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What is the Value of CCS in the Future Energy System?

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Abstract

Ambitions to produce electricity at low, zero, or negative carbon emissions are shifting the priorities and appreciation for new types of power generating technologies. Maintaining the balance between security of energy supply, carbon reduction, and electricity system cost during the transition of the electricity system is challenging. Few technology valuation tools consider the presence and interdependency of these three aspects, and nor do they appreciate the difference between firm and intermittent power generation. In this contribution, we present the results of a thought experiment and mathematical model wherein we conduct a systems analyses on the effects of gas-fired power plants equipped with Carbon Capture and Storage (CCS) technology in comparison with onshore wind power plants as main decarbonisation technologies. We find that while wind capacity integration is in its early stages of deployment an economic decarbonisation strategy, it ultimately results in an infrastructurally inefficient system with a required ratio of installed capacity to peak demand of nearly 2.. Due to the intermittent nature of wind power generation, its deployment requires a significant amount of reserve capacity in the form of firm capacity. While the integration of CCS-equipped capacity increases total system cost significantly, this strategy is able to achieve truly low-carbon power generation at 0.04 t_{CO2}/MWh. Via a simple example, this work elucidates how the changing system requirements necessitate a paradigm shift in the value perception of power generation technologies.

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Keywords: electricity system, Carbon Capture and Storage (CCS), value, intermittency

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1. Introduction

The change in our global climate has evoked an increasing awareness for the necessity of immediate action to reduce emissions of greenhouse gases such as CO_2. Decarbonisation is expected to become a cross-sector phenomenon, relevant in buildings, industry, transportation, and energy production. The Intergovernmental Panel on Climate Change sees this development happening fastest in the energy sector [1]. Additionally, the interaction between energy supply and demand is receive increasing attention and its coordination, such as demand-side management, load shifting, or smart-metering, could facilitate this transition [2].

The necessary scale and rate of the energy transition is unprecedented. The changes will affect the energy sector on an environmental, infrastructural, and economic level. The difficulty of reducing carbon emissions, while ensuring a secure and reliable energy supply, and minimizing energy system cost, is referred to as energy trilemma [3, 4]. Figure 1 illustrates the threefold challenge of the energy transition and states the key characteristic and measure of each facet which are explained in more detail in section 2.

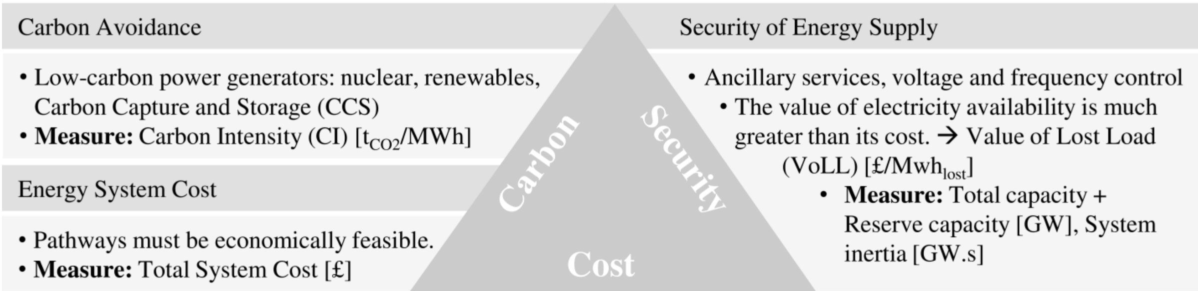

Fig. 1. Energy trilemma with key characteristic and typical measure, adopted from [3, 4].

Often, the types of technologies that are envisaged to be most important for the transition from carbon-intense to low-carbon power production are intermittent renewables energy sources (iRES), such as wind and solar. However, such technologies produce electricity intermittently depending on the availability of the energy source, i.e. wind or solar radiation. With an increasing penetration of iRES capacity in the energy system, the frequency and volume of intermittent power generation stresses the electricity network, putting system security and reliability at risk. To prevent system failures the integration of sufficient back-up, dispatchable capacity or energy storage technologies could remedy the supply-demand-mismatch, albeit at the cost of additional investment and resources.

Conventional thermal power plants can produce electricity on an as-needed basis. The characteristic of a high availability and consequently the potential for a high capacity factor are often called the "firmness" of a power generating technology. The technical implications of *firm and intermittent* power generating technologies have to be considered on every level of energy system planning. Power plants with Carbon Capture and Storage (CCS) combine the important characteristics of being both reliable and also low carbon [5, 6]. Compared to the Carbon Intensity (CI) of unabated coal and gas-fired power stations (approximately t_{CO2}0.8/MWh and t_{CO2}0.4/MWh, respectively), power generation from CCS-equipped power plants is typically in the range of t_{CO2}0.1 /MWh and t_{CO2}0.05/MWh, respectively [7, 8, 9, 10, 11]. The traditional power generation process inherently guarantees firm capacity and reliable electricity supply. The carbon capturing and storing process enables the provision of low-carbon electricity. Whilst CCS on power plants will always be more costly than an unabated power plant, it has the ability to provide permanently available, flexible, low carbon power and the potential to add value to the electricity system [12, 13, 14, 15]. The quantification of this threefold impact of CCS deployment in an electricity system is a main contribution of this work.

We present an electricity system analysis, integrating all aspects of the energy trilemma (emissions, cost, and security of supply). In a thought experiment, we comprehensively differentiate between firm and intermittent power generating technologies comparing an illustrative thermal-wind and thermal-CCS UK-sized energy system. We investigate the effective capacity share, levels of capacity utilization, capital cost (CAPEX), and operational cost (OPEX), as well as the Carbon Intensity (CI) of the resulting systems. The system-level technology analysis enables us to quantify the potential contribution and role of CCS in the efforts of decarbonisation.

The following section 2 deals with the value of electricity (2.1.) and the three challenges of the energy trilemma, being electricity supply security (2.2.), carbon emissions, and system cost (2.3.). Section 3 investigates technology valuation approaches, while section 4 presents a systemic analysis on an illustrative example of the UK's electricity system and its potential decarbonisation strategies following a pathway of firm or intermittent low-carbon capacity expansion. Section 5 concludes.

2. Electricity System Services

2.1. The value of electricity availability

The value of a good or commodity today is typically quantified by its price. The quality, accessibility, or convenience of products can be compared via their cost. Likewise, the cost for electricity can be used as a way of valuation and comparison of electricity from different providers, at different times, or different regions. However, electricity has, unlike other products, no purpose in itself but is rather an enabler for development and growth, industry and commerce. Furthermore, the value of electricity is dependent on its availability in space and time [16]. Given the potential intermittency of its generation and the impermanence of its value, electricity cannot be treated as a homogeneous product [17].

A possibility for electricity valuation is through inference from the cost incurred by its unavailability. The Value of Lost Load (VoLL) defines the value of electricity as monetary damage to a society caused by a power system failure or outage. Recent estimates for the VoLL in the UK are as high as £50,000/MWh for industry and services, and up to £15,000/MWh in the residential sector [18].

2.2. Electricity system security, reliability, and operability

The difficulty of maintaining a reliable electricity system and network becomes clear by the range of different services that are required for the power systems operation. The so called "ancillary services" include the provision of additional capacity for the event of a power plant failure or inaccurate demand forecast, in addition to mechanisms for system frequency and voltage control. To maintain the network security and operability, electricity supply and consumption are matched at every moment in time, keeping the system frequency and voltage level in acceptable limits (in the UK at 50 Hz ± 1% and 230 V). The UK's electric transmission network operator National Grid currently operates more than 20 different ancillary services, ranging from fast reserve, short-term operating reserve to frequency response or black-start service [19]. The "Grid Code" framework sets out the technical requirements for a reliable system operation [20], whereas the Balancing and Settlement Code company ELEXON defines the electricity trading arrangements of the balancing mechanisms [21].

Although ancillary services have always been essential to the operation of the power network, these services are receiving increasing attention in the context of the transition to a low-carbon energy system. To achieve carbon emission targets a substantial proportion of conventional fossil-fuelled and carbon-intense power generation capacity has to make room for low-carbon types of power plants. Besides the adequate amount of capacity replacement, this structural change needs to consider the systems ancillary service requirements to maintain a reliable operation during the transition phase.

However, not all types of power plants are able to provide ancillary services. Conventional thermal power plants can provide frequency and voltage control, whereas intermittent renewable power generators typically cannot provide ancillary services to the system. A common metric to assess power system operability is the level of system inertia, the ability of the electricity system to buffer frequency disturbances. System inertia, measured in GW.s, is the sum of inertia provided by all power plants operating in the electricity system. Power plants with directly connected physical rotating kinetic energy (synchronous generators), such as fossil-fired or nuclear power plants, can provide inertia. IRES power plants provide little or no inertia to the system. With the increasing share of iRES capacity total system inertia decreases, while the amount of intermittent power generation, which intensifies the need for ancillary services, increases. This reverse effect has been studied by academia [22, 23, 24], industry [25, 4], and politics [26], and is seen to become a crucial factor in the electricity sector transition.

2.3. Carbon avoidance and energy system cost

The UK has set strict and legally binding targets on absolute CO_2 emission with the Climate Change Act of 2008 [27]. This legislation is designed to ensure a reduction in total CO_2 emissions of 34 % by 2020, and 80 % by 2050 compared to a 1990 baseline. The introduction of fixed carbon budgets aims at achieving a step-wise reduction and repeated review of the targets. For the electricity sector, the absolute emission targets translate to a reduction of 92 % by 2035 [28]. In terms of the Carbon Intensity of power generation this equals a reduction from a current average of 0.5 t_{CO2}/MWh to 0.045 t_{CO2}/MWh by 2035. To achieve low-carbon power generation, investments in new infrastructure and policies are likely to increase total electricity system cost and the electricity bill to the consumers although not in terms of fraction of household budget in 2035 [29].

In addition to the aspects of system security, reliability, and operability, carbon emission and the cost of electricity show system-wide interdependencies and are integral to the energy trilemma. As some power technologies are able to benefit the security of electricity supply via the provision of ancillary services, others perform well with regards to carbon intensity targets. The integration of power technologies which are able to provide zero-carbon electricity, however, might increase the costs for electricity generation through increased back-up requirements or transmission network reinforcement. Similarly, carbon emissions are caused implicitly by iRES power generation by forcing thermal carbon-intense power plants to increased operational cycling, shut-down and start-ups.

3. Systems analysis on the value of power technologies

3.1. Approaches to technology valuation

The whole-system implications caused by power capacity replacement and integration are not negligible. Metrics which are used to evaluate power generation technologies are often purely cost-based, considering each technology in isolation. For the comparison of technologies with similar performance and cost structures this may be an adequate approach. It is clear, however, that in any power system only the interconnection of power generators to a reliable network has value to the electricity consumer.

The most common and widely-used technology valuation metric is the Levelised Cost of Electricity (LCOE). It relates the lifetime cost of a power plant, including the investment cost, the operational cost and decommissioning cost, to its effective power output, creating a single £/MWh value. While this metric can take the power plant’s capacity factor into account, it does not consider the actual time of electricity provision, how the output profile is correlated or disconnected from the demand profile. The International Energy Agency (IEA) for instance report a median LCOE at 7 % discount rate of 100 $/MWh for a Combined Cycle Gas Turbine (CCGT) as well as for an onshore wind power plant [30]. Two technologies which are inherently different in their performance portfolio are presented by the LCOE as a seemingly equal investment decision. The IEA appreciates that “the LCOE approach reveals little information on the contribution of a given technology to addressing energy security and environmental sustainability” [31]. Importantly, the LCOE does not capture back-up costs, network and grid reinforcement cost, or market dynamics such as time-varying energy prices [16]. The missing component of "integration cost" for iRES technologies also include additional costs for thermal power plants caused by increased cycling and revenue loss due to reduced market access [32]. Reduced running hours for conventional power plants can lead to the operator's inability to recover the fixed investment and operation and maintenance cost, potentially leading to a power plant closure [16]. Unfortunately, the likely affected types of power plants are flexible thermal power plants which are yet the only capacity at scale able to buffer between the stiff nuclear and intermittent power generation. Driving flexible and firm capacity out of the market could lead to a further aggravation of the energy balancing challenge.

3.2. A systems perspective on the value of power generation

The inadequacy of the LCOE metric, especially when comparing firm and intermittent technologies, is now being recognized [33]. Approaches to endogenize the "hidden cost" of a power technology into the LCOE metric [32], however, still fail to assign a value to the environmental impact of the type of power generation. In a 21[st] century electricity system which is characterized by multiple objectives and permanent trade-offs, a one-sided metric such as the LCOE does not assist sound decision making [34]. The necessity to evaluate power technologies in a systemic context rather than in isolation is a core contention of this work.

As an alternative approach, we propose a systems perspective on the value of a power generation technology by assessing the impact on the annual Total System Cost (TSC), in addition to the overall Carbon Intensity (CI) of the electricity system, while setting system security and reliability as necessary constraints. By taking the power system requirements on the one hand and the technology's abilities on the other hand into account, we aim at addressing all facets of the energy trilemma.

We define the TSC of a power system as the sum of all annualized capital expenses ($CAPEX_i$) and operational expenses ($OPEX_{i,h}$) of all power generators i at every hour of the year h, as given by equation (1), while the annuity factor is defined as $A_{r,t} = (1-(1+r)^{-t})/r$. The overall power system CI is given by the total carbon emissions relative to the total electricity generation ($EG_{i,h}$), as given by equation (2). Additionally, we define system security and reliability conditions, such that total installed capacity (CAP_i) equals peak demand (PD) plus the system capacity reserve margin (SM).

$$TSC = \sum_{i=1}^{N} CAPEX_i A_{r,t} + \sum_{i=1}^{N} \sum_{h=1}^{H} OPEX_{i,h} EG_{i,h} \tag{1}$$

$$CI = \frac{\sum_{i=1}^{N} \sum_{h=1}^{H} CI_i EG_{i,h}}{\sum_{i=1}^{N} \sum_{h=1}^{H} EG_{i,h}} \tag{2}$$

$$\sum_{i=1}^{N} CAP_i = PD \cdot (1+SM) \tag{3}$$

The set of equations (1)-(3) addresses the three aspects of the energy trilemma. We propose a systemic evaluation of the impact of a power technology taking costs, carbon, and security of electricity supply into account.

4. Decarbonisation options for the UK electricity system

We conduct a thought experiment comparing two decarbonisation strategies for the UK's electricity system. We hypothesise two possible pathways for the transition from a fully unabated coal-based high-carbon to a low-carbon electricity system. In the first option, onshore wind capacity, and in the second, gas-fired capacity with CCS (gas-CCS) is integrated to the unabated thermal-based system. We investigate the effective capacity share, the level of asset utilization, and total system cost components, as well as the CI of the resulting electricity systems. Table 1 presents the underlying power system and technology data.

Table 1. Illustrative electricity system and technology data. Benchmark values can be found in [35, 36, 37]. Annualized CAPEX values refer to n^{th}-of-a-kind power plants and are discounted at 7.5 % over an economic lifetime of 25 years.

Symbol	CAPEX	$CAPEX_{ann.}$	OPEX	Capacity Factor	Carbon Intensity	Symbol	Electricity demand	Peak demand	Reserve margin
Unit	£/kW	£/kW-year	£/MWh	%-MW	t_{CO2}/MWh	Unit	TWh/year	GW	%-GW
Thermal	1000	89.71	50	80	0.78				
Gas-CCS	2200	197.36	65	80	0.04	System	315	62.5	10
Wind	2000	179.42	0	29	0				

The ability of a technology to displace firm power capacity can be quantified by the Capacity Credit (CC). The CC of an onshore wind power plant changes as a function of the amount of wind capacity present in the capacity mix. At low wind penetration levels, a capacity unit of wind can displace on average 30 % of the equivalent thermal capacity unit, meaning 1 MW of wind capacity can displace 300 kW of thermal capacity. This value reduces to just below 10 % of displacement ability at a wind penetration level of 60 %. Measurements and estimates for the CC of onshore wind vary as a function of wind penetration, on average between ± 10 %. We consider the variation in CC based on data from Gross et al. [38] in figure 2 and 3 as error bars around the thermal capacity and thermal CAPEX, respectively.

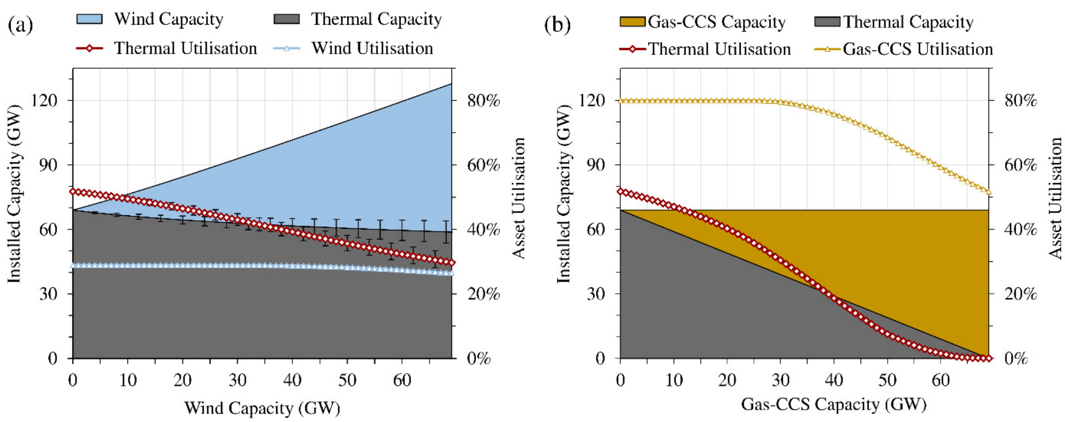

Fig. 2. Capacity share and power plant utilization factor for (a) a thermal-wind integrated system, and (b) a thermal-gas-CCS integrated system as a function of the amount of wind and gas-CCS capacity deployed, respectively. Underlying data on wind availability in the UK is from Staffell and Green [39]. The error bars shown in (a) refer to high (+ 5-10%) and low (- 5-10%) estimates of the wind capacity credit.

Figure 2 (a) demonstrates the propagation of the capacity mix as the wind capacity share increases. We observe how the integration of wind capacity increases total capacity requirements due to its low CC and high intermittency of power generation. The utilization of wind power plants equals its maximum availability level, whereas the utilization of the thermal power plants reduces form initial 52 % to 30 %. Figure 2 (b) illustrates the alternative scenario of gas-CCS capacity deployment. Gas-CCS, being a firm capacity, can displace unabated power plants on a 1:1 basis. The utilization level of gas-CCS power plants is reduced from the maximum availability level as the amount of installed capacity exceeds the average demand and not all power plants are able to run on full load. Thermal plant utilization reduces as the capacity is replaced.

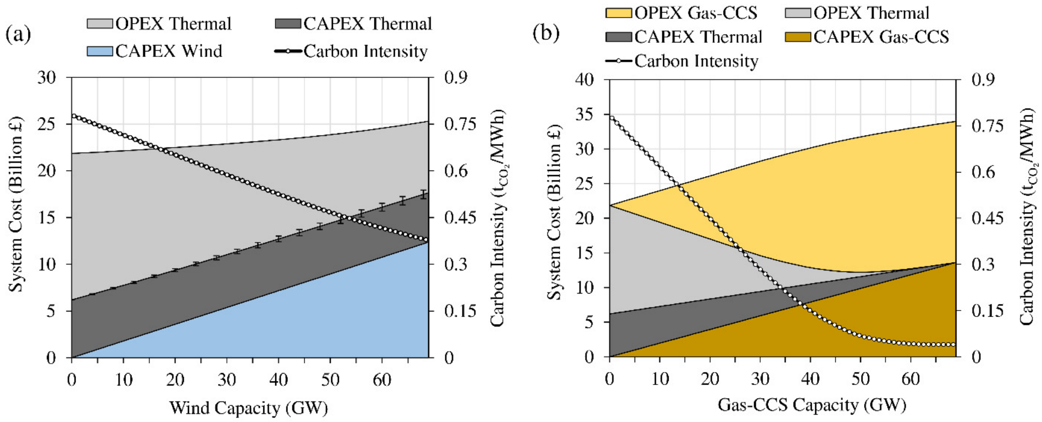

Fig. 3. Total system cost and Carbon Intensity for (a) thermal-wind integrated system, and (b) a thermal-gas-CCS integrated system depending on the wind and gas-CCS capacity deployment level, respectively. Data source and error bar indication are analogous to figure 2.

The total system cost of a wind-heavy system could increase by 16 % as the savings in operational and fuel expenses for thermal power generators do not entirely compensate the capital costs added through the installation of wind power generators. Figure 3 (a) visualizes the corresponding cost mix resulting into a 2/3 fixed cost and 1/3 operational cost structure at maximum wind capacity integration. Additionally, the reduced asset utilization and market access for thermal power plants increases their specific generation costs. The deployment of wind capacity could reduce the emission levels at most by 50 %, resulting in an average CI of 0.38 t_{CO2}/MWh.

The full deployment of gas-CCS increases total system cost, including CAPEX and OPEX, by 55 %. The cost structure consists to approximately 35 % of fixed cost with the remainder being operational expenses from the gas-CCS power plant. However, the gas-CCS based system could achieve a significant carbon emission reduction, resulting in an average CI of 0.04 t_{CO2}/MWh in comparison to an unabated thermal power system.

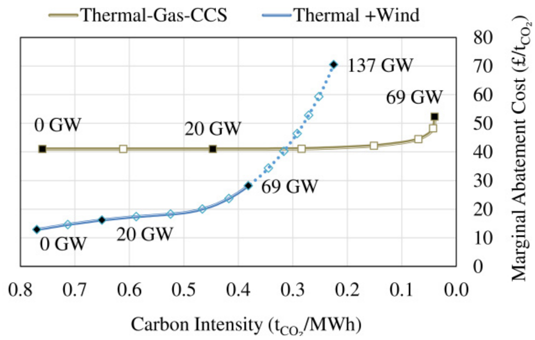

Fig. 4. Carbon abatement cost as a function of the resulting power system carbon intensity for a thermal-wind and thermal-gas-CCS integrated power system.

In figure 4, we present an analysis of the carbon abatement cost as a function of the carbon intensity of the power system for the wind and gas-CCS integrated system, respectively. Initially the deployment of onshore wind capacity proves to be an economical decarbonisation pathway with marginal abatement cost well below the cost a gas-CCS integrated system would face. However, the amount of necessary wind capacity well exceeds the amount of firm low-carbon gas-CCS capacity that would be needed to achieve the equivalent decarbonisation levels. A power system deploying onshore wind capacity as the main decarbonisation strategy faces a significant increase in necessary power infrastructure and cost to achieve CI of below 0.3 t_{CO2}/MWh. Furthermore, a wind-based decarbonisation strategy is incapable of achieving CI levels below 0.23 t_{CO2}/MWh due to the necessary back-up and balancing requirements. Similar results were observed for an evaluation of a system using CCS-equipped coal-fired power generation as a decarbonisation strategy [40]. We note that the results of this analysis are subject to the simplified electricity systems model, omitting the impact of energy storage technologies, demand-side response mechanisms, or their like. In the presence of these technologies, the firm capacity requirements of an iRES-rich system should be reduced. To date however, energy storage technologies at scale are not yet economically feasible [41, 42].

5. Conclusion

The electricity sector is in a transition phase moving from a fossil-based high-carbon system to one which will be characterized by unconventional and low-carbon power generators. For successful energy systems planning, the aspects of security of electricity supply, carbon emissions reduction, and system cost, have to be balanced and their interdependencies explicitly considered. The recognition of inherent technology differences in their operational performance characteristics with respect to firmness and intermittency of power generation, as well as its carbon intensity is crucial.

We present a systems analysis addressing the three main aspects of the energy trilemma. The thought experiment comprehensively differentiates between firm and intermittent power generating technologies and their abilities to decarbonize the UK's electricity system. We have found that, in the absence of sufficient energy storage technologies, onshore wind capacity has the ability to only marginally displaces firm thermal capacity due to the need for back-up and balancing services. A decarbonisation strategy with gas-CCS capacity increases total system cost significantly, however, is able to provide truly low-carbon electricity at 0.04 t_{CO2}/MWh. A wind-based decarbonisation can achieve a reduction in carbon intensity to at most 0.23 t_{CO2}/MWh, while requiring nearly double the amount of total capacity than a system deploying firm low-carbon technology. The resulting low asset utilization is an inefficient use of money and infrastructure and underlines the importance of integrating technology interactions into energy system planning.

A sustainable and economical path can be most likely found in the combination of intermittent and firm low-carbon technologies. The changing system constraints require new valuation techniques for power generation technologies which are capable of explicitly taking system dynamics and dependencies into account.

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