HUMBOLDT-UNIVERSITÄT ZU BERLIN
Faculty of Life Sciences
Department of Agricultural Economics

No. 96/2019

Paul Neetzow

How to go green? The effects of power system flexibility on the efficient transition to renewable generation

WORKING PAPER

Imprint: Department of Agricultural Economics, Faculty of Life Sciences, Humboldt-Universität zu Berlin
c/o Kerstin Oertel, Philippstr. 13, Haus 12, 10099 Berlin
phone: +(49)-30- 2093 46325, e-mail: k.oertel@agrar.hu-berlin.de
https://www.agrar.hu-berlin.de/de/institut/departments/daoe/publ/wp

How to go green? The effects of power system flexibility on the efficient transition to renewable generation

Paul Neetzow[1]

[1] Resource Economics Group, Humboldt-Universität zu Berlin, Unter den Linden 6, 10099 Berlin, Germany

Corresponding author: Paul Neetzow (paul.neetzow@hu-berlin.de)

Abstract

For decarbonization purposes, variable renewable energies (VRE) are widely and quickly deployed in historically fossil-dominated power systems. Yet, some fossil technologies are more suitable than others for integration with VRE due to their higher flexibility. I utilize an analytically tractable model to study the optimal transition to a VRE-dominated system when the endowment of flexible and inflexible conventional generators is rigid. I find that the existence of inflexible fossil generators hampers early deployment of VRE. However, deployment speed increases after VRE begin to substitute generation from inflexible generators, which happens after VRE and inflexible capacities strictly exceed demand together. At this time, the decreasing use of inflexible fossil generation is usually accompanied by an increasing utilization of flexible generators. Nevertheless, constructing additional flexible capacities is only profitable under restrictive conditions. By contributing to a better understanding of the impact of flexibility on efficient VRE deployment, this work may facilitate an efficient transition process.

Keywords: energy transition, renewable energy, flexibility, rigid capacity endowment

JEL: C61, L94, Q41, Q42

1 Introduction

Decarbonizing society requires a broad transition to renewable energy sources in power generation (Williams et al. 2012). A major challenge is that many renewable energy sources like wind and solar power are characterized by variable availability. Nevertheless, electricity demand and supply need to be balanced at all times. As a consequence, an increasing need for system flexibility exists, for balancing purposes, in order to increase the capacities of variable renewable energies VRE (Hirth & Ziegenhagen 2015). During the transition phase, the existing endowment with fossil fuel-powered plants may provide this flexibility (Kubik et al. 2015). However, different conventional technologies are suited more than others to do this, e.g. due to differences in ramping times and minimum loads (Gonzalez-Salazar et al. 2017, Hentschel et al. 2016). For example, gas-fired plants can be dispatched rather flexibly, while coal and nuclear plants are less able to provide flexibility (Brouwer et al. 2015).

As an additional challenge, already existing and planned fossil power generation infrastructure is projected to push emissions beyond the carbon budget to achieve the 1.5 °C target if operated as historically (Tong et al. 2019). It follows that many power plants will have to be retired prematurely. Because of the high specificity of plants, it is thus very unlikely that the capacity mix of conventional and VRE plants will be at an optimal state or even follow an optimal path during the transition process. So far, this fact is often neglected and compromises the results of many recent studies on the efficient energy transition (e.g. Eisenack & Mier 2018, Ambec & Crampes 2019, Helm & Mier 2019).

Addressing these challenges, I distinguish between flexible and inflexible conventional generation technologies. I assume that their capacity endowment is rigid, i.e. it cannot be adapted to changing levels of VRE capacity. I address the following research questions: (i) What are the efficient power generation levels of all technologies? (ii) How does the efficient deployment path of VRE depend on the rigid endowment with flexible and inflexible conventional generation capacities? (iii) Under which conditions can it be beneficial to invest in additional flexible generation capacities?

To this end, I develop a theoretical model that incorporates four generation technologies: *VRE* with stochastic availability, cheap and inflexible *coal*, and medium expensive and flexible *gas* – all with respective capacity limits. Lastly, there is an expensive and flexible *backup* technology without a capacity limit. I assume that the flexible generators may react to the stochastic availability of VRE: they can make their decision after the availability is known, while the inflexible generation cannot react (cf. Eisenack & Mier 2018). I evaluate how a given inelastic electricity demand can be satisfied at least cost. I first derive the optimal generation levels for given capacities. Consequently, I obtain the efficient capacities of VRE for all possible endowments of (in)flexible conventional generators and for given VRE unit capacity costs (cf. Helm & Mier 2019). Furthermore, I evaluate the marginal benefits of adding further flexible generation capacities.

I find that the transition to a renewable power system crucially depends on the initial endowment with flexible and inflexible conventional generators. In general, coal capacities will suppress initial VRE deployment and gas capacities accelerate midterm VRE deployment. In the early phases of VRE deployment, coal generation is used at full capacity. During that time, VRE deployment substitutes gas generation. After coal generation and VRE generation at high availability strictly exceed the demand, some VRE generation is curtailed. At first, it is still cost-efficient to operate with coal at full capacity. Yet, for successively increasing VRE capacity, generation from coal decreases. Here, the efficient VRE deployment speeds up and is likely complemented by rising use of gas generation. At this stage, it might be worthwhile to add further flexible gas capacities. Finally, coal generation ceases, which in turn reduces the speed of efficient VRE deployment again. These findings may contribute to a more efficient planning of future power systems and the design of appropriate policies.

The remainder of the paper is structured as follows: First, I position the paper in the relevant literature. Next, in Section 3, I provide an overview of the theoretical model. In Section 4, I obtain the efficient dispatch for all technologies, while in Section 5, I analyze the optimal deployment of VRE and evaluate if it is viable to also increase flexible generation capacities during the transition. I discuss my results, conclude and provide an outlook in Section 6. The Appendices contain the nomenclature and formal proofs.

2 Related literature

The question of how to efficiently transition power systems to be more sustainable is subject to great research efforts. A common approach is the development of detailed numerical models. Those provide predictions or possible paths of power system development for specific regions and various (policy) scenarios.[1] Such models are well suited for specific analyses but less well suited for general insights on the fundamental principles of power systems. Cochran et al. (2014) provide a meta-analysis of twelve model studies evaluating the feasibility and implications of power systems with high shares of renewables for different countries and regions. They find that the technology mix varies significantly not only due to regional contexts but also because of different assumptions and model constraints.

Theoretical models are a useful supplement to simulations and provide a more general analysis of the relations of different infrastructure options. Results from the peak-load pricing literature provide insights about optimal dispatch and capacity decisions of generators (Steiner 1957), storage (Gravelle 1976) and transmission (Bohn et al. 1984, Lecinq & Ilic 1997, Neetzow et al. 2018). Furthermore, uncertainty (Chao 1983, Kleindorfer & Fernando 1993) or limits in generation flexibility (Eisenack & Mier 2018) can be included. In recent research, renewable energies were added to the picture. Chao (2011), Ambec & Crampes (2012) study optimal pricing and investment in power systems with VRE. Chao (2011) finds that VRE substitute conventional technologies with higher marginal

[1] Detailed numerical power system models are plentiful. Regional focuses include Europe (Haller et al. 2012, Schaber et al. 2012, Jägemann et al. 2013, Heide et al. 2010), the US (Fthenakis et al. 2009, Mai et al. 2014, Jacobson et al. 2015) or other regions (Lawrenz et al. 2018, Elliston et al. 2012, Mason et al. 2010).

generation costs and complement the ones with lower marginal generation costs. A related stream extends the considerations to include the design and efficiency of policies for VRE. Fischer & Newell (2008) analyze the nexus of policies and learning. More recently, Ambec & Crampes (2019) compare the efficiency between a carbon tax and VRE policy. Abrell et al. (2019) consider technology differentiated subsidies and Meya & Neetzow (2019) study simultaneous VRE support of multiple governance levels.

To analyze a system transition, a focus on the temporal progression of VRE deployment is needed. A number of studies have employed dynamic modeling approaches to study transition paths for replacing emission-intensive energy production with renewables. Amigues et al. (2015) study a situation where scarce conventional resources force a switch to renewable generation. In Coram & Katzner (2018) the transition is induced by an allowable emission stock. Although renewable deployment strictly decreases over time in the latter study, it initially increases in the prior study. The contrasting results are likely caused by differences in their cost assumptions. In a more elaborate model, Pommeret & Schubert (2019) also study a dynamic path to a renewable energy system. They take storage and different characteristics of renewables into account – including variability. Notably, they assume that there are abundant capacities of conventional generators. However, all these studies consider only one perfectly flexible conventional technology and that deployment costs stay constant over time.

Coulomb et al. (2018) also employ a dynamic approach, but they additionally distinguish conventional generation in abundant high-emission coal and scarce low-emission gas. They find that coal use strictly decreases for increasing renewable capacities, while gas use and gas capacities are initially increased and only reduced after coal generation fully ceases. In their analysis, renewable generation is deterministic and both conventional technologies are perfectly flexible, such that there are fixed rates of substitution between all generators. Further evaluations on gas use during power system transition include Baranes et al. (2017), who couple a theoretical analysis with empirical observations. They find that at high natural gas prices a further price increase substitutes VRE deployment, while for low prices there exists a complementary relation. They refer to the flexibility of gas to be used with VRE as a possible explanation.

In general, some studies conclude that gas can be a climate-beneficial complement to VRE because of its lower emission intensity compared to coal during power generation (Pless et al. 2015, Coulomb et al. 2018). In particular, this is the case if natural gas use can be substituted by renewable gas from biomass or electrolysis with excess renewable electricity (Mac Kinnon et al. 2018). On the other hand, increasing gas use may delay the switch to renewable generation (Zhang et al. 2016, Shearer et al. 2014, Stephenson et al. 2012). The net climate effect of gas does furthermore depend on the policies in place (Brown et al. 2018) and the speed of the transition (Hausfather 2015). While the generation flexibility is often acknowledged as one of the benefits of gas in tandem with VRE, none of the aforementioned studies models the flexibility explicitly.

The general role of flexibility for VRE integration is in the focus of a rich body of literature as laid out by the review papers of Lund et al. (2015) and Kondziella & Bruckner (2016). Lund et al. (2015) provide a helpful conceptualization of flexibility measures, where they distinguish demand and supply-side approaches, for example, as well as storage and other technology options. In addition to the flexibility of generators, they acknowledge the option of VRE curtailment. Kondziella & Bruckner (2016) conduct a meta-study on physical quantities of flexibility needed to integrate increasing shares of VRE. They find that flexibility requirements increase in relation to rising shares of VRE. Despite many studies on the need of flexibility, to the best of my knowledge, there are no theoretical approaches that take into account the impacts of limited generator flexibility on VRE deployment. In this sense, it is significant that Lund et al.'s (2015) section on supply side flexibility offers only one reference.

This paper closes the research gap on the effects of limited conventional flexibility on the efficient transition to VRE. To this end, I build on the work of Helm & Mier (2019), who analyze the efficient capacity mix of VRE and conventional generation for (exogenously) decreasing deployment costs of VRE. They find that once the maximum renewable generation is able to serve the full demand, efficient deployment and the replacement of fossil generators slows down and thus impedes the transition to a purely renewable power system. I enhance their approach by distinguishing between a flexible and an inflexible conventional generation technology. To do this, I follow Eisenack & Mier (2018), who expand the peak-load pricing literature by including limits on generation flexibility. As opposed to both of these studies, I do not assume that conventional capacities can be perfectly adapted to changes in VRE capacities. Instead, I consider an exogenous and rigid endowment which cannot be changed during the transition.

3 Model overview

I consider a power system that is initially endowed with coal (C) and gas (G) generation capacities only. Furthermore, variable renewable capacities (R) can be deployed. A backup technology (B) provides the power that is not generated (domestically) by the previous technologies. For instance, backup might represent the possibility to import power, some additional peak technology or even lost load. I consider an inelastic demand D, which must be satisfied by generation from the given capacities $D = \sum_j g^j, \; j = R, C, G, B$. The endowment with conventional capacities is assumed to have emerged historically to some non-necessarily optimal mix of coal and gas capacities. As their lifespans are long – compared to the time available to transition power systems (Tong et al. 2019) – capacities are fixed at some exogenous level.[2] The capacities K of the two conventional technologies are large enough to satisfy demand together but not alone, i.e., $K^C + K^G \geq D; K^C, K^G < D$. I assume that backup generation is not bound to a capacity limit. For VRE, I consider that unit capacity costs c^{KR} successively decrease, thus inducing an increase in efficient VRE capacity K^R.[3] I neglect depreciation of capital.

[2] In the initial system without VRE, there would be no reason to install flexible capacity for the given model setup (cf. Eisenack & Mier 2018). However, in reality, there are further uncertainties like fluctuating commodity prices and system flexibility is required not only because of VRE but also due to volatile demand. A first-best endowment is thus very unlikely.

[3] In the paper, I often explain how generation and capacities change "over time" when interpreting the results for falling VRE capacity costs. By doing so, I implicitly assume a linear cost decrease over time.

The realizable generation from the given VRE capacity is uncertain (cf. Ambec & Crampes 2012, Helm & Mier 2019). Its availability is given by the continuous random variable $\tau \in (0, 1)$. The effective VRE generation is bounded by the available generation capacity but can also be lower because of costless curtailment: $g^R \leq \tau K^R$. I assume that τ is uniformly distributed. The probability density function is then given as $f(\tau) = 1$ with cumulative function $F(\tau) = \tau$.

While gas and backup generation are assumed to be *flexible*, generation from coal is *inflexible*. Inflexible generation is not able to react to the variability of the renewable energy source. Thus, the coal generation dispatch has to be committed *before* the random variable τ realizes. As opposed to that, gas and backup generation can be dispatched *after* the realization of τ (cf. Eisenack & Mier 2018). The capacity unit generation costs c^j are considered to be constant and relate as follows: $c^B > c^G > c^C > c^R = 0$.

The model setup naturally implies multiple sequential levels of decision making. I assume that decisions are made by a benevolent planner that minimizes total system costs TC consisting of capacity costs for VRE $c^{KR}K^R$, with $c^{KR} > 0$ and dispatch costs DC for the electricity provision.[4] In the long run, the planner decides on the efficient VRE capacity for a given unit cost. In the short run, taking the capacities as fixed, she decides on the generation of coal *before* she knows about VRE availability, and on the generation of backup, gas and VRE *after* the availability has realized. Applying backward induction, in the following sections, I first address the short-run dispatch problem before turning towards the long-run efficient capacity decision.

4 Efficient generation with limited flexibility

4.1 Dispatch problem formulation

The problem of obtaining the efficient dispatch decisions for given capacities can be formulated as a two-level program which reflects the sequential decision-making process:

[4]Due to the integrated decision making without any strategic interactions, all decisions could also be made at once. However, a sequential structure facilitates the intuition and the clarity of the solution process.

$$\text{level 1:}\quad E[DC]^* = \min_{g^C} \; \left[c^C g^C + c^G E[g^G(\tau)] + c^B E[g^B(\tau)]\right] \tag{1}$$

s.t.

$$g^C - K^C \leq 0 \qquad (\lambda^C), \tag{2}$$

$$\text{level 2:}\quad DC^*(\tau) = c^C g^C + \min_{g^B, g^G, g^R} \left[c^G g^G(\tau) + c^B g^B(\tau)\right] \tag{3}$$

s.t.

$$D - g^C - g^G(\tau) - g^B(\tau) - g^R(\tau) = 0 \qquad (\alpha(\tau)), \tag{4}$$

$$g^G(\tau) - K^G \leq 0 \qquad (\lambda^G(\tau)), \tag{5}$$

$$g^R(\tau) - \tau K^R \leq 0 \qquad (\lambda^R(\tau)). \tag{6}$$

where positive shadow costs on the respective constraints are given in parenthesis. As τ is unknown when deciding on efficient coal generation, it intuitively follows that coal generation will not change for different realizations of τ.

First, before the realization of the VRE availability is known, coal generation is chosen to minimize expected ($E[\cdot]$) dispatch costs $E[DC]$ (Eq. 1). This decision is subject to the capacity constraint of coal generation (Eq. 2). Second, real dispatch costs are minimized by choosing generation from VRE, gas and backup technology for a given coal generation and the realized VRE availability (Eq. 3). This is done subject to the balancing constraint, which equalizes supply and demand (Eq. 4) and the capacity constraints for gas and VRE generation (Eq. 5, Eq. 6).[5]

Applying backward induction, I first solve the lower-level problem for any (exogenously) given coal generation and VRE availability. Consecutively, I solve for efficient coal generation under consideration of the optimality conditions of the lower-level problem and the expectations on the VRE availability.

4.2 Efficient generation of VRE, gas and backup plants

The efficient generation of VRE, gas and backup plants is given by the lower-level optimization problem Eqs. (3)-(6). The solution of this program yields three non-marginal dispatch states, which are formally specified in Lemma 1. They describe the optimal dispatch for a given generation g^C and a known realization of τ.

Lemma 1. *The optimal dispatch decision for given g^C and τ can be described by the three feasible states $\omega^B, \omega^G, \omega^R$.*

[5] There are also non-negativity conditions for generation. I consider those implicitly by allowing the optimality conditions following the Lagrangian $\mathcal{L}$ to be $\forall j : \frac{\partial \mathcal{L}}{\partial g^j} \geq 0$ for $g^j = 0$.

$$\omega^B : g^B(\tau) > 0 \implies \alpha(\tau) = c^B,$$
$$g^G(\tau) = K^G, g^R = \tau K^R, g^B(\tau) = D - K^G - g^C - \tau K^R \quad (7)$$
$$\omega^G : g^B(\tau) = 0, g^G(\tau) = D - g^C - \tau K^R > 0 \implies \alpha(\tau) = c^G,$$
$$g^R(\tau) = \tau K^R \quad (8)$$
$$\omega^R : g^B(\tau) = 0, g^G(\tau) = 0 \implies \alpha(\tau) = 0,$$
$$g^R(\tau) = D - g^C \leq \tau K^R. \quad (9)$$

Proof. See Appendix B. □

Lemma 1 specifies a merit order curve (Figure 1). Backup generation g^B is only used if gas generation g^G is at its capacity limit (state ω^B) and gas generation g^G is only used if coal and renewable generation together do not suffice to satisfy demand (ω^G). Finally, renewable generation together with g^C may satisfy demand (ω^R) with excess VRE potential curtailed. The obtained merit order is different from the standard merit order with VRE and fully flexible generation. Due to its early commitment and inability to react to the realization of VRE generation, the generation of coal rather than its capacity is pivotal. Furthermore, coal cannot be the marginal, i.e., price setting generator. As a consequence, even though it is efficient to use coal, the obtained merit order does not reflect its marginal generation costs. Instead, coal generation corresponds to the marginal costs of VRE generation, which I assumed to be zero. VRE and coal generation together represent a variable component that shifts the merit order right for high VRE availability and large coal use.

4.3 Efficient generation of coal plants

Next, I turn to the upper-level dispatch problem, i.e., the choice of an efficient coal generation. As the full range of possible VRE availabilities needs to be considered when dispatching coal, several of the three states $\omega^B, \omega^G, \omega^R$ might have to be taken into account with different probabilities. For high availability, there could be excess generation, while for low availability expensive gas and backup generation is needed. I call the union of states that might occur after the VRE availability realizes a *configuration of states.* The efficient coal generation can be obtained for any given configuration. To obtain the configurations, I first determine the switch between states. To this end, I define levels for the realization of VRE generation $\underline{\tau}, \overline{\tau} \in (0,1)$ such that $\underline{\tau}$ indicates the lowest level of realized VRE generation for which $g^B = 0$, i.e., no backup generation is needed; $\overline{\tau}$ indicates the lowest level of realized VRE generation for which $g^G = 0$, i.e., there is no gas generation needed after the realization of VRE availability. These levels $\underline{\tau}, \overline{\tau}$ determine the state configuration. If, for instance, under the given capacities a high VRE availability leads to state ω^R a medium availability to ω^G and a low availability to ω^B, I write the respective configuration as Ω^{RGB}. If, however, there is no use of the backup technology even for low VRE availability, this can be expressed by $\underline{\tau} = 0$ resulting in the configuration

Ω^{RG}. All theoretically possible relations between $\underline{\tau}, \overline{\tau}$ and the states' configurations are given in Table 1.

Table 1: Mapping of $\underline{\tau}, \overline{\tau}$ for different configurations of states. States excluded by assumptions in parenthesis.

	$\overline{\tau} = 0$	$0 < \overline{\tau} < 1$	$\overline{\tau} = 1$
$\underline{\tau} = 0$	(Ω^R)	Ω^{RG}	Ω^G
$0 < \underline{\tau} < \overline{\tau}$	n.a.	Ω^{RGB}	(Ω^{GB})
$\underline{\tau} = \overline{\tau}$	n.a.	(Ω^{RB})	(Ω^B)

Given for $\underline{\tau}$ that states ω^G and ω^B exist and for $\overline{\tau}$ that states ω^R and ω^G exist, I set the backup and gas generation from Eqs. (7) and (8) to zero, respectively yielding the levels of $\underline{\tau}, \overline{\tau}$:[6]

$$\begin{aligned} D - K^G - g^C - \underline{\tau} K^R = g^B = 0 &\implies \underline{\tau} = \frac{D - K^G - g^C}{K^R}, \\ D - g^C - \overline{\tau} K^R = g^G = 0 &\implies \overline{\tau} = \frac{D - g^C}{K^R}. \end{aligned} \tag{10}$$

Given the previous assumptions on coal and gas capacities, i.e., $K^C + K^G \geq D$ and $K^C, K^G < D$, the number of configuration can be reduced. For Ω^R, Eq. (10) would imply $g^C = D$. The configuration can thus be excluded. For Ω^{GB}, Ω^B, costs could be reduced by increasing coal generation. Hence, these configurations are only feasible if $g^C = K^C$. However, gas generation is always sufficient to satisfy demand if coal operates at its capacity limit and no backup generation would be needed. It follows that the configurations can be excluded. Finally, for Ω^{RB}, Table 1 together with Eq. (10) would imply that $K^G = 0$. Thus, the feasible configurations are $\Omega^G, \Omega^{RG}, \Omega^{RGB}$ (Figure 1).

The upper level optimization problem Eqs. (1), (2) can then be rewritten as:[7]

$$\begin{aligned} E[DC]^* =& \min_{g^C} c^C[g^C|\omega^R \vee \omega^G \vee \omega^B] + c^G[g^G|\omega^G \vee \omega^B] + c^B[g^B|\omega^B] \\ =& \min_{g^C} \Big[c^C g^C + \int_{\underline{\tau}}^{\overline{\tau}} c^G(D - g^C - \tau K^R)\mathrm{d}\tau \\ &+ \int_0^{\underline{\tau}} c^G K^G + c^B(D - K^G - g^C - \tau K^R)\mathrm{d}\tau \Big] \\ &\text{s.t. Eq. (2)} \end{aligned} \tag{11}$$

[6]Another way to obtain these levels is to endogenize them in the upper-level decision, i.e., to write Eq. (1) as $E[DC]^* = \min_{g^C, \underline{\tau}, \overline{\tau}} [...]$.

[7]Note in Eq. (11) that $\int ... \, \mathrm{d}F(\tau) = \int ... \, \mathrm{d}\tau$ due to the assumed uniform distribution of τ.

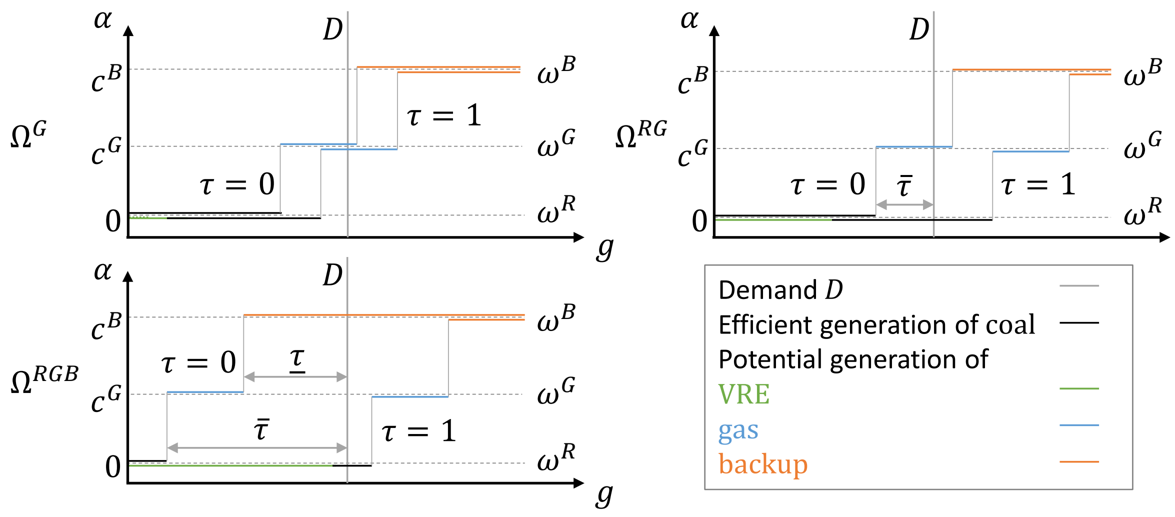

Figure 1: Feasible dispatch state configurations for different efficient choices for coal generation. The two curves for $\tau = 0$, $\tau = 1$ in each panel indicate the minimum and maximum VRE availability. All states – indicated by the possible intersections of supply and demand curves – covered for $\tau \in (0, 1)$ make up the configuration. Vertical shift of curves for illustrative purposes.

Cost for coal generation g^C occurs in all three states, costs for gas in states ω^G, ω^B and costs for backup generation only in state ω^B. The efficient levels of generation for g^B, g^G (Eqs. 7, 8) are directly inserted into the upper-level objective function and thereby satisfy the optimality of the lower-level problem (Eqs. 3-6).

The solution of this program provides the efficient choice of coal generation g^C for any given state configuration. However, within a configuration coal might hit its non-negativity or capacity generation constraint. As a consequence, I obtain five dispatch phases (I)-(V) that depend on the configurations of dispatch states as well as the efficient generation from coal. Each phase can be matched to a range of given VRE capacities. Lemma 2 provides the formal results.

Lemma 2. *Under the assumptions that coal and gas capacities are sufficient to satisfy demand together but not alone ($K^C + K^G \geq D$; $K^C, K^G < D$) there are five dispatch phases* (I)-(V) *which are associated with the following VRE capacity levels.*

$$K^R \in \begin{cases} \left(0, D - K^C\right) & \text{for (I),} \\ \left(D - K^C, (D - K^C)\frac{c^G}{c^C}\right) & \text{for (II),} \\ \left((D - K^C)\frac{c^G}{c^C}, K^G\frac{c^G}{c^C}\right) & \text{for (II),} \\ \left(K^G\frac{c^G}{c^C}, (D - K^G)\frac{c^B}{c^C} + K^G\frac{c^G}{c^C}\right) & \text{for (IV),} \\ \left((D - K^G)\frac{c^B}{c^C} + K^G\frac{c^G}{c^C}, \infty\right) & \text{for (V).} \end{cases} \tag{12}$$

For each phase the efficient coal dispatch differs because it is either linker to a distinct state configuration or hits a generation constraint as follows:

$$\Omega^G, g^C = K^C \qquad \text{for (I)}, \tag{13}$$
$$\Omega^{RG}, g^C = K^C \qquad \text{for (II)}, \tag{14}$$
$$\Omega^{RG}, g^C = D - K^R \frac{c^C}{c^G} \qquad \text{for (III)}, \tag{15}$$
$$\Omega^{RGB}, g^C = D - K^R \frac{c^C}{c^B} - K^G \left[1 - \frac{c^G}{c^B}\right] \qquad \text{for (IV)}, \tag{16}$$
$$\Omega^{RGB}, g^C = 0 \qquad \text{for (V)}. \tag{17}$$

Proof. See Appendix C. □

The relations obtained in Lemma 2 are visualized in Figure 2. For increasing capacities of VRE, i.e. along the phases (I) to (V), coal generation weakly decreases. For small VRE capacities, coal is used at its capacity limit. Interestingly, coal is still fully used when coal and VRE capacities exceed the demand together (Ω^{RG}). Here, if the VRE availability turns out high, VRE generation needs to be curtailed. For further increasing VRE capacity, coal generation starts to decrease linearly. The decrease is slowed after the backup generation must be used for low VRE availability (Ω^{RGB}). Finally, coal generation ceases only after VRE capacity strictly exceeds the demand.[8]

4.4 Expected generation of VRE, gas and backup

So far, I have obtained the efficient dispatch choices for any feasible configuration of dispatch states and related them to the level of VRE capacity. Yet, for VRE, gas and backup generation, the efficient choice depends on the realization of VRE availability. Still, for an unknown availability, I can obtain the expected generation of VRE, gas, and backup. The expected values indicate how generation changes in the long term for changing VRE capacities. Most interestingly, this yields information about the capacity factor of VRE as well as the use of the flexible gas generation. The expected generation of VRE, gas and backup can be obtained from:

$$E[g^R] = \int_{\overline{\tau}}^{1} D - g^C \mathrm{d}\tau + \int_0^{\overline{\tau}} \tau K^R \mathrm{d}\tau \tag{18}$$
$$E[g^G] = \int_{\underline{\tau}}^{\overline{\tau}} D - g^C - \tau K^R \mathrm{d}\tau + \int_0^{\underline{\tau}} K^G \mathrm{d}\tau \tag{19}$$
$$E[g^B] = \int_0^{\underline{\tau}} D - K^G - g^C - \tau K^R \mathrm{d}\tau. \tag{20}$$

[8]To see this, set $K^R \geq (D - K^G)\frac{c^B}{c^C} + K^G \frac{c^G}{c^C} > D$, rearrange to obtain $D(\frac{c^B}{c^C} - 1) > K^G(\frac{c^B}{c^C} - \frac{c^G}{c^C})$. Now notice that increasing the right-hand side of this inequality by substituting c^C for c^G tightens the inequality. Yet, simplifying to $D > K^G$ shows that it still strictly holds.

Inserting for the three feasible configurations the values for $\underline{\tau}, \overline{\tau}$ from Table 1 and Eq. (10) as well as the efficient coal generation (Lemma 2; summarized in Figure 2) directly yields the effective expected generation.[9]

In the following paragraphs, I further characterize the generation for all dispatch phases. For phase (I), the intuition goes that VRE and coal capacities are fully used but still too low to satisfy demand even for the highest availability of RE. This is because this phase only occurs for low VRE capacities. Thus, gas generation must be used no matter the VRE availability. Backup generation is not needed, because gas is always able to cover the remaining demand for fully used coal capacity. Here, any additional VRE generation is fully used and perfectly substitutes generation from gas. The switch to phase (II) marks the point where VRE generation at high availability and coal exceed the demand together. As a consequence, VRE generation is increasingly curtailed. Under (II), the full coal capacity will still be used. Here, due to curtailment, VRE generation can only imperfectly substitute the generation from gas. For further increasing VRE capacity, phase (III) will be reached, under which coal generation starts to be reduced and additional generation from gas guarantees the sufficient supply if VRE availability turns out low. From this point, we see an imperfect substitution of coal use for increasing VRE capacity (one additional unit of VRE decreases coal use by $\frac{c^C}{c^G} < 1$ units; see Eq. 15). Expected gas generation and substitution under (III) can be obtained from Eq. (19) as

$$\text{for (III):} \quad E[g^G] = \frac{K^R}{2}\left[\frac{c^C}{c^G}\right]^2 \iff \frac{\mathrm{d}E[g^G]}{\mathrm{d}K^R} = \frac{1}{2}\left[\frac{c^C}{c^G}\right]^2 > 0. \tag{21}$$

Notably, the expected generation from gas is imperfectly complemented by VRE capacity (one additional unit of VRE increases expected gas use by $0 < \frac{1}{2}\left[\frac{c^C}{c^G}\right]^2 < \frac{1}{2}$ units).

Gas use under low VRE availability is now successively increased up to the point where gas generation reaches its capacity limit in the case that no VRE generation is available ($g^G(\tau \to 0) \to K^G$). This implies the switch to phase (IV), where demand must additionally be covered from the backup generation. The expected gas and VRE generation follow from Eqs. (18), (19) and imply

for (IV):

$$\frac{\mathrm{d}E[g^R]}{\mathrm{d}K^R} = \left[\frac{K^G}{K^R}\right]^2 \frac{(c^B - c^G)^2}{2(c^B)^2} + \frac{c^C}{c^B}\left[1 - \frac{c^C}{c^B}\right] > 0, \tag{22}$$

$$\frac{\mathrm{d}E[g^G]}{\mathrm{d}K^R} = \left[\frac{K^G}{K^R}\right]^2 \left[\frac{c^G}{c^B} - \frac{1}{2}\right] \gtreqless 0 \iff 2c^G \gtreqless c^B. \tag{23}$$

While expected VRE generation is strictly concavely increasing for additional VRE capacities, expected gas generation may increase if its marginal generation costs are rather

[9] I abstain from showing all explicit results, which are mostly inconveniently complex and of no great importance for the implications of the paper. Still, I make further use of some of them in the following and provide a better intuition on their outcomes.

large or decrease if they are small compared to the costs of backup.[10] Hence, the relation of expected gas generation and VRE capacity is ambiguous, but low gas and high backup cost generally increase their substitutability. For coal generation, there is always a substitution with additional VRE capacity. Contrary to the effect on gas, the substitution effect grows stronger as the the marginal costs of the backup technology shrink (per additional unit of VRE capacity, $\frac{c^C}{c^B}$ units of coal generation are substituted; see Eq. 16).

Finally, for high VRE capacity, coal generation ceases, which marks the switch to phase (V). This leads to a lower utilization rate, i.e., higher curtailment rates, of additional VRE capacity as it may no longer substitute the decreasing generation from coal. While expected VRE generation asymptotically approaches the demand, expected generation from gas and backup asymptotically approach zero. An overview of the relation of configurations, VRE capacity and (expected) generation is given in Figure 2. Proposition 1 summarizes the results.

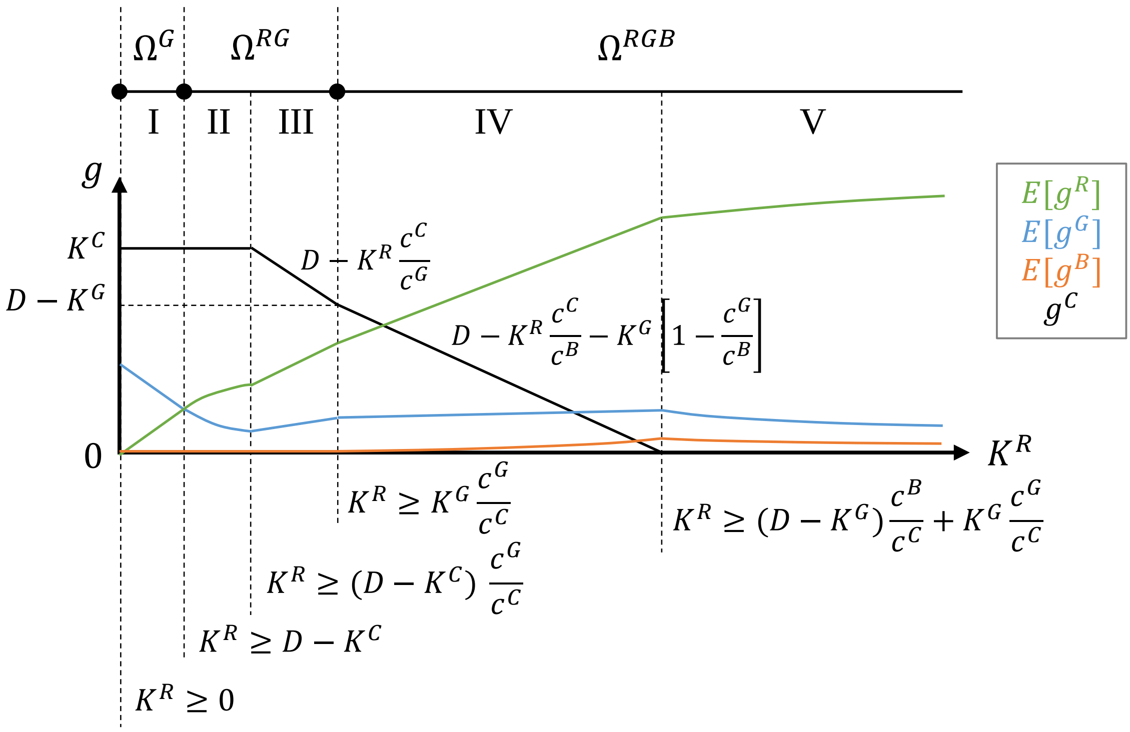

Figure 2: Relation of phases, VRE capacity and efficient (expected) generation.

Proposition 1. *For $K^R \leq (D - K^C)\frac{c^G}{c^C}$, coal is used at full capacity and increasing VRE capacity reduces the efficient gas generation. For $K^R > (D - K^C)\frac{c^G}{c^C}$, efficient coal use starts to decrease and use of gas generation rises if either $K^C + K^G > D$ or $c^G > c^B/2$. Eventually for $K^R \geq (D - K^G)\frac{c^B}{c^C} + K^G\frac{c^G}{c^C}$, coal generation ceases while expected VRE generation approaches total demand and expected gas and backup generation approach zero.*

[10] If this result appears counter intuitive, note that efficient expected gas generation is indeed decreasing in its marginal costs. Only the change upon changing VRE capacity is positively related to its costs.

5 Efficient transition to renewable generation

We have seen that the expected changes in utilization for different power generation capacities is far from a linear process when VRE capacities are increased. While expected VRE generation is sometimes linear and sometimes concave in its capacity, the expected generation from gas and backup is in parts decreasing or increasing. These characteristics of efficient power generation affect the efficient deployment dynamics of VRE capacities. Furthermore, under some circumstances, it might pay off to increase flexible gas capacities to facilitate the VRE integration, i.e., by reducing the need for coal or backup generation as well as VRE curtailment. In the following, I first analyze the efficient deployment of VRE capacities for falling unit capacity costs. Consecutively, I evaluate under what circumstances it can be efficient to increase gas capacities to be used as a transition technology while moving towards a fully renewable power generation.

5.1 Deployment of VRE capacities

To obtain the optimal choice of VRE capacities, I minimize expected total costs $E[TC]$ from dispatching generation and deploying VRE at a constant unit cost c^{KR} (cf. Helm & Mier 2019):

$$E[TC]^* = \min_{K^R} E[DC]^* + c^{KR}K^R. \tag{24}$$

As laid out before, I assume that coal and gas capacities are exogenous and thus not subject to the decision. Inserting the efficiency conditions for generation from Lemmas 1, 2 into the configuration specific solutions for $\underline{\tau}, \overline{\tau}$ together with Table 1 yields the following FOCs:

$$\text{(I)}: \frac{\partial E[TC]^*}{\partial K^R} = -\frac{c^G}{2} + c^{KR} \geq 0, \tag{25}$$

$$\text{(II)}: \frac{\partial E[TC]^*}{\partial K^R} = -\left(\frac{D - K^C}{K^R}\right)^2 \frac{c^G}{2} + c^{KR} \geq 0, \tag{26}$$

$$\text{(III)}: \frac{\partial E[TC]^*}{\partial K^R} = -\frac{(c^C)^2}{2c^G} + c^{KR} \geq 0, \tag{27}$$

$$\text{(IV)}: \frac{\partial E[TC]^*}{\partial K^R} = -\left(\frac{K^G}{K^R}\right)^2 \frac{c^B c^G - (c^G)^2}{2c^B} - \frac{(c^C)^2}{2c^B} + c^{KR} \geq 0, \tag{28}$$

$$\text{(V)}: \frac{\partial E[TC]^*}{\partial K^R} = -\frac{c^B(D - K^G)^2 + c^G K^G(K^G - 2D)}{2(K^R)^2} + c^{KR} \geq 0. \tag{29}$$

The derivatives might be larger than zero only if $K^R = 0$, i.e., if VRE capacities are constrained by their non-negativity condition.

I have already proven that efficient VRE capacities increase throughout the phases from (I) to (V). Thus, following Eq. (25), there exists a maximum level of unit capacity cost for VRE: $c^{KR} = c^G/2$. If unit capacity costs are higher than this, no VRE capacity will be deployed. The level is a direct consequence of the substitution of gas generation in the case of low VRE capacity. Due to the expected generation of half its capacity, unit costs of VRE capacities must fall below half the generation costs of gas to be competitive. In other words, the levelized costs of VRE generation, which amount for $2c^{KR}$, must fall below the ones of gas, c^G.[11] Furthermore, the conditions do not depend on the VRE capacity for phases (I) and (III). Here, the marginal benefits of VRE deployment due to reduced dispatch costs are constant. As a consequence, there is only one particular equilibrium for a distinct level of marginal costs. For (I) that implies that for $c^{KR} = c^G/2$ VRE capacities are immediately deployed up to the switch into phase (II). Similarly, at $c^{KR} = (c^C)^2/2c^G$ there is an immediate switch from (II) to (IV) with a possibly instantaneous increase in VRE capacity. Solving the FOCs of phases (II),(IV),(V) for positive K^R yields the efficient choice of VRE capacity:

$$(\text{II}) : K^R = (D - K^C)\sqrt{\frac{c^G}{2c^{KR}}}, \tag{30}$$

$$(\text{IV}) : K^R = K^G\sqrt{\frac{(c^B - c^G)c^G}{2c^B c^{KR} - (c^C)^2}}, \tag{31}$$

$$(\text{V}) : K^R = \sqrt{\frac{D^2 c^G + [D - K^G]^2 (c^B - c^G)}{2c^{KR}}}. \tag{32}$$

In all three phases VRE capacity is convex in its unit capacity costs. To see this, generalize to $K^R = \frac{s}{\sqrt{tc^{KR} - u}}$, where s is some strictly positive constants and t, u are strictly positive constants in (IV) and $t = 2, u = 0$ in (II), (V). K^R is convex in c^{KR} if the second derivative is positive, i.e., $\frac{\mathrm{d}^2 K^R}{(\mathrm{d}\ c^{KR})^2} = \frac{3st^2}{4(tc^{KR} - u)^{5/2}} > 0$. That clearly holds for $u = 0$ and hence (II) and (V). It also holds for $tc^{KR} - u > 0$. In Eq. (31), the denominator generalized as $tc^{KR} - u$ must be strictly positive to obtain a real solution for K^R. Thus, the second derivative will also be positive for (IV).

As a consequence, if unit capacity costs decrease linearly over time, there will be an accelerated deployment of VRE capacity within each phase. However, deployment may be slowed again after switching phases. Furthermore, and as hypothesized, the endowment with gas and coal capacities affects the efficient deployment of VRE. In phase (II), coal capacity has a suppressing effect on VRE deployment, while gas capacity has no effect. In phases (IV), (V) where coal capacity is never fully used, efficient VRE deployment only depends on the gas endowment. In phase (IV), VRE deployment is positively proportional to gas endowment, while gas capacity reduces VRE deployment during phase (V). Furthermore, the endowment may affect the switch between phases. This is not the case between the phases (I)-(IV) because of the constant efficient values for c^{KR} in (I) and

[11] Usually levelized costs contain capacity and dispatch costs. Here, they are simplified as I neglect capacity cost of gas and assume that VRE dispatch costs are zero.

(III). The switching cost between (IV), (V) can be obtained from equalizing Eqs. (31), (32) to obtain

$$\widetilde{c^{KR}} = \frac{(c^C)^2(c^B(D-K^G)^2 + c^G(2D-K^G)K^G)}{2(c^B(D-K^G)+c^GK^G)^2}. \tag{33}$$

The derivative with respect to gas capacity

$$\frac{\mathrm{d}\widetilde{c^{KR}}}{\mathrm{d}K^G} = \frac{(c^C)^2(c^B-c^G)c^GDK^G}{(c^B(D-K^G)+c^GK^G)^3} \geq 0, \tag{34}$$

which is strictly larger than zero for strictly positive gas capacity shows that increasing gas capacities imply a switch from (IV) to (V) at higher costs. Figure 3 sketches these findings, Proposition 2 summarizes them.

Proposition 2. *Deployment of VRE capacity becomes efficient as soon as its levelized costs are lower than the ones of gas* $2c^{KR} \leq c^G$*. Under the assumption of constant unit VRE capacity costs, VRE deployment is instantaneously undertaken until* $K^R = D - K^C$*. If VRE capacity costs fall further, efficient VRE capacity increases convexly until* $c^{KR} = \frac{(c^C)^2}{2c^G}$*. Here, VRE deployment is instantaneously increased up to* $K^R = K^G\frac{c^G}{c^C}$*. For consecutively falling costs, efficient VRE capacity increases again convexly with a kink when coal generation ceases.*

It is informative to also analyze the two extremes of possible endowment in which either coal or gas capacities approach the total demand while the other tends to zero.[12] If gas capacity approaches the total demand and coal capacity approaches zero, the initial deployment of VRE capacity given from the maximum level of unit capacity cost and Eq. (30) reaches $K^R = D$. Notably, this amount is the maximum of Eq. (30) and any additional coal capacity reduces the initial deployment. Due to the high level of flexibility in the gas dominated system, only after $K^R > D$ VRE curtailment becomes necessary for high VRE availability. Now, if capacity costs decrease further, VRE capacity will follow from Eq. (30). Due to $K^G \to D, K^C \to 0$, phase (V) follows directly on (II) at $K^R \geq K^G\frac{c^G}{c^C}$. This can be seen directly from the VRE capacities that induce switching (Eq. 12), but it is also intuitive as phases (III), (IV) are characterized by $g^C > 0$. Now looking at phase (V), i.e., Eq. (32) with $K^G \to D$, one sees that the efficient solution for VRE deployment is simplified to the solution in phase (II), Eq. (30). Thus, for this system after the instantaneous deployment of VRE capacity in phase (I), there is a smooth and continuous increase in VRE capacity for falling unit capacity costs.

Next, I analyze a mostly inflexible system with coal endowment approaching the full demand and gas approaching zero. Following directly from Eq. (31), there will be no

[12] Remember that by assumption $K^G, K^C < D; K^G, K^C > 0$. Relaxing this might lead to other feasible configurations and thus other outcomes for efficient VRE deployment. We may, however, analyze scenarios that are arbitrarily close to the extremes, i.e., $K^G \to D, K^C \to 0; K^G \to 0, K^C \to D$.

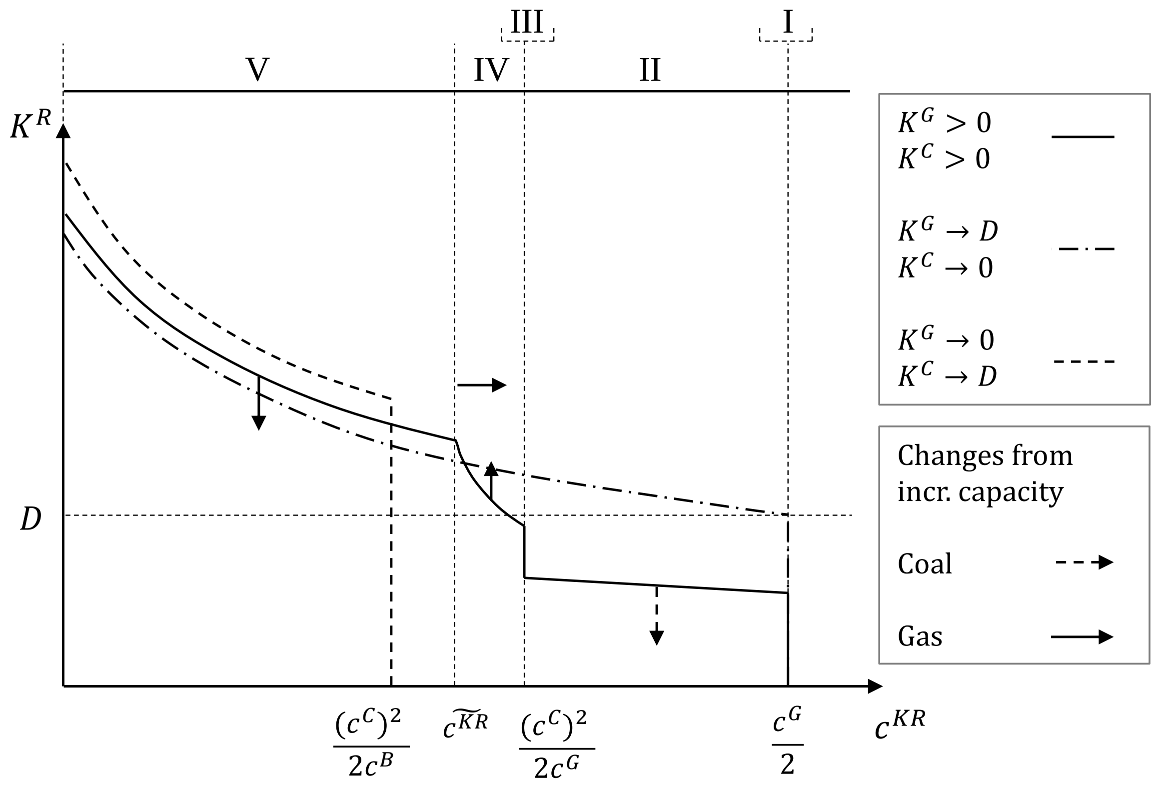

Figure 3: Optimally deployed VRE capacity for given unit capacity costs and different endowment with coal and gas capacities. The displayed phases (I) to (V) correspond to the scenario with mixed capacities ($K^G > 0, K^C > 0$). Arrows indicate changes due to increasing coal or gas capacities. Read from right to left, i.e., phase (I) to (V) such that VRE unit capacity costs are decreasing and VRE deployment is increasing.

VRE deployment during phase (IV) and thus neither for (I)-(III) because VRE capacities must always increase for consecutive phases. In phase (V) with $K^G \to 0$ it is required that $K^R \geq D\frac{c^B}{c^C}$ (Eq. 12). Inserting this in Eq. (32), I obtain the maximum VRE unit capacity cost for which it is efficient to deploy VRE to be $c^{KR} = \frac{(c^C)^2}{2c^B}$. This cost level is strictly lower than the one in a system with gas capacity ($\frac{c^G}{2}$). Thus, VRE capacity deployment in a coal only system starts later than in a more flexible system with gas generators. As soon as the maximum cost level is reached, VRE capacities are instantaneously deployed up to a level of $K^R = D\frac{c^B}{c^C}$, while coal generation stops. As I have shown that gas capacities in phase (V) suppress VRE deployment from that point on and for further falling capacity costs, the efficient VRE capacity exceeds the one in the systems with gas capacity reaching $K^R = D\sqrt{\frac{c^B}{2c^{KR}}}$ (following Eq. 32).

The results on the extremes of possible conventional endowment are also visualized in Figure 3. Comparing the mixed endowment with the two extremes, we see that VRE deployment with mixed capacities starts at the same costs as in a fully flexible system. Yet, the efficient VRE deployment turns out to be lower the larger the coal capacities are. When VRE capacity costs are low enough, coal starts to be phased out. At this point there is a boost in VRE deployment, which quickly approaches and finally exceeds the efficient path in the fully flexible endowment scenario.[13] Interestingly, this acceleration in VRE deployment occurs only after VRE curtailment is already necessary due to large capacities. If there is only inflexible endowment, the beginning of VRE deployment will be delayed. However, as soon as deployment starts, VRE capacities will even exceed the ones in the flexible or mixed systems.

5.2 The use of gas as a transition technology

It is often debated whether flexible conventional generators, in particular gas-fired plants, are necessary for the transition to a renewable power system (e.g. Shearer et al. 2014, Hausfather 2015). On the one hand, gas generation has a rather low CO_2-intensity. From a climate perspective, it is thus preferable to coal. Furthermore, due to greater flexibility gas can cope better with variable generation from renewable capacities (Mac Kinnon et al. 2018). On the other hand, increased use of gas might delay the transition to VRE and thus confer climate benefits (Zhang et al. 2016). In Section 4, I analyzed when and how persisting gas plants should be operated during the transition to high shares of VRE. Here, I examine whether and when it might be efficient to invest in new flexible (gas) generators. As before, I focus on the cost and flexibility aspects of the different technologies. Hence, my analysis complements the work of Coulomb et al. (2018), who assume a perfectly flexible generation of coal and gas and an allowable budget of CO_2 emissions.

It is efficient to invest in additional gas capacities if the expected dispatch cost reduction from new capacities exceed their marginal costs. Here, I depict the dispatch cost reduction as the marginal benefits of capacity (MB). As opposed to the levelized costs approach, the costs from additional gas generation are thus reflected in the marginal benefits and are weighed against savings in coal and backup generation. I assume that marginal capacity costs are constant and given as c^{KG}.[14] The expected marginal benefits, i.e., dispatch cost reduction, of investing in gas for given VRE and coal capacities are given as

$$E[MB^G] = -\frac{\mathrm{d}E[DC]^*}{\mathrm{d}K^G}. \tag{35}$$

Lemma 1 shows that gas capacities are only utilized at their full capacity when also backup generation is used. This is only the case for phases (IV), (V). Thus, for (I)-(III) it is obvious that additional gas capacities have no benefit because they would not be used. Inserting the efficiency conditions for generation from Lemmas 1, 2 and the configuration specific solutions for $\underline{\tau}, \overline{\tau}$ together with Table 1 into Eq. (35) yields the following expected marginal benefits for gas capacity:

[13] Even though it is not directly obvious from the formal results on VRE capacity, VRE deployment must be higher in the mixed scenario because it starts lower in phase (II) and ends up higher in (V).

[14] As my approach is static, c^{KG} could be interpreted as marginal cost per time unit of operation.

$$(\text{IV}) : E[MB^G] = \left(1 - \frac{c^G}{c^B}\right)\left(c^C - c^G \frac{K^G}{K^R}\right), \tag{36}$$

$$(\text{V}) : E[MB^G] = (c^B - c^G)\frac{D - K^G}{K^R}. \tag{37}$$

The switching condition for phase (IV) $K^R \geq K^G \frac{c^G}{c^C} \implies c^C - c^G \frac{K^G}{K^R} \geq 0$ implies that $E[MB^G] \geq 0$ in phase (IV). Furthermore, the expected marginal benefits strictly increase for rising VRE capacity in phase (IV) and strictly decrease in phase (V). As a consequence, $E[MB^G]$ are maximized at the switch from (IV) to (V). Their maximum, $E[\overline{MB}^G]$, can be derived by inserting the respective switching VRE capacity (Eq. 12) into either Eq. (36) or (37). It is

$$E[\overline{MB}^G] = c^C \frac{(c^B - c^G)(D - K^G)}{c^B(D - K^G) + c^G K^G}. \tag{38}$$

Setting $E[\overline{MB}^G] = c^{KG}$ and solving for K^G yields the maximum efficient gas generation capacity:

$$\overline{K}^G = \frac{D}{c^B - c^G}\left[c^B - \frac{c^C c^G}{c^C - c^{KG}}\right]. \tag{39}$$

It can only be efficient to deploy additional gas capacities if the initial endowment is strictly lower than $\overline{K}^G$, which increases in the marginal generation cost of backup and coal.[15] Interestingly, this capacity does not depend on the initial endowment with coal capacity. As a consequence, even if gas capacities are chosen to be optimal, there can be overcapacity, i.e. coal and gas capacities combined exceed demand. Remember, however, that the assumption of $K^C + K^G \geq D$ underlies the analysis. Thus, coal and gas capacity will in general not operate at their capacity limits at the same time and their efficient capacities are independent.

Setting $\overline{K}^G > 0$, I derive the highest unit capacity cost of gas which may still lead to an efficient positive gas capacity deployment:

$$\overline{K}^G > 0 \iff c^{KG} < c^C \left[1 - \frac{c^G}{c^B}\right]. \tag{40}$$

If this unit cost for gas capacity is exceeded, it can never be efficient to deploy additional gas capacities even if there were none in the original endowment. On the one hand, this

[15] The respective derivatives are $\frac{\mathrm{d}\overline{K}^G}{\mathrm{d}c^B} = \frac{c^G c^{KG} D}{(c^B - c^G)^2(c^C - c^{KG})} > 0$; $\frac{\mathrm{d}\overline{K}^G}{\mathrm{d}c^C} = \frac{c^G c^{KG} D}{(c^B - c^G)(c^C - c^{KG})^2} > 0$. Note, that in this static consideration it must be $c^C > c^{KG}$ as otherwise generation from coal would always be preferred over gas capacity extension.

cost threshold is directly proportional to the marginal generation cost of coal. In fact, the VRE capacity at the switch from (IV) to (V) where gas capacity is most valuable is inversely proportional to the marginal cost of coal generation. Thus, if coal generation is more expensive, coal will be phased out at lower VRE capacities, inducing higher benefits for gas capacity. On the other hand, if the marginal generation cost of gas generation approaches the marginal cost of backup, then the marginal benefits of gas capacity tend to zero. This is intuitive as backup generation without any capacity constraints may then be used instead of gas.

The here derived threshold values (Eqs. 38-40) are obtained for the situation where gas capacity is most valuable. However, additional gas capacities would certainly be deployed for a range of VRE capacities as those will increase while the plant is in operation. As a consequence, taking into account some temporal deployment dynamics, the actual thresholds for the efficiency of gas capacity additions are even more restrictive.[16] Whether it is efficient to deploy additional gas capacities during the transition then also depends on other factors as the transition speed. For instance, if the transition is slow, additional gas capacity might operate close to its maximum value for a long time, thus increasing its cost-efficiency. Proposition 3 summarizes the findings.

Proposition 3. *Expected marginal benefits of gas capacity are positive while gas generation is used at its capacity limit. They reach their maximum when coal generation ceases. Yet, it is never efficient to deploy more than the maximum efficient gas capacity* $\overline{K}^G = \frac{D}{c^B - c^G}\left[c^B - \frac{c^C c^G}{c^C - c^{KG}}\right]$ *or to deploy any additional capacities if the unit capacity costs reach or exceed the upper bound* $c^{KG} = c^C\left[1 - \frac{c^G}{c^B}\right]$. *The efficiency conditions for gas deployment are even more restrictive if temporal deployment dynamics are considered.*

6 Conclusion

I have studied how different endowments of flexible conventional plants affect the efficient transition to a renewable power system. I show that limited flexibility does hamper early deployments of VRE. Later, during the phases when inflexible generation is reduced, the VRE capacity increases quickly, even exceeding the efficient levels of fully flexible systems. Thus, when VRE capacities are already very high, the limits in conventional generator's flexibility have no impairing effect on their deployment. However, the limits on flexibility lead to more discontinuations in the VRE deployment along the transition path (cf. Helm & Mier 2019).

As opposed to the cost-efficient path with partly surging and partly stagnating VRE deployments, regulators may prefer a rather smooth transition to avoid sudden disruptions in the power system or the associated labor market and to synchronize other infrastructure development. As a consequence, regulators of rather inflexible power systems could decide to increase VRE subsidies or to promote research in VRE during the early deployment

[16]Of course the per time unit costs c^{KG} increase proportionally to a longer time period while the benefits of gas capacity decrease.

phases to facilitate the transition. Increasing flexibility, for instance by installing flexible generators or storage, does not facilitate early VRE deployment. The policy support can be reduced when VRE deployment speeds up, such that the transition path is smoothed over time.

Another core result is that it can be efficient to utilize flexible, inflexible and VRE capacities at the same time. This contradicts the assertion from Eisenack & Mier (2018) that inflexible generation can in general not be efficiently used together with VRE. The difference can be traced back to their assumption of optimal capacity choice while I consider non-optimal and rigid endowment of coal and gas. Even though their approach is reasonable for long-term planning, the need for a quick shift from mostly conventional to VRE-based power systems necessitates acknowledging off-equilibrium transition dynamics.

Concerning the role of gas as a transition technology, I show that the expected generation from flexible plants is likely to increase for rising capacity shares of VRE due to the increased need for flexible generation (cf. Kondziella & Bruckner 2016). This finding persists under the consideration of a binding emission budget as shown by Coulomb et al. (2018). As opposed to my approach, they differentiate coal and gas by their respectively higher and lower emission intensities (and not by their flexibility potential). They obtain a qualitatively similar result: gas use increases in the interim, while coal generation falls and VRE capacities are increased. The alignment of the results from flexibility and emission perspectives facilitates the power system transition as low-emission plants have flexibility co-benefits and vice versa. Nonetheless, evaluating the ultimate efficiency of deploying new gas capacities will require the comprehensive analysis of cost, climate and flexibility issues of all technologies.

The generality of my results may be impacted by the employment of static optimization instead of the use of a dynamic approach. In particular, this simplification disregards the fact that the VRE endowment changes over a capacity's lifespan and thus affect benefits over time. For instance, additional VRE deployment will reduce the benefits of existing VRE capacities. Coram & Katzner (2018) undertake a dynamic analysis and find that efficient deployment decreases over time. However, they consider constant unit capacity costs at all times. Assuming decreasing costs may easily shift their results and induce deployment increases over time. Also empirically the worldwide VRE deployment has increased in the last two decades (Ritchie & Roser 2019). While a dynamic analysis might depict a promising extension for future research, I expect my main results to carry over.

Evaluating my assumption of inelastic demand can be done by comparing the extreme endowment scenario where gas capacity approaches total demand with findings of Helm & Mier (2019), who consider reactive consumers but no inflexibility. Generally, inelastic demand is a reasonable and common assumption for electricity markets, for instance, because many consumers are not subject to wholesale market prices (Lijesen 2007). Still, there are some modeling specifics to be addressed. An inelastic demand curve can only intersect the merit order supply curve at horizontal levels, implying constant marginal benefits of VRE as long as the marginal generation technology does not change. As opposed to that, an elastic demand leads to decreasing marginal benefits of VRE deployment when intersecting vertical parts of the merit order curve. Thereby, it also increases the number of dispatch phases that need to be considered. As a consequence, in Helm & Mier (2019) there are no instantaneous increases in efficient VRE deployment. By applying these insights to the scenario with mixed endowment of coal and gas, I expect that the VRE deployment path is smoothed, in particular at the switches between different phases. Nevertheless, I expect the general findings on the effects of limited flexibility to persist. Here, my results underline the importance of considering the interplay between generation variability and the flexibility of conventional generators for efficient VRE deployment.

Furthermore, I follow a cost-minimizing approach that neglects most institutional and market features of power systems. Such features might include market structures (e.g. zonal vs. nodal pricing), market concentration, subsidies for renewable generation or deployment, prices on carbon and payment for capacity reserves (Newbery et al. 2018). Hence, the findings do not predict real-world VRE deployment, but rather a desirable path. If policies shall be designed to achieve an efficient power system transition, it is necessary to determine the optimal transition path as well as possible challenges beforehand. My paper contributes to advancing knowledge in this direction by emphasizing the role of flexibility for efficient transitions.

The obtained results apply to power systems worldwide. In particular, the openness towards all feasible conventional endowment scenarios allows the nuanced interpretation of countries and regions with distinct characteristics. Furthermore, the inflexible and flexible capacities can be understood not only as coal and gas, but also as other generation technologies. For instance, they might depict generation from nuclear and oil or even from renewable generation with similar characteristics in terms of generation costs and flexibility. Furthermore, applications beyond power systems are conceivable. The limits on flexibility might also apply to other sectors like transport, telecommunications or food production (Eisenack & Mier 2018). In the case that also the endowment with production assets is rigid, the insights from this paper might be transferable.

To conclude, regulators and operators of power systems should be cautious when extrapolating past data on efficient VRE deployment into the future because, during the transition, deployment can successively speed up and be suppressed. Furthermore, cross-regional spillovers of knowledge on power system transitions might be limited if the capacity endowments of the systems are different. Therefore, it is all the more important to gain differentiated insights on efficient deployment strategies that can facilitate the transition towards sustainable power systems.

Future research may address the influence of further flexibility options like demand-side management, storage or grids. Those options are integral towards the realization of a fully renewable power system. The time and extent to which they must be implemented will be highly relevant for power system transitions and probably depend greatly on the flexibility of endowed plants. Furthermore, the developed theoretical model can be quantified with empirical data. In turn, the results can be compared to the extensive body of numerical studies that analyze efficient system transitions for different regions. This might be informative, especially concerning the effects of limited flexibility, which is so far seldom considered. Finally, my approach, which considers rigid instead of optimized conventional capacities, can be extended to study asset stranding of fossil fuel-based power system infrastructures.

Appendix A Nomenclature

$\tau \in (0,1)$	Random variable determining VRE availability
$j \in \{R, C, G, B\}$	Generation technology for VRE, coal, gas, backup
g^j	Generation of technology j [kW]
D	Demand [kW]
K^j	Capacity of technology j [kW]
c^j	Marginal generation cost of technology j [$/kW]
c^{Kj}	Unit capacity cost of technology j [$/kW]
DC	Dispatch costs [$]
TC	Total costs [$]
$E[\cdot]$	Expectation operator
$\omega^R, \omega^G, \omega^B$	Instantaneous dispatch states
$\Omega^G, \Omega^{RG}, \Omega^{RGB}$	Feasible dispatch state configurations
α	Shadow cost of balancing constraint [$/kW]
λ^j	Shadow cost on capacity constraints [$/kW]
MB^G	Marginal benefits of gas capacity [$/kW]

Appendix B Proof of Lemma 1

Proof. The Lagrangian of that problem reads (no longer explicitly indicating the dependence on τ):

$$\begin{aligned}\mathcal{L}(\tau) = c^C g^C + c^G g^G + c^B g^B + \left[D - g^C - g^G - g^B - g^R\right]\alpha \\ + \left[g^G - K^G\right]\lambda^G + \left[g^R - \tau K^R\right]\lambda^R \end{aligned} \tag{41}$$

The first order optimality conditions (FOCs) including their complementary slackness conditions are then:

$$\frac{\partial \mathcal{L}(\tau)}{\partial g^B} = c^B - \alpha \begin{cases} = 0 \\ \geq 0 \end{cases} \iff g^B \begin{cases} > 0 \\ = 0 \end{cases}, \tag{42}$$

$$\frac{\partial \mathcal{L}(\tau)}{\partial g^G} = c^G - \alpha + \lambda^G \begin{cases} = 0 \\ \geq 0 \end{cases} \iff g^G \begin{cases} > 0 \\ = 0 \end{cases}, (g^G - K^G)\lambda^G = 0, \tag{43}$$

$$\frac{\partial \mathcal{L}(\tau)}{\partial g^R} = -\alpha + \lambda^R \begin{cases} = 0 \\ \geq 0 \end{cases} \iff g^R \begin{cases} > 0 \\ = 0 \end{cases}, (g^R - \tau K^R)\lambda^R = 0. \tag{44}$$

From the FOCs it follows that the shadow price for power generation α may take three different values for non-marginal cases. If backup generation is used $g^B > 0$ we have $\alpha = c^B$. As a consequence, the shadow costs of generating with gas or VRE are strictly positive: $\lambda^G(\tau) > 0, \lambda^R(\tau) > 0$ and thus the available capacities are fully utilized $g^G(\tau) = K^G, g^R(\tau) = \tau K^R$. The solution for g^B then directly follows from the balance in Eq. (4). I denote this state by ω^B as backup generation is the marginal, i.e., price setting, technology.

Otherwise, there might be no backup generation needed $g^B = 0$, either because there is a higher renewable availability or ex-ante more coal generation. If additionally there is strictly positive and below capacity limit gas generation $0 < g^G < K^G$, this implies $\lambda^G = 0 \implies \alpha = c^G$. Hence, the marginal value of electricity is given by the marginal cost of using gas generation. As before, it follows that $\lambda^R(\tau) > 0 \implies g^R(\tau) = \tau K^R$. The solution for g^G directly follows from Eq. (4). The transition between the state ω^B and this state occurs at the point where there is no more backup generation but gas still operates at capacity limit $g^B = 0, g^G = K^G$. It marks a marginal boundary case as VRE generation is at its limit and coal generation exogenous (cf. Eq. 4). Hence, this state will only be reached for exactly one realization of (the continuous) τ and thus with probability zero. Due to the assumption of fixed demand, there is no unique equilibrium for the marginal value of electricity in this case. Instead, there is a continuum of equilibria such that $\alpha \in (c^G, c^B)$. For completeness, I assume that in this state $\lambda^G = 0 \implies \alpha = c^G$.[17] I denote this state by ω^G as gas generation is the marginal, i.e., price setting, technology.

Finally, there might be no backup and no gas generation needed $g^B = 0, g^G = 0$. If VRE generation is strictly positive and under the maximum available amount, i.e., $0 < g^R < \tau K^R$ it follows that $\alpha(\tau) = 0$. Note, that $g^R > 0$ must be satisfied following Eq. (4) as I assumed $K^C < D$. Similar to the line of argument above and with the same implications, the probability that coal generation must exactly be complemented by the full available VRE generation to satisfy demand is only marginal (cf. Eq. 4). If the availability is lower, gas generation is needed (implying ω^G) and if it is higher there is excess VRE generation which is curtailed $g^R < \tau K^R$. For completeness, I assume that in the marginal state of $g^C + \tau K^R = D$ that $\lambda^R = 0 \implies \alpha = 0$. The solution for g^R directly follows from Eq. (4). I denote this state by ω^R as VRE generation is the marginal, i.e., price setting, technology.

□

Appendix C Proof of Lemma 2

Proof. The Lagrangian of Eq. (11) reads:

[17] The marginal value of electricity is thus obtained from the marginal generation cost and not from the maximum willingness to pay. This issue of multiple equilibria could be fixed if one allows for some demand elasticity (cf. Helm & Mier 2019). However, this comes at the cost of an increased number of states which greatly increases complexity. More caution is required if capacity levels are optimized because optimally chosen capacities are usually fully utilized hence greatly increasing the probability that boundary cases occur (cf. Eisenack & Mier 2018).

$$
\begin{aligned}
\mathcal{L} = & \int_{\overline{\tau}}^{1} c^C g^C \mathrm{d}\tau + \int_{\underline{\tau}}^{\overline{\tau}} c^C g^C + c^G (D - g^C - \tau K^R) \mathrm{d}\tau \\
& + \int_{0}^{\underline{\tau}} c^C g^C + c^G K^G + c^B (D - K^G - g^C - \tau K^R) \mathrm{d}\tau \\
& + (g^C - K^C)\lambda^C . \qquad (45)
\end{aligned}
$$

Solving the integrals for the three feasible configurations by inserting the values for $\underline{\tau}, \overline{\tau}$ from Table 1 and Eq. (10) and taking the derivative with respect to g^C yields the following FOCs, where the conditions in Eq. (49) holds for all prior equations.

$$
\Omega^G : \frac{\partial \mathcal{L}}{\partial g^C} = c^C - c^G + \lambda^C \begin{cases} \geq 0 \\ = 0 \end{cases} , \qquad (46)
$$

$$
\Omega^{RG} : \frac{\partial \mathcal{L}}{\partial g^C} = c^C - c^G \frac{D - g^C}{K^R} + \lambda^C \begin{cases} \geq 0 \\ = 0 \end{cases} , \qquad (47)
$$

$$
\Omega^{RGB} : \frac{\partial \mathcal{L}}{\partial g^C} = c^C - c^G \frac{K^G}{K^R} - c^B \frac{D - g^C - K^G}{K^R} + \lambda^C \begin{cases} \geq 0 \\ = 0 \end{cases} , \qquad (48)
$$

$$
\iff g^C \begin{cases} = 0 \\ > 0 \end{cases} , (g^C - K^C)\lambda^C = 0. \qquad (49)
$$

For Ω^G it is clearly $\lambda^C > 0$ and thus

$$
\text{for } \Omega^G : g^C = K^C . \qquad (50)
$$

For Ω^{RG}, if $g^C = 0$, gas generation would need to be able to cover the full demand if $\tau = 0$, i.e., $K^G \geq D$, which I have excluded by assumption. Thus, it must be $g^C > 0$ and solving Eqs. (47), (49) for g^C yields

$$
\text{for } \Omega^{RG} : g^C = \begin{cases} K^C & \text{if } \lambda^C > 0, \\ D - K^R \frac{c^C}{c^G} & \text{if } \lambda^C = 0. \end{cases} \qquad (51)
$$

Finally, for Ω^{RGB}, it must be $g^C < K^C$ and hence $\lambda^C = 0$ because for $g^C = K^C$ coal and gas generation would always be able to cover demand even in times with no VRE availability. Thus, as backup generation is needed, coal generation must be below its full capacity. For $g^C > 0$, the efficient solution for coal generation is obtained by solving

Eq. (48) for g^C. However, for large VRE capacities, this solution may turn negative. This can be avoided by considering the non-negativity constraint for coal generation:

$$\text{for } \Omega^{RGB} : g^C = \begin{cases} D - K^R \frac{c^C}{c^B} - K^G \left[1 - \frac{c^G}{c^B}\right] > 0, \\ 0. \end{cases} \tag{52}$$

The obtained five combinations of dispatch states and efficient coal generation, which I call phases in the following, correspond to the ones given in Lemma 2. Next, I provide the order of these phases and obtain the conditions on K^R that distinguish them.

Imagine starting from nearly zero capacities of VRE, i.e., $K^R \to 0$, and then successively increasing this capacity. For very low VRE capacity, $g^C + g^R < D$ and thus ω^R cannot occur. As two of the three feasible configurations include the state ω^R only Ω^G obtains for low VRE capacities. Efficient coal generation is given in Eq. (50). I define this as the phase (I). Once combined VRE and coal generation are sufficient to satisfy demand at least for the highest VRE availability ($\tau = 1$), we have the switch from Ω^R to Ω^{RG}. Following Lemma 1 and Eq. (51) this is the case once $K^R \geq D - K^C$, which can also be seen from setting $\overline{\tau} \leq 1$ in Eq. (10). To determine when it is efficient to use less than the full capacity, I set $g^C < K^C$ in Eq. (51) with $\lambda^C = 0$. Solving for VRE capacity yields $K^R \geq (D - K^C)\frac{c^G}{c^C}$, which is clearly larger than $D - K^C$, i.e., the VRE capacity where the switch to Ω^{RG} occurs. Hence, only after this threshold is reached and within Ω^{RG} coal generation falls under its capacity limit. I define phase (II) as Ω^{RG} with $g^C = K^C$ and phase (III) as Ω^{RG} with $g^C < K^C$.

For even higher VRE capacities, coal generation might get so low that gas is insufficient to cover demand at low VRE availability. This indicates the switch from Ω^{RG} to Ω^{RGB}. To obtain the respective level of VRE capacity, set $\underline{\tau} \geq 0$ in Eq. (10), insert g^C from Eq. (52) and solve for VRE capacity to obtain $K^R \geq K^G \frac{c^G}{c^C}$. Note further that $K^G \frac{c^G}{c^C} \geq (D - K^C)\frac{c^G}{c^C}$ directly follows from the assumption that $K^C + K^G \geq D$. If exactly $K^C + K^G = D$ their will be a direct switch from full capacity coal use in Ω^{RG} to Ω^{RGB}. I define phase (IV) as Ω^{RGB} with $g^C > 0$. For an even further increase of VRE capacity, efficient coal generation ceases. To obtain the associated level of VRE capacity set $g^C \leq 0$ in Eq. (52) and solve to obtain $K^R \geq (D - K^G)\frac{c^B}{c^C} + K^G \frac{c^G}{c^C}$. I define phase (V) as Ω^{RGB} with $g^C = 0$. □

Acknowledgements

I gratefully acknowledge funding by the Reiner Lemoine-Stiftung. Additionally, parts of the work have been funded by the German Ministry for Education and Research under Grant No. 01LA1811C (Social-Ecological Research). I thank Mathias Mier, Achim Hagen and Christoph Sproul for comments on earlier drafts of the paper. Preliminary versions of the paper were presented and discussed at AURÖ young researchers Workshop 2019 in Kassel and EAERE Conference 2019 in Manchester.

References

Abrell, J., Rausch, S., & Streitberger, C. (2019). The economics of renewable energy support. *Journal of Public Economics*, *176*, 94–117.

Ambec, S., & Crampes, C. (2012). Electricity provision with intermittent sources of energy. *Resource and Energy Economics*, *34*, 319–336.

Ambec, S., & Crampes, C. (2019). Decarbonizing electricity generation with intermittent sources of energy. *Journal of the Association of Environmental and Resource Economists*, *forthcoming*.

Amigues, J.-P., Kama, A. A. L., & Moreaux, M. (2015). Equilibrium transitions from non-renewable energy to renewable energy under capacity constraints. *Journal of Economic Dynamics and Control*, *55*, 89–112.

Baranes, E., Jacqmin, J., & Poudou, J.-C. (2017). Non-renewable and intermittent renewable energy sources: Friends and foes? *Energy Policy*, *111*, 58–67.

Bohn, R. E., Caramanis, M., & Schweppe, F. (1984). Optimal pricing in electrical networks over space and time. *RAND Journal of Economics*, *15*, 360–376.

Brouwer, A. S., van den Broek, M., Seebregts, A., & Faaij, A. (2015). Operational flexibility and economics of power plants in future low-carbon power systems. *Applied Energy*, *156*, 107–128.

Brown, T., Bischof-Niemz, T., Blok, K., Breyer, C., Lund, H., & Mathiesen, B. (2018). Response to 'Burden of proof: A comprehensive review of the feasibility of 100% renewable-electricity systems'. *Renewable and Sustainable Energy Reviews*, *92*, 834–847.

Chao, H.-p. (1983). Peak load pricing and capacity planning with demand and supply uncertainty. *The Bell Journal of Economics*, *14*, 179.

Chao, H.-p. (2011). Efficient pricing and investment in electricity markets with intermittent resources. *Energy Policy*, *39*, 3945–3953.

Cochran, J., Mai, T., & Bazilian, M. (2014). Meta-analysis of high penetration renewable energy scenarios. *Renewable and Sustainable Energy Reviews*, *29*, 246–253.

Coram, A., & Katzner, D. W. (2018). Reducing fossil-fuel emissions: Dynamic paths for alternative energy-producing technologies. *Energy Economics*, *70*, 179–189.

Coulomb, R., Lecuyer, O., & Vogt-Schilb, A. (2018). Optimal transition from coal to gas and renewable power under capacity constraints and adjustment costs. *Environmental and Resource Economics*, *73*, 557–590.

Eisenack, K., & Mier, M. (2018). Peak-load pricing with different types of dispatchability. *Oldenburg Discussion Papers in Economics*, *V-411-18*.

Elliston, B., Diesendorf, M., & MacGill, I. (2012). Simulations of scenarios with 100% renewable electricity in the Australian National Electricity Market. *Energy Policy*, *45*, 606–613.

Fischer, C., & Newell, R. G. (2008). Environmental and technology policies for climate mitigation. *Journal of Environmental Economics and Management*, *55*, 142–162.

Fthenakis, V., Mason, J. E., & Zweibel, K. (2009). The technical, geographical, and economic feasibility for solar energy to supply the energy needs of the US. *Energy Policy*, *37*, 387–399.

Gonzalez-Salazar, M. A., Kirsten, T., & Prchlik, L. (2017). Review of the operational flexibility and emissions of gas-and coal-fired power plants in a future with growing renewables. *Renewable and Sustainable Energy Reviews*, *82*, 1497–1513.

Gravelle, H. S. E. (1976). The peak load problem with feasible storage. *The Economic Journal*, *86*, 256.

Haller, M., Ludig, S., & Bauer, N. (2012). Decarbonization scenarios for the EU and MENA power system: Considering spatial distribution and short term dynamics of renewable generation. *Energy Policy*, *47*, 282–290.

Hausfather, Z. (2015). Bounding the climate viability of natural gas as a bridge fuel to displace coal. *Energy Policy*, *86*, 286–294.

Heide, D., von Bremen, L., Greiner, M., Hoffmann, C., Speckmann, M., & Bofinger, S. (2010). Seasonal optimal mix of wind and solar power in a future, highly renewable Europe. *Renewable Energy*, *35*, 2483–2489.

Helm, C., & Mier, M. (2019). On the efficient market diffusion of intermittent renewable energies. *Energy Economics*, *80*, 812–830.

Hentschel, J., Babić, U., & Spliethoff, H. (2016). A parametric approach for the valuation of power plant flexibility options. *Energy Reports*, *2*, 40–47.

Hirth, L., & Ziegenhagen, I. (2015). Balancing power and variable renewables: Three links. *Renewable and Sustainable Energy Reviews*, *50*, 1035–1051.

Jacobson, M. Z., Delucchi, M. A., Bazouin, G., Bauer, Z. A. F., Heavey, C. C., Fisher, E., Morris, S. B., Piekutowski, D. J. Y., Vencill, T. A., & Yeskoo, T. W. (2015). 100% clean and renewable wind, water, and sunlight (WWS) all-sector energy roadmaps for the 50 United States. *Energy & Environmental Science*, *8*, 2093–2117.

Jägemann, C., Fürsch, M., Hagspiel, S., & Nagl, S. (2013). Decarbonizing Europe's power sector by 2050 — Analyzing the economic implications of alternative decarbonization pathways. *Energy Economics*, *40*, 622–636.

Kleindorfer, P. R., & Fernando, C. S. (1993). Peak-load pricing and reliability under uncertainty. *Journal of Regulatory Economics*, *5*, 5–23.

Kondziella, H., & Bruckner, T. (2016). Flexibility requirements of renewable energy based electricity systems – a review of research results and methodologies. *Renewable and Sustainable Energy Reviews*, *53*, 10–22.

Kubik, M., Coker, P. J., & Barlow, J. F. (2015). Increasing thermal plant flexibility in a high renewables power system. *Applied Energy*, *154*, 102–111.

Lawrenz, L., Xiong, B., Lorenz, L., Krumm, A., Hosenfeld, H., Burandt, T., Löffler, K., Oei, P.-Y., & von Hirschhausen, C. (2018). Exploring energy pathways for the low-carbon transformation in India—A model-based analysis. *Energies*, *11*, 3001.

Lecinq, B., & Ilic, M. (1997). Peak-load pricing for electric power transmission. In *Proceedings of the Thirtieth Hawaii International Conference on System Sciences* (pp. 624–633). Wailea, HI, USA: IEEE Comput. Soc. Press volume 5. URL: `http://ieeexplore.ieee.org/document/663225/`. doi:`10.1109/HICSS.1997.663225`.

Lijesen, M. G. (2007). The real-time price elasticity of electricity. *Energy Economics*, *29*, 249–258.

Lund, P. D., Lindgren, J., Mikkola, J., & Salpakari, J. (2015). Review of energy system flexibility measures to enable high levels of variable renewable electricity. *Renewable and Sustainable Energy Reviews*, *45*, 785–807.

Mac Kinnon, M. A., Brouwer, J., & Samuelsen, S. (2018). The role of natural gas and its infrastructure in mitigating greenhouse gas emissions, improving regional air quality, and renewable resource integration. *Progress in Energy and Combustion Science*, *64*, 62–92.

Mai, T., Mulcahy, D., Hand, M. M., & Baldwin, S. F. (2014). Envisioning a renewable electricity future for the United States. *Energy*, *65*, 374–386.

Mason, I., Page, S., & Williamson, A. (2010). A 100% renewable electricity generation system for New Zealand utilising hydro, wind, geothermal and biomass resources. *Energy Policy*, *38*, 3973–3984.

Meya, J. N., & Neetzow, P. (2019). Renewable energy policies in federal government systems. *Oldenburg Discussion Papers in Economics*, *V-423-19*.

Neetzow, P., Pechan, A., & Eisenack, K. (2018). Electricity storage and transmission: Complements or substitutes? *Energy Economics*, *76*, 367–377.

Newbery, D., Pollitt, M. G., Ritz, R. A., & Strielkowski, W. (2018). Market design for a high-renewables European electricity system. *Renewable and Sustainable Energy Reviews*, *91*, 695–707.

Pless, J., Arent, D. J., Logan, J., Cochran, J., Zinaman, O., & Stark, C. (2015). *Pathways to Decarbonization. Natural Gas and Renewable Energy. Lessons Learned from Energy System Stakeholders*. Technical Report. NREL/TP–6A50-63904 The Joint Institute for Strategic Energy Analysis. URL: `http://www.osti.gov/servlets/purl/1215173/`. doi:`10.2172/1215173`.

Pommeret, A., & Schubert, K. (2019). Energy transition with variable and intermittent renewable electricity generation. *CESifo Working Paper*, *7442*, 1–41.

Ritchie, H., & Roser, M. (2019). *Our World in Data: Renewable Energy*. Technical Report. URL: `https://ourworldindata.org/renewable-energy`.

Schaber, K., Steinke, F., & Hamacher, T. (2012). Transmission grid extensions for the integration of variable renewable energies in Europe: Who benefits where? *Energy Policy*, *43*, 123–135.

Shearer, C., Bistline, J., Inman, M., & Davis, S. J. (2014). The effect of natural gas supply on US renewable energy and CO_2 emissions. *Environmental Research Letters*, *9*, 094008.

Steiner, P. O. (1957). Peak Loads and Efficient Pricing. *The Quarterly Journal of Economics*, *71*, 585–610.

Stephenson, E., Doukas, A., & Shaw, K. (2012). "Greenwashing gas: Might a 'transition fuel' label legitimize carbon-intensive natural gas development?". *Energy Policy*, *46*, 452–459.

Tong, D., Zhang, Q., Zheng, Y., Caldeira, K., Shearer, C., Hong, C., Qin, Y., & Davis, S. J. (2019). Committed emissions from existing energy infrastructure jeopardize 1.5 °C climate target. Nature. doi:`10.1038/s41586-019-1364-3`.

Williams, J. H., DeBenedictis, A., Ghanadan, R., Mahone, A., Moore, J., Morrow, W. R., Price, S., & Torn, M. S. (2012). The technology path to deep greenhouse gas emissions cuts by 2050: The pivotal role of electricity. *Science*, *335*, 53–59.

Zhang, X., Myhrvold, N. P., Hausfather, Z., & Caldeira, K. (2016). Climate benefits of natural gas as a bridge fuel and potential delay of near-zero energy systems. *Applied Energy*, *167*, 317–322.