W_t}{(1-\vartheta)}\right)^{1-\vartheta}\left(\frac{R_t^{EP}}{\vartheta}\right)^\vartheta$	(S.23)	$P_{SS}^{EP} = \frac{1}{S_{SS}^{EP}}\left(\frac{W_{SS}}{(1-\vartheta)}\right)^{1-\vartheta}\left(\frac{R_{SS}}{\vartheta}\right)^\vartheta$
(24)	$\frac{B_{t+1}}{R_t^B} - B_t + N_t = P_t^A EG_t^A + P_t^{TD} I_t^{TD} + P_t^D D_t$	(S.24)	$\frac{B_{SS}}{R_{SS}^B} - B_{SS} + N_{SS} = P_{SS}^A EG_{SS}^A + P_{SS}^{TD} I_{SS}^{TD} + P_{SS}^D D_{SS}$
(25)	$S_{t+1}^{EG} = \mu D_t$	(S.25)	$S_{SS}^{EG} = \mu D_{SS}$
(26)	$\Psi_{NB} = \frac{N_t}{B_t}$	(S.26)	$\Psi_{NB} = \frac{N_{SS}}{B_{SS}}$
(27)	$Y_t = C_t + I_t + EG_t^A + I_t^{TD} + D_t$	(S.27)	$Y_{SS} = C_{SS} + I_{SS} + EG_{SS}^A + I_{SS}^{TD} + D_{SS}$

Table B.5: The model's solved steady state equations

Endogenous variable	No.	Equation
Return on private capital	(28)	$R_{SS} = \frac{1}{\beta} - (1-\delta)$
Return on bonds	(29)	$R_{SS}^B = \frac{1}{\beta}$
Factor productivity of inputs from the regulated electricity sector	(30)	$S_{SS}^{EG} = \mu D_{SS}$
Power grid infrastructure capital stock	(31)	$EG_{SS}^{TD} = \frac{1}{\delta^{TD}} I_{SS}^{TD}$

Inputs from the public electricity sector	(32)	$EG_{SS} = EG_{SS}^{A} + EG_{SS}^{TD}$
Bonds	(33)	$B_{SS} = \dfrac{P^{A}EG_{SS}^{A} + P^{TD}I_{SS}^{TD} + P_{SS}^{D}D_{SS}}{\left(\frac{1}{R_{SS}^{B}} - 1 + \Psi_{NB}\right)}$
Network fees	(34)	$N_{SS} = P_{SS}^{A}EG_{SS}^{A} + P_{SS}^{TD}I_{SS}^{TD} + P_{SS}^{D}D_{SS} - \dfrac{B_{SS}}{R_{SS}^{B}} + B_{SS}$
Wage rate	(35)	$W_{SS} = [X_1]^{\frac{1}{\alpha+\xi\vartheta-1}}$
	(36)	$X_1 = \dfrac{R_{SS}}{\alpha A_{SS}^{G}}\left(A_{SS}^{E}\dfrac{\alpha}{\xi R_{SS}}\right)^{\xi}\left(\dfrac{\alpha}{R_{SS}(1-\alpha-\xi)}\right)^{1-\alpha-\xi} X_2$
	(37)	$X_2 = \left(\dfrac{1}{S_{SS}^{EP}V_{SS}\Phi_{SS}(U_{SS}S_{SS}^{EG}EG_{SS})^{\varepsilon}}\left(\dfrac{1}{(1-\vartheta)}\right)^{1-\vartheta}\left(\dfrac{R_{SS}}{\vartheta}\right)^{\vartheta}\right)^{\xi}$
Private electricity sector price level	(38)	$P_{SS}^{EP} = \dfrac{1}{S_{SS}^{EP}}\left(\dfrac{W_{SS}}{(1-\vartheta)}\right)^{1-\vartheta}\left(\dfrac{R_{SS}}{\vartheta}\right)^{\vartheta}$
Electricity supply sector price level	(39)	$P_{SS}^{E} = \dfrac{P_{SS}^{EP}}{V_{SS}(VRES) * \Phi_{SS}(EG_{SS}^{TD}) * (U_{SS}S_{SS}^{EG}EG_{SS})^{\varepsilon}}$
Final goods sector output	(40)	$Y_{SS} = \left[X_3\dfrac{(1-\alpha-\xi\vartheta)^{\eta}}{W_{SS}{}^{1+\eta}}\right]^{\frac{1}{-\eta-1}}$
	(41)	$X_3 = \left[1 - \delta\dfrac{1}{R_{SS}}\left(\alpha + \vartheta\dfrac{\xi}{V_{SS} * \Phi_{SS} * (U_{SS}S_{SS}^{EG}EG_{SS})^{\varepsilon}}\right)\right]$
Private consumption	(42)	$C_{SS} = Y_{SS}{}^{-\eta}\dfrac{W_{SS}{}^{1+\eta}}{(1-\alpha-\xi\vartheta)^{\eta}}$
Private investments	(43)	$I_{SS} = Y_{SS}\delta\dfrac{1}{R_{SS}}\left(\alpha + \vartheta\dfrac{\xi}{V_{SS} * \Phi_{SS} * (U_{SS}S_{SS}^{EG}EG_{SS})^{\varepsilon}}\right)$
Final goods sector capital	(44)	$K_{SS}^{G} = \alpha\dfrac{Y_{SS}}{R_{SS}}$
Final goods sector electricity	(45)	$E_{SS} = \xi\dfrac{Y_{SS}}{P_{SS}^{E}}$
Final goods sector labour	(46)	$L_{SS}^{G} = (1-\alpha-\xi)\dfrac{Y_{SS}}{W_{SS}}$
Private electricity sector inputs	(47)	$EP_{SS} = \dfrac{E_{SS}}{V_{SS} * \Phi_{SS} * (U_{SS}S_{SS}^{EG}EG_{SS})^{\varepsilon}}$
Private electricity sector capital	(48)	$K_{SS}^{EP} = \vartheta EP_{SS}\dfrac{P_{SS}^{EP}}{R_{SS}}$
	(49)	$K_{SS}^{EP} = \vartheta EP_{SS}\dfrac{P_{SS}^{EP}}{R_{SS}}$
Labor distribution	(50)	$L_{SS} = L_{SS}^{G} + L_{SS}^{EP}$
Private capital distribution	(51)	$K_{SS} = K_{SS}^{G} + K_{SS}^{EP}$

Appendix C: Power grid investment specific parameters

C.1 Depreciation rate of power grid infrastructure capital

For the estimation of the depreciation rate of power grid infrastructure capital in Germany, a straight-line depreciation as determined in Art. 6 StromNEV is presumed. The joint depreciation rate for transmission and distribution grid infrastructure capital can then be estimated as

$$\delta^{TD} = \frac{1}{s^{T}l^{T} + s^{D}l^{D} + s^{S}l^{S}} \tag{C.2}$$

with s^T the share of transmission grid infrastructure capital in [%], s^D the share of distribution grid infrastructure capital in [%], l^T the lifetime of transmission grid infrastructure in [a] and l^D the lifetime of distribution grid infrastructure in [a]. Furthermore, the depreciation rate is impacted by “stranded assets”, i.e. power grid infrastructure whose full technical lifetime is not exploited, as externally induced transformations within the electricity sector lead to an early shutdown. The share of stranded power grid infrastructure assets is represented by s^S, their lifetimes as l^S in [a].

For the minimum value $\delta^{TD,min}$, $l^T = l^D = 60$ a is assumed, based on Oswald et al. (2007) and Hinz et al. (2014). It is further assumed $s^S = 0$. Then, $s^T + s^D = 1$ and $\delta^{TD,min} = 0.0167$. Setting values for $s^S > 0$ and $l^S < l^T$ respectively $l^S < l^D$, it is possible to depict stranded power grid infrastructure assets as $\delta^{TD,stranded} > \delta^{TD,min}$.

C.2 Output elasticity of quasi-public power grid infrastructure

We estimate the output elasticity ε of quasi-public power grid infrastructure based on the definition

$$MRTS_{EG_t,EP_t} = \frac{MP_{EG_t}}{MP_{EP_t}} = \frac{\frac{\partial E_t}{\partial EG_t}}{\frac{\partial E_t}{\partial EP_t}} \tag{C.3}$$

with the already introduced variables. Substituting the respective model equations reveals

$$MRTS_{EG_t,EP_t} = \frac{\varepsilon A_t^E V_t * \Phi_t * (U_t S_t^{EG} EG_t)^{\varepsilon-1} * EP_t}{A_t^E V_t * \Phi_t * (U_t S_t^{EG} EG_t)^{\varepsilon}} \tag{C.4}$$

and hence

$$MRTS_{EG_t,EP_t} = \varepsilon \frac{EP_t}{U_t S_t^{EG} EG_t} \quad . \tag{C.5}$$

In the SS, the exogenous variables U_t and S_t^{EG} are assumed to be $U_t = S_t^{EG} = 1$. The MRTS is then

$$\varepsilon = MRTS_{EG_t,EP_t} \frac{EG_t}{EP_t} \tag{C.6}$$

Based on data from the TSOs’, DSOs’ and generators’ financial statements[28], it is assumed that the ratio between inputs from the private and regulated sectors in the electricity value chain does not significantly deviate from unity.

[28] The respective financial statements are available online. Amprion: https://www.amprion.net/Dokumente/Amprion/Gesch%C3%A4ftsberichte/2018/Amprion-GB18-Finanzbericht-EN.pdf, EnBW (as TransnetBW is 100% subsidiary company of EnBW): https://www.enbw.com/enbw_com/downloadcenter/annual-reports/enbw-integrated-annual-report-2017.pdf, Tennet: https://www.tennet.eu/fileadmin/user_upload/Company/Profile/2018_pic/TenneT-Integrated-Annual-Report-2018.pdf, https://www.tennet.eu/company/investor-relations/key-figures/, 50Hertz: https://www.50hertz.com/en/InvestorRelations/, E-On: https://www.eon.com/content/dam/eon/eon-com/investors/presentations/facts-and-figures-2018.pdf, all accessed on July 10, 2019.

With further assuming low MRTS based on considerations in dena (2010) and NDP (2019b,c), an output elasticity of $\varepsilon = 0.001$ is estimated. A more accurate determination can be subject to future research and strongly depends on the availability, appropriateness, realizability and cost of different potential flexibility options.

C.3 Flexibility options in the German case

To point to further potential refinements in the determination of MRTS between different flexibility options, a brief overview of the available options and assessments of their substitutability that exists in the literature is provided. Generally, most discussed flexibility options in Germany apart from power grid infrastructure investments, i.e. grid expansions, as well as ancillary services (cf. Kemfert et al., 2016) are: flexible conventional generation, VRES curtailment or management, demand-side management (DSM), PtX, battery electric vehicles (BEV) and stationary energy storage (SES) (cf. ewi, 2018).

The potential role of DSM is *inter alia* discussed in dena (2010) and Esmat et al. (2018a). The role of SES is for instance discussed by dena (2010), Agora (2016), Sinn (2017), Cebulla et al. (2018) and Blanco et al. (2018). Furthermore, both literature and NDP models assess substitution potentials of all mentioned flexibility options (Bauknecht et al., 2016; BNetzA, 2017; dena, 2018; Neetzow et al., 2018; NDP, 2019a-c).

C.4 Efficiency of R&D activities of the regulated electricity sector

Based on Harada (2018), an efficiency of R&D activities in the regulated electricity sector of 0.025 is assumed, interpreting the probabilistic value into a deterministic share. Even though Harada (2018) determines his values for the private sector, they can be applied to the regulated electricity sector as regulatory inefficiencies potentially decreasing R&D efficiency in the regulated sector compared to the private ones are incorporated in the variable U_t in the model.

C.5 Price ratio for ancillary services

The price ratio of ancillary services is set to $p^A = 1.$ Hence, the price for ancillary services in the economy is assumed to be the same as the average price level, as p^A expresses the price level of ancillary services as the share of the overall German national economy's price level, set as numéraire.

C.6 Price ratio for power grid infrastructure investment

Like the price ratio for ancillary services, the price ratio for power grid infrastructure investment is set to $p^{TD} = 1$.

C.7 Price ratio for regulated electricity sector's R&D activities

Like the price ratio for ancillary services and the price ratio for power grid infrastructure investment, the price ratio for regulated electricity sector's R&D activities is set to $p^D = 1$.

Appendix D: Exogenous shocks

D.1 Specification of shocks

Table D.6: Shocks specification, scenarios E to H

Var	Description	Shock specific.	Scenario E	Scenario F	Scenario G	Scenario H
I_τ^{TD}	Investment in transmission and distribution grid infrastructure	M* [*10^{-3}]	4.58058	3.9848	3.8713	2.2903
		D** [t]	τ^{ITD}; 64	τ^{ITD}; 64	τ^{ITD}; 64	τ^{ITD}; 64
Φ_τ	Externalities of connectivity and market size	M*	0.159297	0.105035	0.090497	0.0796485
		D** [t]	τ^{ITD}; $\tau^{ITD} = 0 \dots T$	τ^{ITD}; $\tau^{ITD} = 0 \dots T$	τ^{ITD}; $\tau^{ITD} = 0 \dots T$	τ^{ITD}; $\tau^{ITD} = 0 \dots T$
EG_τ^A	Ancillary services	M* [*10^{-3}]	1.05003	1.575045	1.05003	1.575045
		D** [t]	$t = 0$; $0 \dots \tau^{ITD}$	$t = 0$; $0 \dots \tau^{ITD}$	$t = 0$; $0 \dots \tau^{ITD}$	$t = 0$; $0 \dots T$
D_τ	Power grid operator R&D activities	M* [%]	n.a.	n.a.	n.a.	n.a.
		D** [t]	n.a.	n.a.	n.a.	n.a.
V_τ	Mismatch between power supply and demand, i.e. due to VRES integration	M* [%]	-0.01	-0.01	-0.01	-0.01
		D** [t]	t; T	t; T	t; T	t; T
A_τ^G	Factor productivity in final goods sector	M* [%]	n.a.	n.a.	n.a.	n.a.
		D** [t]	n.a.	n.a.	n.a.	n.a.
A_τ^E	Factor productivity in electricity supply sector	M* [%]	n.a.	n.a.	n.a.	n.a.
		D** [t]	n.a.	n.a.	n.a.	n.a.
S_τ^{EP}	Factor productivity in private electricity sector	M* [%]	n.a.	5	n.a.	n.a.
		D** [t]	n.a.	τ^{ITD}; $\tau^{ITD} = 0 \dots T$	n.a.	n.a.
U_τ	Regulatory inefficiencies	M* [%]	n.a.	n.a.	n.a.	n.a.
		D** [t]	n.a.	n.a.	n.a.	n.a.
Ψ_{NB}	Share of fee over debt finance	M* [%]		n.a.	n.a.	n.a.
		D** [t]		n.a.	n.a.	n.a.

* Magnitude
** Duration. One time period t equates 3 months. $\tau^{ITD} = 0$ designates the first period of investment in power grid infrastructure.

D.2 Magnitude of exogenous shocks

In the following, exogenous shocks, i.e. deviations from the SS, are defined and displayed as shares of SS output Y. It is assumed that the SS describes a state in which mismatches between supply and demand in the electricity supply sector are non-existent, i.e. that the variable V_t has no impact on the PF. Deviations, i.e. shocks, are further related to that state.

D.2.1 Power grid infrastructure investment I_{τ}^{TD}

To determine the magnitude of the shock for power grid infrastructure investments, planned power grid infrastructure investment volumes are presented converted to the model's overall economic output Y in the SS.

Therefore, firstly, four different cases of power grid infrastructure investments are determined from the investment volumes planned in the NDP (2019b,c) for transmission grid and the IAEW D2 2035 (2014) scenario[29] for distribution grid, displayed in Table A.7.

Table D.7: Transmission and distribution grid investment volumes

	Power grid infrastructure investment volumes [million €]					
	Transmission grid*				**Distribution grid****	
	A 2030	**B 2030**	**C 2030**	**B2035**	**D1 2035**	**D2 2035**
DC	30,000	30,000	30,000	35,000	n.a.	n.a.
AC	31,000	31,000	32,000	32,000	n.a.	n.a.
Total	*61,000*	*61,000*	*62,000*	*68,000*	*26,662.49*	*41,778.66*

* Values from scenarios in NDP (2019b,c), not discounted, induced OPEX excluded.
** Values as calculated based on IAEW (2014), not discounted, induced OPEX excluded
Source: Own representation, based on data from NDP (2019b,c) and IAEW (2014)

Firstly, two cases "as planned" are determined. Therefore planned investment volumes of scenarios B 2035 and D1 2035 and of B 2035 and D2 2035 are combined to determine a range of aggregated investment volumes until 2035. Hence $I_T^{TD,abs,min} = \sum_{\tau=1}^{T} I_{\tau}^{TD,abs,min} = € \, (68{,}000.00 + 26{,}662.49) \, mio = € \, 94{,}662.49 \, mio$ and $I_T^{TD,abs,max} = \sum_{\tau=1}^{T} I_{\tau}^{TD,abs,max} = € \, 109{,}778.66 \, mio$ are obtained. With $t \equiv 3$ months and the total investment period $T = (2035 - 2019) * 4 = 64$, $I_{\tau}^{TD,abs,min} = \frac{€ \, 94{,}662.49 \, mio}{64} = € \, 1{,}479.10 \, mio$ and $I_{\tau}^{TD,abs,max} = \frac{€ \, 109{,}778.66 \, mio}{64} = EUR \, 1{,}715.29 \, mio$ are obtained. A third and fourth case are determined, describing developments in which actual investments deviate from the planned ones. As it

[29] As the DSO other than the TSO do not publish an NDP, data about planned investments and investments in progress is not as detailedly available as data on TSOs' prospective investments. Investigations carried out by the German Energy Agency (dena, 2012) and the Federal Ministry for Economic Affairs and Energy (BMWi, 2015) anticipate investment requirements in the period from 2013 to 2022 between € 15,400 million and € 29,600 million and in the period from 2022 to 2032 between € 7,933 million and € 18,925 million (cf. IAEW et al., 2014: 49). Hence, these investigations project total investment requirements in the time period from 2013 to 2032 between € 23,333 million and € 48,525 million. Given historical investment data of the Monitoringbericht, 2018, cumulated investments in the time period from 2013 to 2018 amounted to € 20,799 million. Furthermore, the BMWi has announced investment volumes in 2019 of about € 10,400 million (cf. pv-magazine, 2019). In sum, these in-vestments amount to € 31,199 million. To date, investments have hence already sur-passed the minimum estimated total investment volumes of € 23,333 million until 2032. Hence, an orientation towards the upper end of the estimated spectrum when estimating future investment requirements seems more reasonable. From the considerations in IAEW (2014), the two still realistic scenarios are used, name them Scenarios D1 2035 and D2 2035, respectively, and extrapolate them, assuming linearity until 2035 for reasons of simplicity and comparability. Currently, different research projects holistically assess different new power grid structures and particularly different layout options for distribution grids including their potential techno-logical and economic design and characteristics. A central research project under BMWi patronage is the ENSURE project, in which demonstrator grids shall generate insights regarding the advantageousness of investment options. Currently, also cost structures are assessed and data about magnitude and composition of investment costs are generated.

becomes obvious from more closely considering the development of planned and realized power grid infrastructure investments throughout the NDP (2012 to 2019), a considerable number of investments is delayed, and it is thinkable that delays will persist also for future investments. Therefore a third case is considered in which only 50% of the overall prospective investments are realized, leading to $I_{\tau}^{TD,abs,delay} = \frac{0.5 * € \, 109{,}778.66 \, mio}{64} = € \, 857.65 \, mio$. A fourth case describes a "decentral" case, characterized by less transmission and more distribution grid investments. It is assumed that only 75% of the transmission grid investments of NDP scenario B 2035 are realized in combination with the D2 2035 distribution grid investments. It is $I_{\tau}^{TD,abs,decentral} = \frac{€ \, (0.75*68{,}000.00+41{,}778.66) \, mio}{64} = € \, 1{,}449.67 \, mio$.

Secondly, the introduced values converted to the size of Y in the model are presented. With a GDP of the German national economy of € 3,388.2 bn. in 2018 (destatis, 2019) and a conversion factor to Y of $2.67044 * 10^{-6}$, it is $I_{\tau}^{TD,min} = 0.0039848$, $I_{\tau}^{TD,max} = 0.0045806$, $I_{\tau}^{TD,delay} = 0.0022903$ and $I_{\tau}^{TD,decentral} = 0.0038713$.

D.2.2 Ancillary services EG_{τ}^{A}

We consider ancillary services based on the development of their aggregated annual cost. Costs for ancillary mechanisms have exhibited an increasing trend throughout the last years (Monitoringbericht, 2018: 178f; BNetzA, 2017a,2018a,b, 2019c). The intensified implementation of those mechanisms can predominantly be reasoned by increased shares of VRES having been integrated into the electricity system throughout the last years (Fraunhofer ISE, 2019). Power grid infrastructure investment can decrease spending for ancillary mechanisms by increasing system adequacy. Figure A.7 shows the development of costs for ancillary mechanisms as incurred on the transmission and distribution level in million Euro in Germany (primary axis), and of VRES shares as a percentage of total electricity generation in Germany (secondary axis).

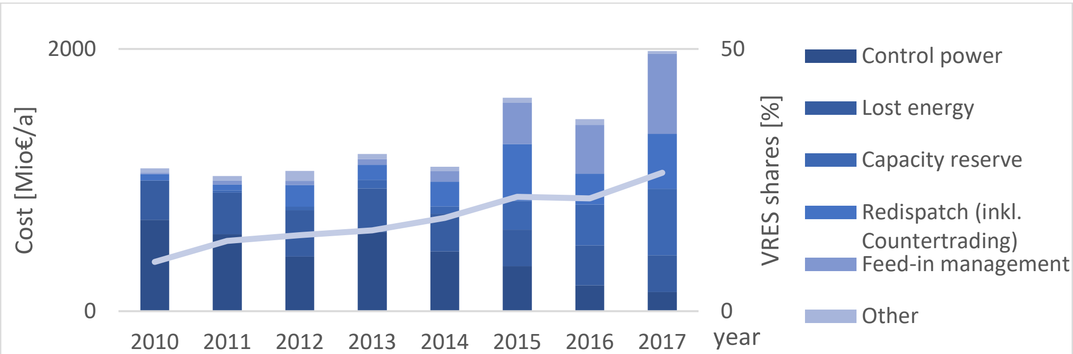

Figure D.6: Cost of ancillary mechanisms and VRES shares, Germany, 2010-2017

Source: Own representation, based on data from BNetzA (2017-2019); Fraunhofer ISE (2019)

For ancillary services, three cases are considered, based on the assumption of a linear ceteris paribus relation between VRES integration and cost for ancillary mechanisms[30] of the form

$$Cost\ [mio€] = 55.36 * VRES\ share\ [\%] + 521.57 \qquad (A.7)$$

For all cases, the planned RES shares of 60% until 2035 is assumed. With the assumption of constant non-VRES shares of 12.6%, VRES shares of $60.0\% - 12.6\% = 47.4\%$ until 2035 are obtained. In a first extreme case, power grid infrastructure investments successfully and fully mitigate the requirement for VRES-induced ancillary services and it is $EG_{\tau}^{A,nc,min} = 0$ [31]. In a second extreme case, it is assumed that deviations of supply and demand are fully compensated for by deploying more ancillary services. It follows a maximum per period value[32] of $EG_{\tau}^{A,nc,max} = \frac{€\ 3{,}145.634\ mio}{4} = €\ 786.4085\ mio$. As a mean case, it is assumed that 50% of the VRES-induced ancillary services are mitigated by power grid infrastructure investments, leading to $EG_{\tau}^{A,mean} = €\ 393.20425\ mio$. With the conversion factor as above of $2.67044 * 10^{-6}$, it is $EG_{\tau}^{A,min} = 0$, $EG_{\tau}^{A,max} = 2.10006$ and $EG_{\tau}^{A,mean} = 1.05003$.

D.2.3 Connectivity externalities Φ_t

Different connectivity externalities caused by transmission and distribution grid infrastructure investments are assumed. For transmission grid infrastructure, externalities are assumed to be comparably higher, amounting to 5% of the investment volumes. For distribution grid infrastructure, externalities are assumed to amount to 2% of the investment volumes.

D.2.4 Innovation activities of the regulated electricity sector D_{τ}

As investment in innovation is an integral part of many German TSOs' and DSOs' strategies (cf. e.g. Elia, 2019; TenneT, 2019a,b), the impact of innovation activities conducted by the regulated electricity sector is tested. Therefore, R&D investment volumes of $D_{\tau} = 0.3 * I_{\tau}^{TD}$ are inserted in the relevant scenario.

D.2.5 Mismatch between power supply and demand V_{τ}

Increases of the mismatch between supply and demand due to VRES integration of 10% compared to SS levels are tested. A precise determination of the variable can be done at a further stage of research.

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[30] Costs can be considered here, since $p^{TD} = 1$.

[31] VRES-induced ancillary services of 0 do not mean that there are no ancillary services, but that the levels of ancillary services go back to the pre-VRES integration ones.

[32] In the years before 2035, the deviation is less while in the years after 2035, due to also increasing VRES shares, the deviation further increases. Hence, a constant value of deviation over the simulated time period is assumed.

D.2.6 Energy efficiency in the final goods sector A_τ^E

Germany pursues the goal to decrease primary energy consumption of the overall national economy by 50% until 2050 compared to 2008. As primary instrument to achieve this goal, the federal government counts on energy efficiency, as embedded in the National Action Plan for Energy Efficiency (*Nationaler Aktionsplan Energieeffizienz*, NAPE). The NAPE points to the implementation of three policy instruments to increase energy efficiency (EE): Firstly, building refurbishments leading to increased EE of the building shall be subsidized. Secondly, EE measures shall be competitively tendered. Thirdly, EE networks particularly for the producing sectors shall be supported, aiming at a facilitated exchange about the most impactful and promising EE measures and production technologies (BMWi, 2014, 2019b).

With these specifications in mind, a scenario is tested in which EE measures are successfully implemented as planned, modeled as A_t^E, the energy efficiency in the final goods sector. Based on the considerations above and hence following the policy makers' logic, the 50% goal to decrease primary energy consumption in Germany is directly translated to the goal to increase EE in the German national economy by 50% until 2050. Considering historical data from the reference year for the EE goal until 2018, it is found that primary energy consumption in Germany has decreased by 10.29%, leading to a remaining goal of 39.71% decrease (cf. Umweltbundesamt, 2018).

D.2.7 Factor productivity in the private electricity sector S_τ^{EP}

For factor productivity in the private electricity sector, a randomly selected 10% efficiency increase is tested. In a prospective refined version of the model, the now exogenous variable shall be endogenized.

D.2.8 Efficiency of the institutional regime U_τ

D.2.8.1 General considerations

Many approaches are currently thought through and implemented to increase the efficiency of the institutional regime in Germany (cf. e.g. Younis, 2014; Buffie et al., 2016; Monitoringbericht, 2018). Therefore, a scenario is tested in which the efficiency of the institutional regime increases by 10%. Potential for improvements results from various inefficiencies in the status quo institutional regime, which can be assigned to the three categories of efficiency determinants for the institutional regime: Regulatory efficiency, market design and investment finance.

D.2.8.2 Regulatory efficiency, market liberalization and investment finance in the German case

In Germany, TSOs and DSOs are subject to incentive regulation in the form of a revenue-cap regulation since 2009 (*Anreizregulierungsverordnung*, ARegV). This mode of regulation allows TSOs and DSOs to pass on their costs through the power grid operation hierarchy via cost rollups to electricity consumers. The magnitude of allowable cost is hereby determined based on the general structure of a revenue-cap regulation,

$$RC_t = (BR_{t-1} - X) * RC_{t-1} \tag{D.8}$$

according to which the revenue cap RC_t in regulation period t is determined based on a reference value of basis revenues BR_{t-1} from period $t-1$ less a parameter X accounting for an efficiency increase during the regulation period times the revenue cap of the previous regulation period RC_{t-1}. In the German case, the formula to determine revenue caps (RC) and hence the allowable magnitude of network charges, anchored in Annex 1 to Art. 7 ARegV looks slightly longer

$$RC_t = CS_{pni,t} + \left(CS_{tni,t} + (1 - DF_t) * CS_{i,t} + \frac{I_0}{T}\right) * \left(\frac{CPI_t}{CPI_0} - PF_t\right) + CCD_t + Q_t + VC_t - VC_0 + S_t \tag{D.9}$$

including variables[33] primarily aiming at refining short- and long-term efficiency within utilities. The duration of one regulation period (RP) is 5 years according to Art. 3 Abs.2 ARegV. The determination of the different cost components is carried out by the BNEtzA, and predominantly based on benchmark methodologies[34]. Regulatory inefficiencies in the short term largely result from information asymmetries between the regulating authority BNetzA and the regulated utility company when determining the magnitude of the different variables included in Eq. (A.9), despite approaches to improvements, e.g. via the introduction of benchmark methodologies. In the long term, the structure of the RC determination itself as well as the imputability of investment costs to different RP has led and still leads to inefficiencies. As is visible from the general structure of the RC regulation (A.8), any efficiency increase, accounted for via X, leads to a decrease in the allowable revenue cap. Hence, utility companies can be disincentivized to invest in efficient technologies and innovation. Disincentives to invest have been reduced since the introduction of the 2016 amendment of the ARegV. According to the amendment, TSOs and DSOs have been enabled to adjust their non-influenceable cost shares in (A.9), via which they recover investment costs, within the same RP as the investment

[33] Equation (A.4) is valid from the third regulation period onwards. Variables are $CS_{pni,t}$, a permanently non-influenceable cost share, $CS_{tni,t}$ a temporarily non-influenceable cost share, DF_t distribution factor according to which existing inefficiencies shall be reduced throughout the regulation period, $CS_{i,0}$ an influenceable cost share, CPI the consumer price index, PF_t a productivity factor, EF_t an extension factor, Q_t surcharges and discounts on revenue caps, VC volatile cost shares, $\frac{I_0}{T}$ an inventory parameter, CCD_t a capital cost discount parameter and $S_t = \sum_{t=1}^{n} Q_t$, with $S_t = 0$ for $t = 0$. Indices 0 and t refer to a basis value or a value in the RP t respectively. The indicated parameters are further specified in Annexes 2-4 of the ARegV.

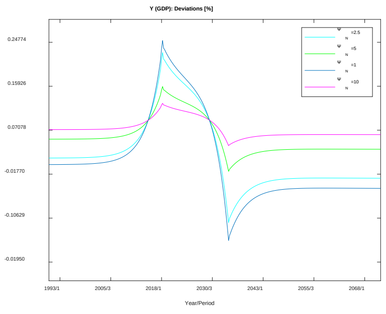
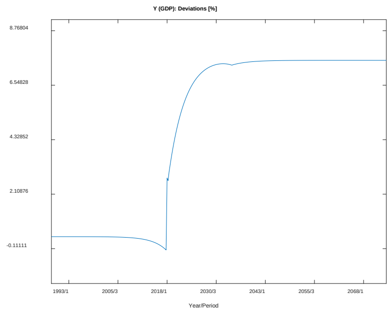
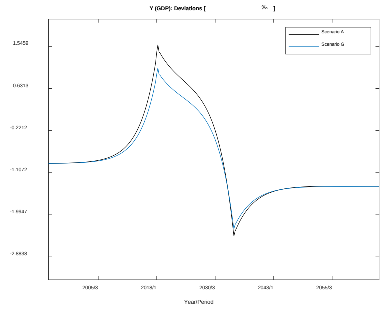
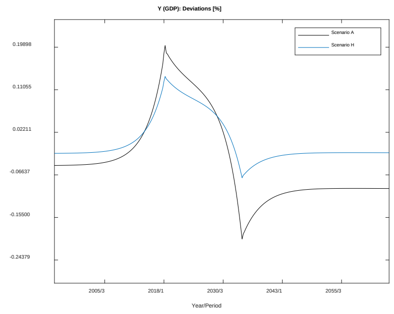
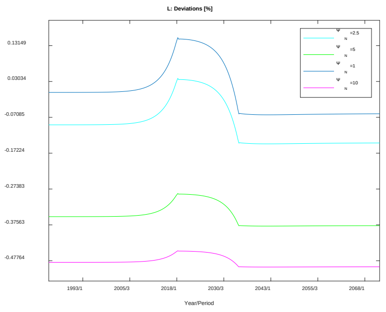
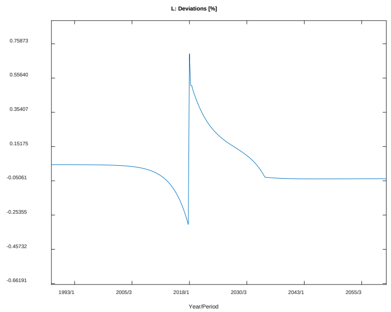
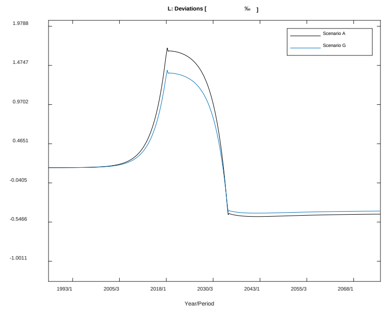
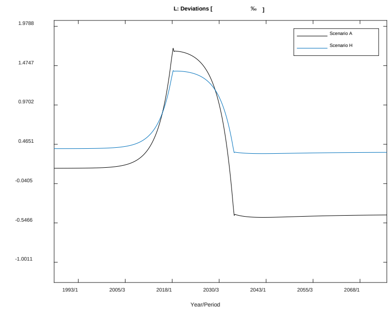
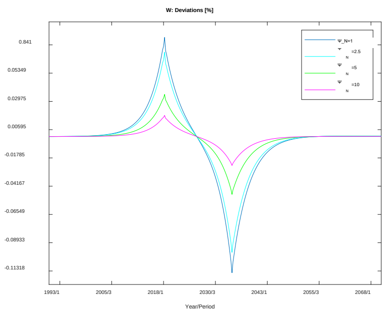
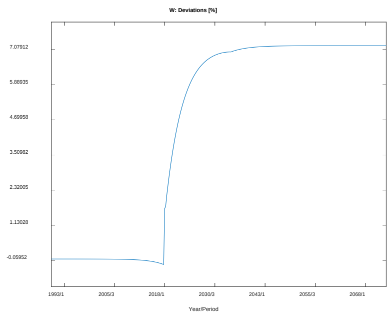
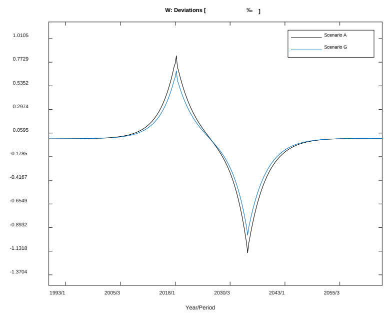
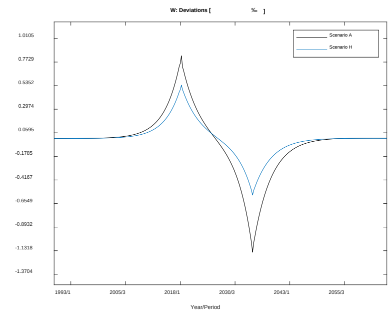
[34] The applied benchmark methodologies are the so-called Data Envelopment Analysis (DEA) and Stochastic Frontier Analysis (SFA), and are further described in the ARegV or related literature (cf. Subal et al., 2000; Cooper et al., 2004; Culliane et al., 2006).

and not as before only in the subsequent one, which in the worst case caused delays in cost recovery of five years. However, disincentives still persist: Investments remain subject to an ex post control through the regulator, and utility companies can only recover their upfront investment cost in case of the regulator's approval. Approaches to improve this constraint come down to the question of efficient risk allocation. Inhowfar the described disincentives distort economic efficiency and how efficiency improvements can be realized is subject to current investigation (Goetz et al., 2014; Monitoringbericht, 2018).

As the German electricity sector has been partially liberalized, competitive mechanisms in generation and retail stages of the value chain and regulating transmission and distribution stages have been introduced. This institutional setup and market design impact particularly long-term efficiency, i.e. efficiency in power grid infrastructure investment decision-making. In the German case, the coordination problem becomes evident when having a closer look at the investment decision-making process of TSOs. Investment decisions are based on different scenarios estimating future developments in the liberalized components of the electricity sector's value chain, i.e. generation or flexibility options potentially provided by liberalized agents such as storage or PtX applications. Further observing a rather low consistency of estimated scenarios throughout the 2010 to 2019 NDPs suggests that these estimates are rather inaccurate (NDP 2010-2019; Bundesnetzagentur, 2017). Hence, the likelihood that investments exhibit inefficiencies is high. Incentivizing investments based on the intensified introduction of market mechanisms in Germany, however, remains problematic. For efficiency increases, network charges would have to reflect the actual utilization of the power grid, which is not the case when connecting the allocation of network charges to the magnitude of energy consumption. Instead, usage fees would be the appropriate cost allocation scheme. However, for instance, in Germany no zonal or nodal pricing exists as a prerequisite and its introduction might face considerable political resistance. The realization of improvements to the present situation is, however, subject to ongoing research in the community.

Power grid infrastructure investment finance in the German case generally occurs via network fees. More detailed considerations which can also serve as a basis for a potential model refinement, can take for instance Mayer et al. (2018) as a starting point.

Appendix E

	Scenario E: Quasi-tax vs. debt finance	Scenario F: Innovative private el. sector	Scenario G: Decentral el. system	Scenario H: Delays and cancellations
Y_t				
L_t				
W_t				

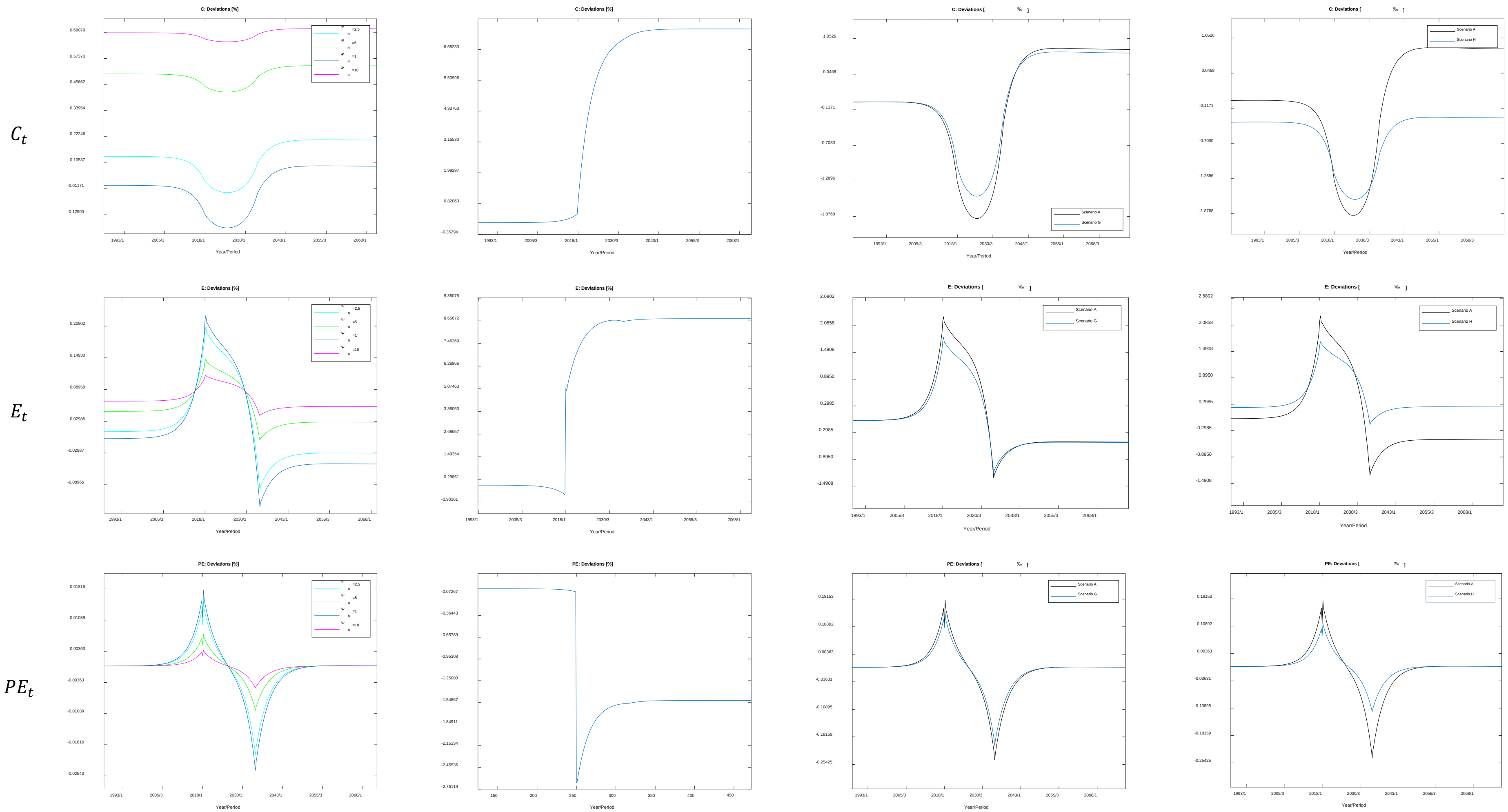


Figure E.7: DSGE model results for Scenarios E to H

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