Why fully liberalised electricity markets will fail to meet deep decarbonisation targets even with strong carbon pricing

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ABSTRACT

Full decarbonisation of the electricity system is one of the key elements to limit global warming. As this transition takes place, the electricity system must maintain system adequacy and remain affordable to consumers. In liberalised electricity markets investors are seen as key actors driving this transition.

Due to the intermittent character of renewable assets, such as wind or solar parks, electricity systems with large shares of renewable electricity will need to become increasingly flexible. Evaluating whether specific market designs provide the right incentives to invest in flexibility, requires the simulation of realistic investor behaviour. Agent-based modelling provides the means to explore heterogeneous, imperfectly informed and boundedly rational investor behaviour within different electricity market designs.

We evaluated two market designs; "energy-only" markets and markets with a Capacity Remuneration Mechanism (CRM). We conclude that energy-only markets, even with strong carbon pricing, do not incentivise investors to deliver a fully renewable, reliable and affordable energy system. Therefore policy makers should focus on developing CRMs which can work in combination with market incentives to reach a fully renewable, reliable and affordable electricity system in the second half of this century.

1. Introduction

The electricity system will play a key role in the energy transition now that zero-carbon energy technologies such as photovoltaic panels and wind turbines are becoming attractive to market players (Bloomberg New Energy Finance, 2017). Increasing the share of these renewable, but intermittent electricity sources in the electricity system has to take place while maintaining affordability for consumers and reliability of electricity supply – the energy trilemma (Newbery, 2015).

Meeting these three requirements (renewable, affordable and reliable) will be challenging; ongoing electrification is likely to introduce large peaks in electricity demand while the increasing share of variable, non-dispatchable renewables will bring additional challenges in supply (Sensfuß et al., 2008).

To integrate ever larger shares of intermittent renewable assets in the supply mix, the electricity system will need to become more flexible (Denholm and Hand, 2011; Delft et al., 2016; Steinke et al., 2013). Next to increased transmission and demand response, this flexibility can be provided by storing excess supply, profiting from price differences (i.e. arbitrage). As battery costs have been steadily decreasing, utility scale storage is becoming a realistic investment opportunity (Lazard, 2016) and various studies have shown circumstances under which storage investments would be profitable (e.g. (Bradbury et al., 2014; Walawalkar et al., 2007; Connolly et al., 2011; Weis and Ilinca, 2008)).

Investors look increasingly into developing wind and solar assets combined with flexibility options such as electricity storage, as other options face various constraints: In many regions the potential for hydro-power has largely been exploited (International Energy Agency (IEA), 2017), nuclear energy and carbon capture and storage lack societal support and the use of biomass is constrained by resource needs, environmental impact and sustainability concerns (Scott et al., 2012). Moreover, the limited resource base for biomass (Deng et al., 2015) combined with its potential for other sectors which are more difficult to decarbonise (e.g. chemical industry and mobility; aviation and marine transport), makes biomass for the electricity system a non-favourable option.

1.1. Three challenges for liberalised electricity markets

Since the 1990's many electricity markets have been liberalised

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around the world (International Energy Agency (IEA), 2016). These liberalised electricity markets are set up to ensure that supply meets demand continuously at least costs (Cramton, 2017). Now that ambitious decarbonisation targets are set, the market design of these markets will need to incentivise the investment in an efficient mix of renewables assets and flexibility. The decarbonisation of the electricity system however poses three challenges to the design of these markets. The first is that wind and solar energy have negligible Short Run Marginal Costs (SRMC) while the current market designs assume that power generators can be ranked based on their marginal costs in the merit order. Second, current market designs assume the majority of the generators to be dispatchable, which renewables are clearly not. Third, policy makers try to serve two masters with conflicting needs. On the one hand, they try to offer a fair playing field to producers and consumers, and on the other hand they try to persuade these players towards certain choices in order to achieve desired policy targets. While the market liberalisation has resulted in a fair playing field, now that ambitious targets are set, it is unclear whether specific market designs, which were constructed to accommodate the liberalisation, are compatible with set targets.

1.2. Electricity market design

In "energy-only" markets investors are only compensated for the electricity they actually produce. The electricity price is set by the bid from the last dispatched generator in the merit order (i.e. the marginal costs of the marginal producer). Producers are compensated for fixed costs by the infra-marginal rent they receive when they are in merit. For the marginal producer, the infra-marginal rent equates to zero, but they may be able to raise prices when electricity production is scarce. This ensures system adequacy (North American Electric Reliability Corporation, 2008): when electricity is scarce higher prices give investors an incentive to invest in new capacity. If however, electricity prices are regulated and/or capped, this can result in the well known "missing money problem" (Scott et al., 2012), where marginal producers do not earn back their initial investment.

Scarcity pricing should, in theory, ensure system adequacy (Riesz and Gilmore Iain MacGill, 2016; Hogan, 2005; Cramton, 2017); internalising the social cost of carbon emissions within full liberalised electricity markets is often seen as a cost-effective means for the decarbonisation of the electricity market (Newbery et al., 2017). This would entail that internalising these costs would incentivise investors to invest in the flexibility of the electricity system, necessary to integrate ever larger shares of non-flexible sources. This necessary flexibility is argued (Cramton, 2017) to arise automatically as market forces will incentivise investors to invest in demand response, increased transmission, and/or electricity storage. This assumes that in a decarbonised electricity system "the market" accommodates the required flexibility to ensure sufficient electricity is supplied to meet demand at all times.

While some researchers and policy makers advocate the effectiveness of energy-only markets (Newbery, 2015; European UnionDirective of 2009/72/EC of the European Parliament and of the Council of 13 July 2009, 2009), in practice we have seen other market designs being proposed and implemented around the world (especially in Western Europe (Mastropietro et al., 2015)). These alternative designs aim to ensure system adequacy while integrating larger shares of intermittent capacity (Joskow and Tirole, 2008; Joskow, 2008; Keles et al., 2016; Rodilla and Batlle, 2012), and incorporate various types of Capacity Remuneration Mechanisms (CRMs) in which operators also receive compensation for their capacity and not only for produced electricity (Batlle and Rodilla, 2010; Cepeda and Finon, 2011; Bhagwat et al., 2017; Höschle et al., 2017).

To evaluate whether a) energy-only markets or b) markets with a CRM deliver on set targets, we focus on the question whether these market designs will incentivise investors to develop a fully sustainable (i.e. reliable, affordable and renewable) electricity system. Although we are aware different CRMs have been developed and analysed, in this study we study CRMs in general, under the assumption it is functioning effectively.

Reaching this target would require investors to invest in flexibility of the system. Although different technical solutions are possible to accommodate this flexibility, here we focus on utility scale electricity storage. Therefore we evaluate the aforementioned two market designs based on the question: Are investors incentivised to invest in the required mix of renewable and storage assets to reach a fully renewable electricity system in the period 2070 to 2100, while maintaining system adequacy and affordability?

To answer this question we have modelled the realistic behaviour of investors in the electricity market in an agent-based model. The conceptualisation of this model and the decision making structures of these investors will be elaborated in Section 3; it is the core of this paper. Results from the experiments we have conducted with the model will illustrate and show the effect of this rationale on the reliability, affordability and renewable share of the electricity system. Although we focus on reaching a fully renewable electricity system in the period between 2070 and 2100, the investment decisions that will influence the electricity mix in that period will be made in the decades running up to that period, due to build times and asset life times in the range of decades. This means that although 2070 looks far away, the decisions investors and policy makers make today about the design of the electricity market will influence the electricity mix for decades to come. For policy makers it is therefore important to get the right incentives in place as soon as possible.

This paper is organised as follows; in Section 2 we shortly discuss the literature on electricity market modelling and give more background into the used modelling method. In Section 3 we describe our methodology. Here we discuss our system conceptualisation, the rationale of decision making structures and subsequently how this conceptualisation has been implemented. Section 4 discusses the experimental setup, the KPIs (reliability, affordability and renewable) and the hypotheses for the different experiments. Results from experiments are presented in Section 5 and discussed in Section 6. Conclusions and policy recommendations are given in Section 7.

2. Background

2.1. Modelling electricity markets

There are various modelling techniques to analyse electricity markets (Pfenninger et al., 2014; Rivier, 2005; Foley et al., 2010; Ventosa et al., 2005; Connolly et al., 1016). Most dominant are optimisation models that have proved to be successful by showing policy makers cost-optimal pathways of the energy transition based on assumptions of rational actors and neoclassical economics (Capros et al., 2014; Arabali et al., 2013; Mastropietro et al., 2016), often focused on a 100% renewable target (Diesendorf and Elliston, 2018; Cochran et al., 2014) and/or utility scale storage (de Sisternes et al., 2016; Nyamdash and Denny, 2013; Braff et al., 2016; Denholm et al., 2010; Nyamdash et al., 2010)).

While the assumption of rational agents for the design of a fair market is in general broadly sufficient, in designing electricity markets for the achievement of a specific purpose, analysing of specific market designs requires simulation of more realistic behaviour of investors. To provide effective legislation, policy makers therefore should also consider how issues like heterogeneity of investors, market power, imperfect information, and bounded rationality of players play out. Policy options would therefore need to be evaluated by simulating how different policies will affect the more realistic expected behaviour of investors. Agent-based modelling is a simulation method with which these behavioural drives can be implemented and analysed (e.g. (Guerci et al., 2010; Weidlich and Veit, 2008; Sensfuß et al., 2007))

2.2. Agent-based modelling of electricity markets: storage and market power

Agent-based modelling is an approach to model the electricity system from the complex adaptive systems perspective. This system perspective enables us to come to grips with the emerging behaviour of systems such as the electricity system, that are composed by inter-related and heterogeneous actors (Macal, 2016; Shalizi, 2006; Kauffman, 1993).

With regards to the modelling of electricity markets, agent-based modelling is well suited to model heterogeneous investors that, with their investment decisions, shape the emerging system behaviour in terms of carbon emissions, electricity prices, and system adequacy. This can give insights into the possible future development of the electricity system and the appropriate policy instruments to guide this development.

Several large scale agent-based models of electricity market have been developed in last years, e.g. (Chappin et al., 2017; North et al., 2002), some focussing on evaluating CRMs, e.g. (Bhagwat et al., 2016) (for reviews of these agent-based modelling approaches to electricity markets we refer to (Guerci et al., 2010; Weidlich and Veit, 2008; Sensfuß et al., 2007)). Some studies also have focused on the role of storage, mainly at household level (Zheng et al., 2014; Furusawa et al., 2009; Wehinger et al., 2010) and found its effect on the system to be largely depending on the operating dynamics (Wehinger et al., 2010), but that storage at household level can be profitable under certain sets of conditions (Zheng et al., 2014).

To our knowledge, only three agent-based modelling studies integrated the possibility of utility scale electricity storage. Geneouse et al. (Genoese et al., 2014) found that utility-scale storage could be profitable under certain conditions in Germany. They however did not consider the role of market power and the practicality of market designs on system adequacy. Similarly, Khan et al. (2018) studied the impact of electricity storage and demand response in different market design on investment decisions. They analysed the impact of these flexibility options vis-a-vis a capacity mechanism and concluded that the case for a capacity mechanism is weakened if the system is more flexible. They also conclude that flexibility options (demand response and electrical energy storage) may significantly reduce the risk of shortages in an energy-only market even if investment decisions are myopic. However, while we consider renewable power generation and flexibility of the system to emerge endogenously from investors' decisions, Khan et al. considered renewable power generation as exogenously put into the system. Moreover, where Khan et al. focused on system adequacy, we evaluated market design on its ability to deliver to long term targets on sustainability (i.e. renewable, affordable and reliable).

3. Methodology

Building on the vast knowledge base in the field of agent-based electricity market modelling, our modelling approach differentiates itself in five areas: i) our conceptualisation with endogenous investment in renewables and flexibility, ii) the focus on the long term dynamics in electricity markets with simulations of the system to 2100, iii) our choice of key performance indicators, focussing on a fully sustainable electricity system in 2070, vi) our conceptual approach combining several building blocks (investor behaviour, market design, flexibility market), into a coherent model and finally v) the focus on transparency, reproducibility and tractability by modelling from a minimum set of assumptions.

To address this last point, because transparency, reproducibility and tractability are three of the fundamental challenges of agent-based modelling (Weidlich and Veit, 2008; Macal, 2016), our approach has been based on a minimum set of assumptions that would still adequately encapsulated system behaviours to be able to evaluate policy options.

This paper is based on an extension of an existing agent-based model of investors in the electricity market (Kraan et al., 2018), augmenting it with the possibility to invest in utility-scale storage. Section 3.1.1. will give a short description of the existing model, for a detailed description of the previous model we refer the reader to (Kraan et al., 2018).

3.1. System conceptualisation

3.1.1. Existing model: investors in the electricity market

The existing model focusses on the first phase of the transition with renewables penetrating the electricity market and showed how an agent-based approach to electricity market modelling could be beneficial to give a different perspective on electricity market design (model conceptualisation is discussed in Section 3.2). The system conceptualisation starts with the assumption that investors are profit maximising and they evaluate investment opportunities on that basis. They calculate the Net Present Value (NPV) of investment opportunities based on a heterogeneous and dynamic discount rate. An NPV in excess of zero triggers an investment action. The fact that investors have differing (i.e. heterogeneous) views about the future is expressed through a discount rate in the NPV calculations. Their discount rates change based on the profitability of their asset portfolios. How much revenue an investor expects to gain from an asset is determined by the future electricity price, which in turn depends on the emerging power generation portfolio in the lifetime of the asset. This electricity price is set by the bid of the marginal producer. Rationally they will bid their Short Run Marginal Costs (SRMC) and the electricity price is then set by the SRMC of the marginal producer. Investors profits then consists of the difference between the SRMC of the marginal producer and their own SRMC.

However, because electricity consumers are willing to pay a much higher price then the SRMC of the marginal producer to prevent a black-out (up to the value-of-lost-load (VOLL)), market players can increase their bids when electricity is scarce. The margin with which producers can raise prices when supply is scarce, the scarcity rent, reflects a combination of true scarcity and market power investors can employ. Wilson (2000) discusses the relation between scarcity rent and market power in more detail.

This scarcity rent incentivises investors to invest in generation capacity as profit margins and the expected profitability of new assets in these moments increase. In short, the profit an asset makes is made up by the infra-marginal rent, i.e. the difference between their SRMC and SRMC of the marginal producer, plus a possible scarcity rent when electricity is scarce.

These scarcity rents tend to follow a curve (Cramton, 2017) as depicted in Fig. 1 and given in Equation (1).

$$S(t) = \frac{S_{max} - S_{min}}{\alpha - 1} * \alpha^{1/e_s(t)} + S_{min} - \frac{S_{max} - S_{min}}{\alpha - 1} \tag{1}$$

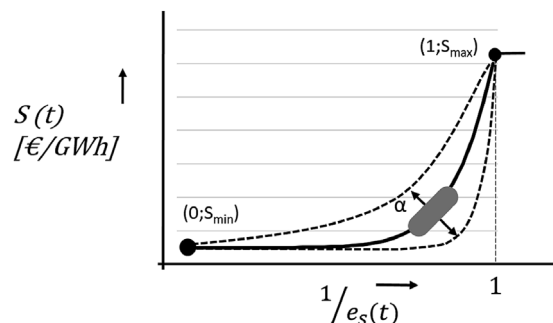**Fig. 1.** Scarcity rent. Figure shows the development of the scarcity rent ($S(t)$) with regards to the excess capacity factor (e_s), i.e. the supply/demand ratio given in Equation (2). α determines the curvature of the curve, S_{min} and S_{max} determine the minimum and maximum value of the scarcity rent subsequently.

In Fig. 1 the horizontal axis indicates the inverse ratio of potential power generation over demand, given by $e_s(t)$ the excess capacity factor, following Equation (2). $G_p(t)$ depicts the potential power generation at time t and $D(t)$ depicts electricity demand at time t. $G_p(t)$ depends on the potential power generation of the coal assets (G_c), the gas assets G_g and the (intermittent) potential power generation of the renewable assets $G_r(t)$. The potential power generation is equal to the sum of the potential power generation of all assets, including the variability of renewable power generating assets, see Equation (3). $e_s(t)$ is related to the adequacy margin which is simply $1 - e_s(t)$.

$$e_s(t) = \frac{G_p(t)}{D(t)} \tag{2}$$

$$G_p(t) = \sum G_c + \sum G_g + \sum G_r(t) \tag{3}$$

When there is enough spare capacity no market power can be employed ($S_{min} = 0$) but when demand matches maximum supply (and e_s reaches 1) the electricity price can go up the maximum price consumers are willing to pay to avoid a contingency (S_{max}) which is equal to the value of lost load (VOLL). α in this figure is a system variable and will depend on the installed capacity mix and the system adequacy (or avoided contingency risk) consumers are willing to pay for. An efficient system would zigzag around in the grey area; higher scarcity rent levels incentivise investments which decrease possible market power and vice versa. With the target of a fully renewable electricity mix in mind, we need to consider how this system will work with increasing shares of renewables.

3.1.2. Extended model: flexibility as investment option and the functioning of an energy-only market with increasing shares of renewables

As renewables can produce for zero marginal costs, they are in front of the merit-order and thus gain the largest rents (infra-marginal & scarcity). With decreasing investment costs, these renewable assets therefore get increasingly competitive. However, deploying more renewables is self-cannibalising, as the merit-order effect depresses prices when they produce. Moreover, as they are non-dispatchable and tend to produce at the same time, they cannot exercise market power. If we want to use intermittent sources at moments they are not available and supply is higher than demand, this excess power could be stored. This stored energy could then be used at other moments in time. This would add a term $G_s(t)$ to G_p, setting G_p equal to Equation (4):

$$G_p(t) = \sum G_c + \sum G_g + \sum G_r(t) + \sum G_s(t) \tag{4}$$

Storing excess power and selling it at a later point in time could be a business opportunity for investors. This brings us to the evaluation of the business case of a storage asset. First of all, we need to realise that storage assets don't produce power but only provide flexibility. Although we are aware storage operates can make use of several financial flows (a.o. balancing services), here we assume that their business case depends on the price difference between buying and selling power; arbitrage. Furthermore, we assume that storage assets can only store excess renewable power.

But how and what will they pay for this excess power? In case of excess supply, the electricity price is near zero, so storage assets could go on the market and store for near zero. However, when there is more storage capacity than excess supply, storage assets will be willing to pay for this surplus as they suspect to be able to sell for a higher price, when renewables don't produce and conventional units with non-zero SRMC set prices. We argue that the price which storage assets are willing to pay, the floor price, will follow a similar curve as the scarcity rent curve, depicted in Fig. 2 and given in functional from in Equation (5). The horizontal axis in this figure depicts the fraction of excess renewable power supply E_r, given by $G_r(t) - D$ if $G_r(t) - D > 0$ over storage capacity C_s given by e_f in Equation (6).
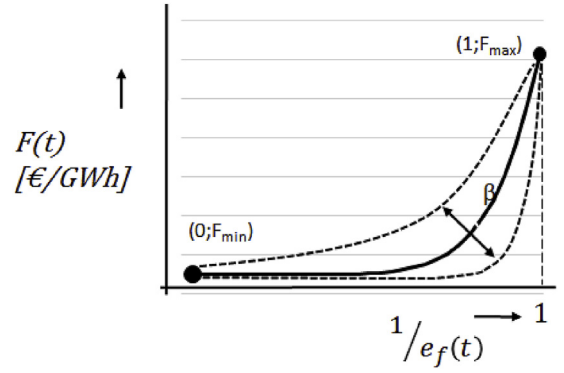

Fig. 2. Floor price. Development of the floor price ($F(t)$) with regards to the ratio of available storage capacity and excess renewable production (e_f). β determines the curvature, F_{min} and F_{max} determine the minimum and maximum floor price respectively.

$$S(t) = \frac{F_{max} - F_{min}}{\alpha - 1} * \alpha^{1/e_f(t)} + F_{min} - \frac{F_{max} - F_{min}}{\alpha - 1} \tag{5}$$

$$e_f(t) = \frac{\sum E_r(t)}{\sum C_s(t))} \tag{6}$$

When this inverse of e_f is small, a case with ample excess of renewable power but small storage capacity, storage assets will pay a near zero premium. However, when renewable excess power is scarce, and the fraction approaches 1, the maximum premium they are willing to pay is equal to the price they can sell for minus their OPEX. This sell-price depends on the capacity mix because possibly they can use their market power when they sell in the case electricity is scarce. F_{max} therefore is calculated with the relationship shown in Fig. 1. F_{max} is equal to the VOLL when no conventional thermal units are left in the system, because if the excess power wouldn't be stored, then a contingency would occur for which consumers would be willing to pay the VOLL to prevent.

The curvature of this curve is determined by the value of β. It is determined by the renewable excess power capacity to fill the storage assets. The floor price is necessary for renewable assets to regain their fixed costs, even when power is in excess. Otherwise an incentive to create excess capacity is lacking while it is necessary to fulfil demand in a fully renewable electricity system.

3.1.3. Scarcity rent and floor price with high shares of renewables

Fully liberalised systems without governmental interference would in theory ensure system adequacy and with a high enough carbon price, meet set targets (see Section 2). However, in a system with increasing shares of renewables, α as well as β decrease dramatically, thereby removing incentives for investment in storage as well as renewable assets.

Let's assume that somehow, miraculously, we have a system that meets the set targets, only producing from renewable and storage assets, with precisely enough excess power supply to supply the precisely large enough storage capacity to fulfil demand in scarce-hours (i.e. $1/e_s = 1$ and $F(t) = F_{max}$). This would be the most cost-effective system with regards to renewables and storage, with theoretically the best return on capital employed. What would the value of α and β need to be for the system to be sustainable with healthy profits for investors while maintaining system adequacy?

To analyse the required values of α and β, let us start with the extreme cases, assuming that $1/e_s = 1$ and $F(t) = F_{max}$. With ample conventional thermal power generation capacity in the system (i.e. $1/e_f \approx 0$), the maximum price storage assets are willing to pay for excess renewable power, F_{max} is equal to the scarcity rent which approaches zero, see Fig. 1. In the other extreme case, with no conventional power generation in the system, the ratio $e_f(t)$ is equal to 1 which makes F_{max}
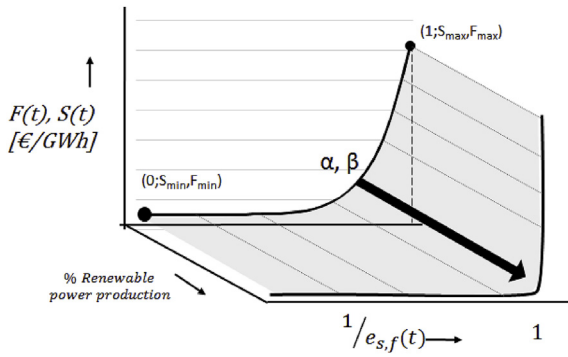
Fig. 3. Scarcity rent and floor price development with increasing shares of renewable power production. Figure shows that the curvature of the scarcity rent and floor price increases with larger shares of renewable power production.

equal to S_{max}. However, what is the value of the scarcity rent and floor price when the ratios are just below 1? That is the moment that investment would need to be incentivised, otherwise the ratios will rise even further and contingencies are expected.

At that moment, with only marginal conventional thermal power generation left in the system, the scarcity rent and floor price approach zero. The scarcity rent and floor price approach zero, because when there is slightly more excess renewable power supply than storage capacity (i.e. $1/e_f$ is just below 1), storage assets will not be willing to pay for excess power. If they would, they end up at the end of the merit order and will not sell their power. This would mean α and β go to zero with increasing renewable power generation in the mix and both functions will become a step-function, see Fig. 3.

This means that when the system is in its ideal state ($e_f = 1$), the business case for conventional power generators disappears and thermal power generating assets will be removed from the system, either actively or when their lifetime is exceeded. This drives the inverse of e_s to 1. In this process, incentives for new investment are given at the point that contingencies cannot be prevented because of the delay between the opening up of an investment opportunity and the actual power production.

We infer that this system would not be acceptable from a policy perspective. To compensate for this market failure, α and β need to increased. Various policy alternatives have been proposed to do just that. Essentially they are various forms of CRM. The main point here is that only the presence of back-up capacity (ensuring that $S(t) > 0$ when e_s is just below 1) will increase the price for which storage assets can sell, which will be just below the SRMC of the back-up capacity. The presence of a flexibility market in which storage operators are able to pay for excess renewables would be a prerequisite.

3.1.4. A business innovation: storage-backed-renewables

To circumvent this flexibility market, investors could consider to invest in an asset with a combination of renewable power generation and electricity storage. Given the right mix of asset types, this could provide firm capacity (i.e. dispatchable capacity). Excess power in that case would not be sold to the market, but would be stored in the storage asset. As this asset class is not depending on the market to store its electricity, it will only sell electricity if it can regain its investment costs. Therefore, our assumption is that it will bid its Long Run Marginal Costs (LRMC) into the market; if the market price is under its LRMC, it is more profitable to store electricity than to sell to the market.

3.2. Model conceptualisation

To integrate the system conceptualisation in the model, we extended the existing model conceptualisation with two asset classes;

storage and storage-backed-renewables. The model and its extension are written in the software environment Netlogo, following best practices for scientific computing (Wilson et al., 2014). For the model description, the ODD protocol (Grimm et al., 2006, 2010) has been followed. The model is open source and can be found on-line together with the ODD protocol. The model is extensively verified through single-agent testing, recording and tracking behaviour and multi-agent testing (van Dam et al., 2013). Here we first briefly discuss the existing model and then describe its extension.

3.2.1. Existing model

The current model describes the time evolution of the electricity system over decades. It consists of heterogeneous investors and various types of electricity generating assets; coal-fired, gas-fired and renewable-based assets. In the model, investors evaluate investments based on economic criteria (Net Present Values). The expected profits from an asset type are based on the historical returns of the same asset type. The heterogeneous discount rates investors apply in the financial opportunity evaluation is the numeric pars pro toto of the investors long-term outlook. This outlook will colour future decisions and is dynamics: Investors will see their discount rates in- or decrease over time based on the average profitability of their asset portfolio.

Investors own assets that produce electricity. Assets have one GW name-plate capacity and have different properties with regards to their investment costs, CO_2 intensity, SRMC (based on fuel costs), lifetime and efficiency. Where coal and gas assets have a constant dispatchable production, in the specific runs discussed in this paper, renewable assets have a variable supply on daily scale, modelled as a cosine function.

In the electricity market, assets produce electricity that satisfies the inelastic and constant electricity demand. The electricity price is set by the SRMC of the marginal producer plus the scarcity rent as discussed in Section 3.1.

3.2.2. Model extension: storage

To integrate the possibility to invest in assets providing flexibility, the asset-type *storage* has been implemented. Distinctive from a normal power generation asset, a storage asset can only produce electricity if it has stored it previously. It has a certain energy storage capacity and flux-capacity. Just as normal assets it has a lifetime and efficiency. Its SRMC depends on the average price of electricity it had to pay to charge, weighted to the amount of electricity stored for that price. The SRMC together with the time depended electricity generation capacity of the storage unit is incorporated in the merit order.

Because of the distinctive properties of electricity storage versus electric generation capacity, the electricity market algorithm of the existing model (Kraan et al., 2018) has been modified to be able to integrate storage as asset type. As described in Section 3.1.2, G_p would need to include the capacity the storage asset has (with its limits of energy capacity and flux capacity).

To facilitate the storage and selling of electricity, a flexibility-market was set up in which the price is determined that storage operators are willing to pay electricity generators. It has been implemented following the conceptualisation described in Section 3.1.2.

3.2.3. Model extension: storage-backed-renewables

An additional asset class that has been implemented is the asset class *storage-backed renewables*. This asset-class has a constant potential production of 1 GW. To deliver this power this asset is an integration of two conventional renewable assets of 1 GW each and one storage asset of 1 GW each. Its investment costs are based on the required mix of renewable and storage assets and include integration costs. This asset-class is implemented following the description in Section 3.1.4.

4. Experimental setup and hypotheses

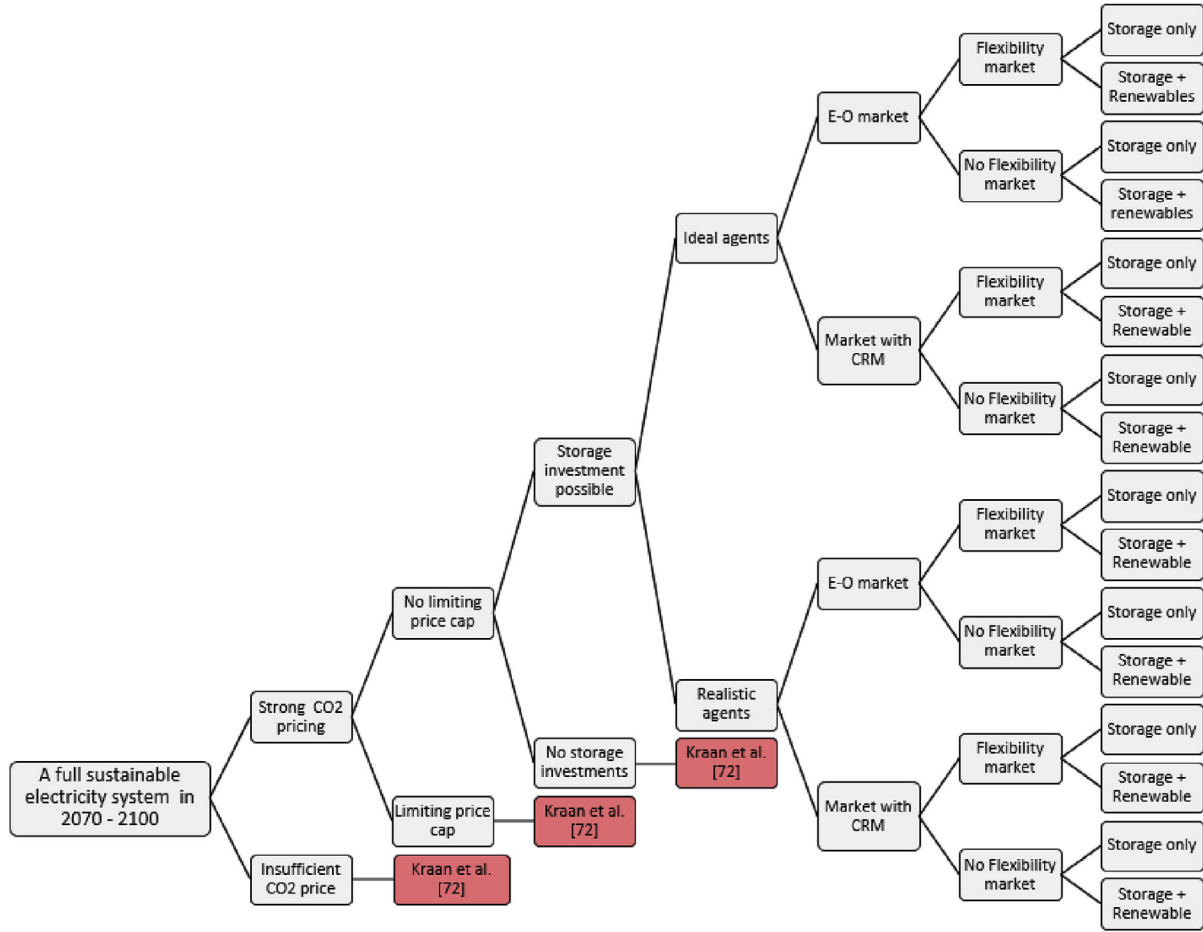To answer the question whether in specific market designs a

Fig. 4. Experiment-tree. Figure shows how the experiments are differentiated starting from our criterion of success given in the box on the far left.

sustainable electricity system emerges, we conducted experiments and determined the value of three Key Performance Indicators (KPIs) capturing reliability, affordability and the percentage of renewables in the electricity mix. With these three KPIs we then could draw a final conclusion on the sustainability of the system.

We varied four elements in a full-factorial fashion and designed hypotheses of the extent to which the KPIs will be met. These sixteen experiments are grouped in four groups of four and based on the experiment-tree given in Fig. 4. Here the overall success requirement was defined as a fully sustainable (i.e. reliable, renewable and affordable) electricity system in the period 2070 to 2100.

These three KPIs are:

Reliability This parameter measures whether the system meets the requirements on system adequacy. The average reliability over the period 2070–2100, $\overline{Rel}$, is defined as,

$$\overline{Rel} = \frac{\sum_{y=2071}^{2100} O(y)}{365*24*30} \tag{7}$$

with $O(y)$ the number of hours without outage in year y divided by the total number of hours in the 30 year time period. Success on this parameter is defined as Reliability being larger than 0.975 over the 30 year period.

Affordability This parameter measures whether the system is affordable relative to a reference system. This parameter, described by the total capital employed, is measured by summing the capital employed per asset-class (i.e. the investment size of the asset in a specific class times the number of assets in that asset class) in a specific year and averaged over the period 2070–2100. The reference system is a fully renewable system with similar load factor as the system at initialisation

(75%). The average affordability over the period 2070–2100, $\bar{A}$ is the defined as,

$$\bar{A} = \frac{\frac{1}{30}*\sum_{y=2071}^{2100} C(y)}{C_r} \tag{8}$$

with $C(y)$ the average capital employed in year y divided over the reference capital employed (C_r). Success on this parameter is defined as being smaller than 1.75.

Renewable This parameter measures whether the system reaches the 100% renewable target. Average renewable power production, $\overline{Ren}$, is determined by summing the power generation from renewable assets, storage-backed renewables assets and storage assets (described together as renewable-based electricity production) and taking the ratio of total demand. It is defined as,

$$\overline{Ren} = \frac{\frac{1}{30}*\sum_{y=2071}^{2100} R(y)}{D} \tag{9}$$

with $R(y)$ the average daily renewable-based electricity production in year y divided by the average daily power demand D. Success on this parameter is defined as Renewable being larger than 0.975 over the 30 year period.

Results from the first part of this experiment tree were presented in a previous paper based on this model (Kraan et al., 2018). Here we found that an insufficient CO_2 price would not lead to success as too little incentive would be in place to invest in renewable power generation. Other factors that would limit the system to meet the set target are a limiting price cap that would lead to the missing money problem (see Section 2) and lack of investment possibilities for flexibility, i.e. storage to be able to integrate intermittent renewables while meeting
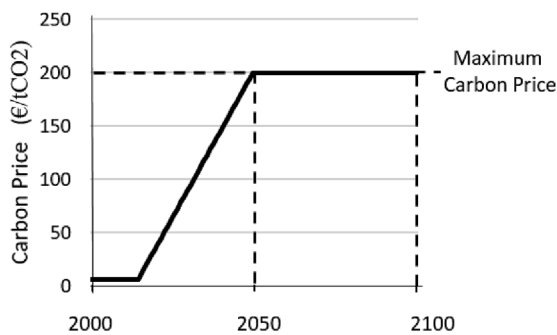
Fig. 5. Carbon price scenario. Figure shows the reference CO_2 scenario. In subsequent experiments the Maximum Carbon Price has been varied but the reference year of 2050 is kept the same (see Section 5.1.4).

demand. These finding have been replicated in this study (see Fig. 10) and our further analysis has focused on the subsequent four layers.

4.1. Agents: ideal versus realistic

In the first experiment we differentiate between ideal and more realistic agent behaviour. Ideal agents will invest whenever an NPV is larger than zero and assets that do not require a build-time and would immediately be active in the electricity market. They are also myopic as they do not have full information but react on signals from the market. More realistic agents will only invest if the NPV of an investment option is positive for a longer period of time parameterised to three years. Furthermore, assets have a specific build-time before they become active, parameterised to seven years.

Our hypothesis is that, with erratic investment signals from an energy-only market under previously discussed conditions, realistic behaviour of investors and assets would severely affect the reliability of the overall system due to insufficient investments.

4.2. Market design: energy only versus market with CRM

The second element in which experiments differ is whether a CRM is implemented. Specifically, this means that in an energy-only market the slopes of curves (α and β) in Figs. 1 and 2 are dynamic, and linearly dependent on the percentage of renewables in the system, as depicted in Fig. 3. In experiments where markets have a CRM, α and β are static. The value of α is determined under the assumption that outages cannot occur and is set at the minimum level that meets that requirement. β is set at the minimum value at which enough excess renewables emerge to match the residual load, i.e. the demand minus the renewable production. This market design can be understood of as a simulation of a capacity market as explained in Section 3.1.3.

We expect the investment signal to become discontinuous and ultimately binary, making energy-only markets behave erratically, especially when more renewables enter the electricity system. In non-energy-only markets, however, the investment signal will follow a more continuous curve. We expect that, given that storage operates will pay for excess renewables, β will ensure enough excess renewables will be produced to meet the residual load, and α will ensure the reliability requirement will be met. With an adequate carbon price this system should be able to meet our overall success requirement.

4.3. Flexibility market: presence of flexibility market versus absence of flexibility market

Thirdly, we run simulations with and without a flexibility market in place. The presence of this market gives storage operators the possibility to pay for excess renewable power. In the absence of such a market, storage operates will not pay for excess renewables and will just go to

the regular electricity market.

Our hypothesis is that when renewable operators mainly produce when the electricity price is near zero, and will not gain financial compensation for their excess production, the incentive to build renewable assets strongly decreases. This will lead to insufficient excess renewable power to store and supply the residual load.

4.4. Storage-backed renewables: presence of asset-class versus absence of asset-class

In this last experiment-differentiation, we differentiated experiments in which investors, besides the possibility to invest in storage, also have the possibility to invest in the asset class storage-backed renewables as described in Section 3.1.4.

Our hypothesis is that storage-backed renewables will be attractive for investors as the market-uncertainty of the interaction between storage and renewables is removed. From a system perspective however, we expect this option to be less efficient and affordable as centralised storage would be more capital-efficient than separate storage assets that can only store for a local renewable asset.

4.5. General experimental setup

The model has been parametrized to represent the Dutch electricity system as pars pro toto for the European Electricity market. The starting point is the year 2000. The model has been initialised with 20 GW capacity and 15 GW demand, with 5 initial investors representing the utility companies. These values are representative for The Netherlands, though we stress we do not aim to simulate the electricity market of a particular country accurately. The model has granularity of hours and runs for 100 years, the time frame of interest for the transition of the electricity system. Carbon prices between 2000 and 2015 are based on historic prices of the EU-ETS. Carbon prices beyond 2015 are based on a carbon price scenario. This carbon price scenario brings the carbon price from 2015 to a pre-set carbon price level in 2050, see Fig. 5. The default carbon price level is set at 200 €/tCO_2, a carbon price level that would be sufficient to reach climate goals (Royal Dutch Shell, 2018). Renewable power generation is modelled to represent a utility-scale solar farm and modelled as cosine with a 24 h period. Experiments are run 30 times for each experiment. The experimentation of a selection of experiments with 100 runs showed that the experimentation with 30 runs was sufficiently representative with regards to the average and standard deviation of the model outcomes. Table 1 gives an overview of the important values at initialisation.

5. Results

The results from the sixteen experiments as discussed in Section 4 are outlined in Fig. 6. The experiment-tree is on the left and the results of the experiments are summarized in the table on the right. In the table the three KPIs are given, i) reliability (green), ii) affordability (blue) and iii) renewable (black). Numbers are the average values over 30 model runs, meeting the success criterion described in 4 is denoted with green for yes and red for no. The column on the far right shows the experimental result measured against the overall success criterion.

The table in Fig. 6 shows that most experiments fail on one or several criteria. Only one experiment meets the overall success criterion, experiment 4.1 which will be discussed in more detail in Section 5.1.3.

From the experiment-tree, three experiments have been selected to develop three scenarios. The first scenario, "Ideal E-O market" is a scenario with ideal agents; rational risk-taking investors and instantaneous asset development that act within an energy-only market. The second scenario, "Realistic energy-only market" shows how the more realistic agent behaviour influences the development of an energy-only market. Because this scenarios does not meet our success

Table 1
Values of variables of parameters at initialisation.

Variables per model component	Value at initialisation	Type
Electricity market		
Number of investors	5	dynamic
Demand	15 GW	constant
Installed capacity	20 GW	dynamic
Time resolution	days	constant
Runtime	100 years	constant
Investors		
Discount rate	Uniform distribution (6%–20%)	dynamic
Number of assets per investors	4 assets of 1 GW	dynamic
Discount rate at bankruptcy	20%	constant
Assets		
Lifetime assets	Uniform distribution (28–32 years)	constant
Natural gas price	4.5 €/GJ	constant
Coal price	2 €/GJ	constant
Gas/coal asset efficiency	40%	dynamic
Age assets	Uniform distribution (0–30 years)	dynamic
Investment coal asset	1.2 €/W	constant
Investment gas asset	0.6 €/W	constant
Investment storage asset	1 €/W	constant
Investment storage-based renewables	1.3 €/W	constant
Investment renewable asset	1 €/W	constant
Capacity storage asset	8 GWh	constant
Storage asset efficiency	90%	constant

criterion, a third scenario was explored. This third scenario "Realistic market with CRM" shows how the success criterion can be met with an CRM.
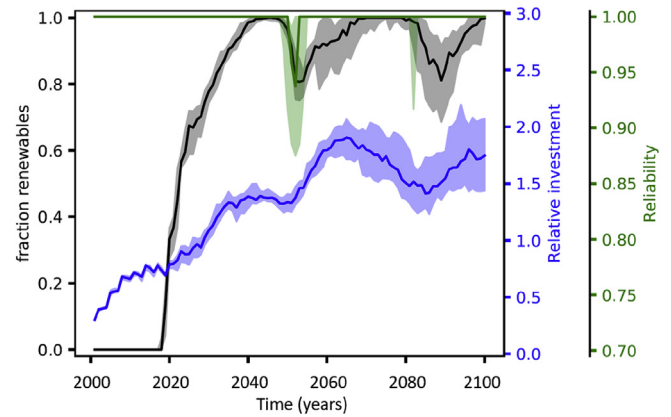
Fig. 7. Ideal energy - only market. Figure shows that under ideal circumstances and unrealistic assumptions on investors behaviour, targets can be met but investment cycles emerge. The shaded areas show the first quartile on both sides of the median while the thick lines show the median. Figure is based on experiment 1.1.

5.1. Three scenarios

To further explore the three scenarios, these scenarios will be discussed subsequently. Figs. 7–9 show the time development of the KPIs for the three selected scenarios, namely: i). Renewable, the percentage renewable electricity generation in the energy mix in black (left y-axis), ii). Reliable, the reliability percentage in green (right y-axis), and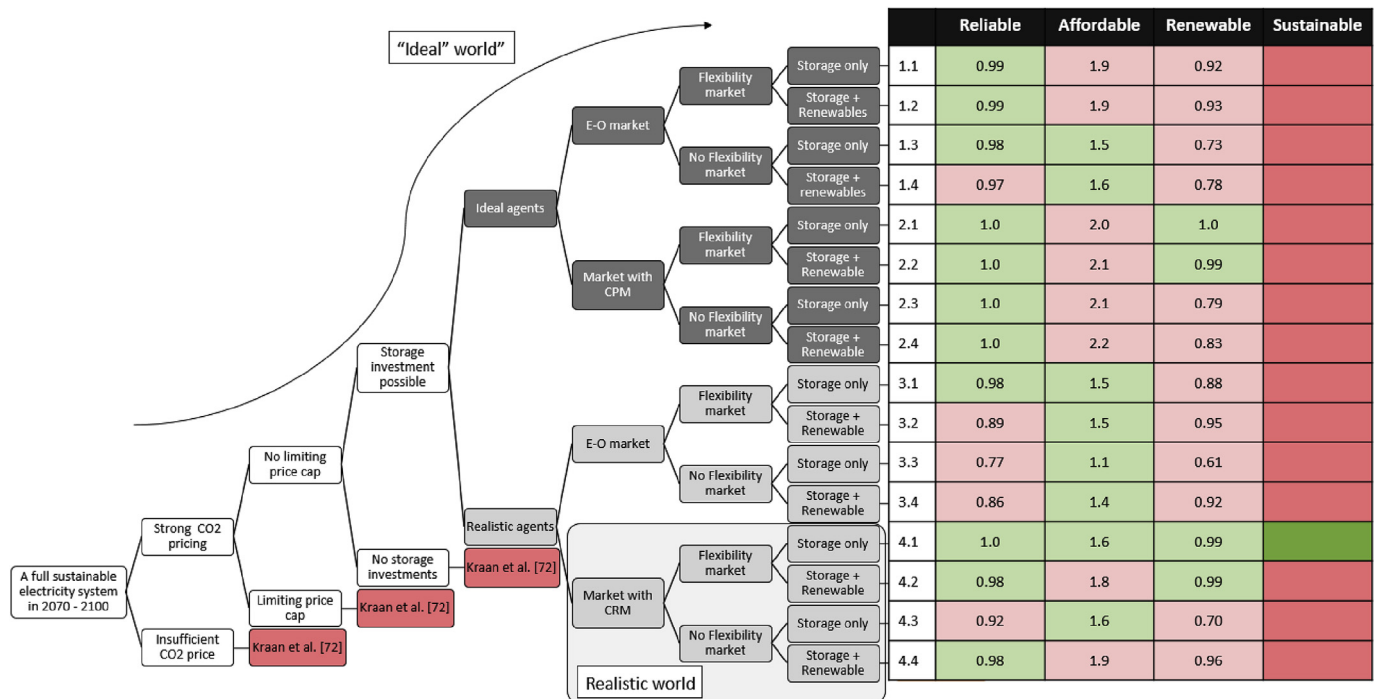 iii) Affordable, the total capital employed in blue (right y-axis). The shaded areas show the first quartile on both sides of the median while the thick lines show the median.

		Reliable	Affordable	Renewable	Sustainable
Storage only	1.1	0.99	1.9	0.92	
Storage + Renewables	1.2	0.99	1.9	0.93	
Storage only	1.3	0.98	1.5	0.73	
Storage + renewables	1.4	0.97	1.6	0.78	
Storage only	2.1	1.0	2.0	1.0	
Storage + Renewable	2.2	1.0	2.1	0.99	
Storage only	2.3	1.0	2.1	0.79	
Storage + Renewable	2.4	1.0	2.2	0.83	
Storage only	3.1	0.98	1.5	0.88	
Storage + Renewable	3.2	0.89	1.5	0.95	
Storage only	3.3	0.77	1.1	0.61	
Storage + Renewable	3.4	0.86	1.4	0.92	
Storage only	4.1	1.0	1.6	0.99	
Storage + Renewable	4.2	0.98	1.8	0.99	
Storage only	4.3	0.92	1.6	0.70	
Storage + Renewable	4.4	0.98	1.9	0.96	

Fig. 6. Results from experiments. The top-branch (dark) of the experiment-tree depicts the experiments with ideal agents, while the lower branch (light-grey) depicts the experiments with more realistic agents. Table shows the average results of the three outcome criteria (reliable, affordable, renewable) over the model runs. Colours depicts whether or not they met the success criterion (red = no, green = yes) based on the defined success criteria. Far right hand column shows result for the overall success criterion: a fully sustainable electricity system in the period 2070 to 2100. Experiment 1.1, 3.1 and 4.1 are treated more extensively in Section 5.1 and subsequently in Figs. 7–9. Graphs show the three outcome parameters, reliability, affordability and renewable ratio; the thick line depicts the median while the shaded areas depict the 25% and 75% percentiles for the models runs. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)
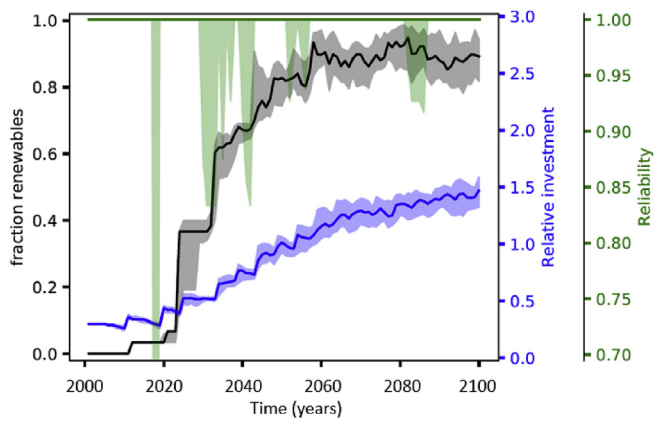
Fig. 8. Realistic energy-only market. Figure shows that renewable target cannot be reached in this scenario. The shaded areas show the first quartile on both sides of the median while the thick lines show the median. Figure is based on experiment 3.1.
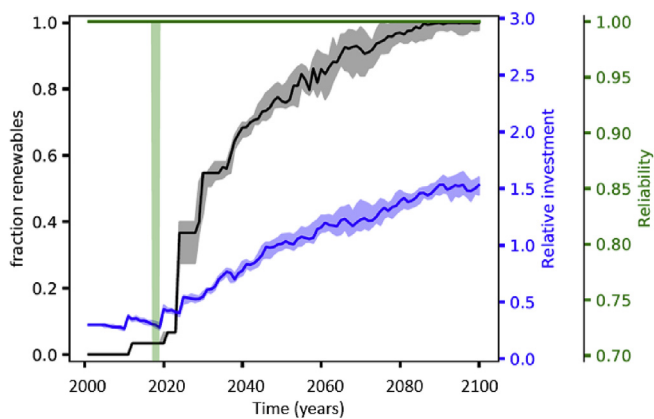
Fig. 9. Realistic market with CRM. Figure shows that this scenario can reach the set target on all three KPI, showing it can attain a fully sustainable electricity system in the period 2070–2100. The shaded areas show the first quartile on both sides of the median while the thick lines show the median. Figure is based on experiment 4.1.

5.1.1. Energy-only market with ideal agents

This scenarios explores the effect of ideal agents in an energy-only market and corresponds with the most upward going path in the experiment-tree. Results are depicted in Fig. 7. The erratic behaviour corresponds with our hypothesis given in Section 4.2. Since agents, investors as well as assets, behave ideally, i.e. respond immediately to investment signals that create assets instantaneously, reliability is not a concern. While in this scenario a fully renewable system is reached the fastest, due to the erratic investment signals and myopic investors, investment cycles emerge; when there is an incentive to invest, agents

immediately invest and remove the investment incentive and vice versa. These market fluctuations represent a major element of uncertainty and result in inefficiencies.

5.1.2. Energy-only market with realistic agents

This scenario explores the emerging electricity system in an energy-only market in which (more) realistic investors make investment decisions. Fig. 8 shows that a fully renewable electricity system does not emerge in this scenario. Reliability is of (minor) concern in line with our hypothesis expressed in Section 4.1 that realistic agents need time to respond to investment signals. However, this scenario mainly fails on delivering a renewable electricity system. This scenario shows that an energy-only market, with its erratic investment signals when renewables deeply penetrate the electricity mix, does not give the right mix of investment signals to investors to invest in an efficient mix of renewables and storage assets.

5.1.3. Market with realistic agents and CRM

Fig. 9 shows that in markets with a successful implemented CRM a fully renewable energy system can emerge while meeting requirements on reliability and affordability if a set of conditions are met. These conditions include:

- No price cap
- Strong CO_2 pricing
- Existence of storage investment possibility
- Existence of flexibility market in which storage operators can pay for excess renewable electricity

Essentially a CRM has the effect of smoothening the curves in Fig. 3, giving a more consistent investment signal with a varying supply-demand ratio. With a strong carbon price, a fully renewable, reliable and affordable electricity system can emerge.

In the next section (Section 5.1.4) several CO_2 scenarios are explored to see at what point in time this sustainable system emerges and to test robustness of results of the three scenarios against different carbon price scenarios.

5.1.4. Sensitivity to carbon price scenarios

To further test these three scenarios, we explored them under different carbon price developments, see Fig. 10. The maximum carbon price (see Fig. 5) is varied for each experiment. The average KPIs (in the period 2070–2100) over all model runs with the specific carbon price scenario are depicted.

Fig. 10.a shows that in a realistic energy-only market, even with a doubling of carbon prices compared to the experiments depicted in Fig. 6, a fully renewable energy system does not emerge. This suggest that an energy-only market *can not* deliver a sustainable electricity system.

A fully renewable electricity system *can* emerge from a market with a successfully implemented CRM. It would however require a
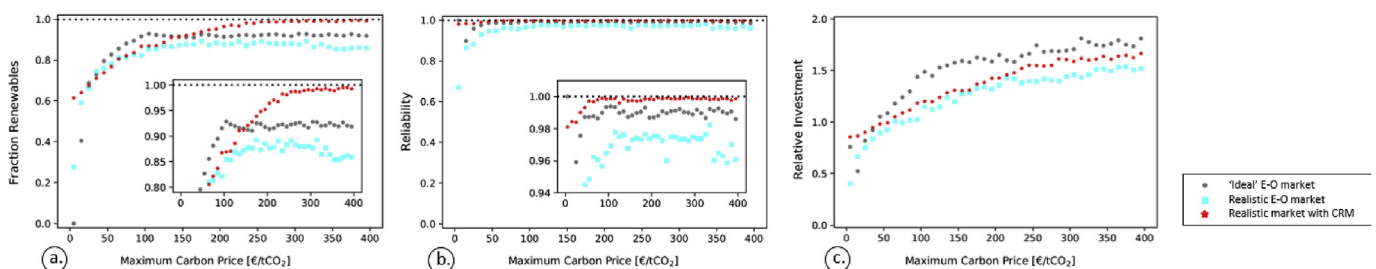
Fig. 10. Sensitivity to carbon price scenarios: a. Renewable fraction; b. Reliability; c. Relative Investment. Graphs show that a CO_2 price in the excess of 200 €/tCO_2 is necessary to reach a fully renewable energy system in scenario Realistic market with CRM. Graphs also show that results from the Realistic energy-only market are robust against higher carbon price scenarios; these fully liberalised markets will fail to deliver a fully sustainable electricity system even with strong carbon pricing.

substantial increase from current carbon price, to > 200 €/tCO$_2$. Furthermore we see that an "ideal" energy-only market needs the lowest carbon price to reach its maximum renewable fraction but because of the investment cycles in this scenario, its average over the 30-year time period is less than 100%.

Fig. 10b shows that reliability requirements can be met in markets with a CRM, while especially in realistic energy-only markets, reliability is of concern. Fig. 10c shows that a realistic market with CRM would require a larger investment than realistic energy-only markets, but at the dispense of a lower renewable fraction (Fig. 10a).

5.2. Additional observed trends in the experiments

Other general trends we observed in the experiments are:

- Without a flexibility market, a market in which storage operators can pay for excess renewables, there is not enough investment in renewable power generation to cover the residual load. The storage capacity size is not the limiting factor, the availability of excess renewables is.
- In the majority of scenarios in which storage-backed renewables emerge, the overall system becomes inefficient as the affordability (i.e. total capital employed), becomes impaired. This can be understood by considering that market-based storage assets can be more efficiently operated than a storage asset that can only store electricity from the connected renewable asset.
- With deep penetration of renewables in the electricity mix, the required reliability margin needed to sustain a full reliable electricity system over long periods becomes larger.
- Total capital employed in all scenarios grows substantially across the modelled time-period. This illustrates the fact that the costs of the system are increasingly internalised; while the current system heavily depends on fossil resources with low capital/fuel cost ratios, a renewable-based electricity system fully relies on invested capital. A sustainable electricity system will therefore have substantial higher capital requirement relative to today. This is reflected in the rising relative investment costs which will reflect back to the customer.

6. Discussion

Here we discuss how different choices on four critical elements have affected our modelling results and how further research could address identified relevant further questions. These four elements are: i) the chosen market designs, ii) the included technologies, iii) the agent behaviour and vi) the chosen model approach.

6.1. Market design

In our model we focused on two market designs: markets with CRM and fully liberalised, energy-only markets. In reality a variety of market interventions have emerged. These include, amongst others, power purchase agreements, feed-in-tariffs, investment subsidies etc. There is also a wide variety of capacity remuneration mechanisms; different types of capacity markets, strategic reserves etc. To assess these market designs would need detailed modelling of these policy measures.

We argue that all of these measures are some form of institutional intervention and deviations from fully liberalised energy-only markets. Given our conclusions a further evaluation of these market designs would be a logical follow-up for further research. As we have seen that institutional intervention would be needed to reach set targets and evaluating policies would need simulation of more realistic agent-behaviour, an agent-based approach for this future research would be the logical next step.

6.2. Technologies

This research considered only one type of variable, renewable technology (solar PV) and one type of flexibility technology (electricity storage). Therefore we only considered daily variability. In reality, these technologies are also variable on longer time scales which leads to concerns about seasonal variability and rare weather events.

We would expect however, that inclusion of these dynamics would confirm our model results. As both are relatively uncommon (being "seasonal"/"rare"), we would expect that in fully liberalised markets, the investment signal to be deficient for large scale investments by investors. Therefore, to reach set targets, the successful implementation of CRM would be more challenging. It would put more strain on the design of these CRMs with regards to costs and efficiency but if successfully implemented, based on our results, we would expect these CRMs to be able to give sufficient investment signals.

Moreover, other carbon-neutral technologies such as nuclear, biomass, carbon capture and storage (CCS) and pumped hydro were not considered to be investable for investors as they face constrains with regards to regulatory risk, high capital costs, infrastructural requirements and sustainability concerns (as explained in Section 1). Investing in these technologies, we would argue, would need strong governmental support apart from higher CO$_2$ prices, supporting our conclusions.

An interesting further extension of our model would be the integration of the interaction of other sectors such as heat demand and storage opportunities in the mobility sector. For now we looked at the electricity system in solitude. Although currently coupling of these sectors is limited, there is literature (Moraga González et al., 2018; Moraga González and Mulder, 2018) that suggests that we can expect that in the future the coupling of sectors via power-to-heat and electric vehicles could be influential.

6.3. Agent behaviour

In our model we distinguished two types of agents; investors and assets which conceptualisation has been based on a minimum set of assumptions, resulting in a relatively simple behavioural algorithm. We realise that investor behaviour is more complex and that in reality a large variety of factors contribute to an investor's decision to invest. However, incorporating additional factors such as preference for types of assets, previous experiences (i.e. company history), outlook for governmental intervention, risk appetite amongst others, is beyond the scope of this paper (Masini and Menichetti, 2013). Moreover, we are convinced that our conceptualisation is justified, given the purpose of the model and the balance of model detail over the model elements. Even more so because meaningful quantification of these extremely uncertain factors would be impossible, especially looking at decades from now.

6.4. Modelling approach

Electricity markets are subject to an active field of scientific research fuelling the policy discussion on their most effective design. In last decades agent-based approaches to the evaluation of these market design clearly have grown from its infancy to a mature field of research (Weidlich and Veit, 2008).

In the broad spectrum of agent-based approaches, our modelling approach has been relatively conceptual to be able to combine several buildings blocks of the electricity system (investors, market design, flexibility) into a coherent model that has preserved the balance of model detail over the different model elements. Details matter, especially in complex systems such as the electricity system, but one cannot circumvent the fundamental dynamics of these markets.

This agent-based modelling approach has given us a natural way to think about the behaviour of investors and its consequence for the

emerging electricity market. The great benefit of our approach is that it has allowed us to engage stakeholders (also non-scientific-modellers) actively in the conceptualisation of the model doing full justice to the power of an agent-based approach.

7. Conclusions and policy implications

7.1. Conclusions

In this study we explored whether a fully sustainable electricity market, i.e. one that is renewable, reliable and affordable, can emerge from fully liberalised electricity markets. We introduced a model that incorporates more realistic behaviour of investors acting on limited information, heterogeneous outlooks and decision times and whose decisions take effect only after a realistic asset building time. Using an agent-based model, we explored the interplay between these key characteristics of investors and investments and two market designs: i) a fully liberalised energy-only market in which electricity producers are only paid for the electricity produced and ii) a market with a capacity remuneration mechanism (CRM) in which the capacity requirement of the system is institutionalised.

We have explored these three performance indicators, Renewable, Reliability and Affordability from an investor, policy maker and end-user perspective. The requirement of increasing the share of renewable electricity generation came from a policy perspective while the requirement of retaining a reliable electricity supply was viewed from a system perspective. Lastly, the affordability was considered from an end-user perspective as this affordability is impacted by the increase in capital employed with increased internalisation of the system costs and low capital/fuel ratios.

We conclude that a fully liberalised energy-only market will not lead to investments in an efficient mix of renewables and storage assets, even with strong CO_2 pricing. We showed that under a carbon price scenario running up to 200 €/tCO_2, these markets give insufficient stable investment signals for realistic investors to invest in a sustainable electricity system. Our sensitivity analysis shows that these results are robust under even higher CO_2 prices of up to 400 €/tCO_2.

We also show a possible solution direction and have listed what would be needed to attain a fully sustainable electricity system: i) Price caps would need to be removed ii) a 2500% higher CO_2 from today's levels would need to be imposed iii) a flexibility market in which storage operators can pay for excess renewable power would need to be created, and finally iv) a capacity remuneration mechanism would need to be successfully implemented. However, currently, price caps have strong political support, decades of discussion on CO_2 pricing has not resulted in a strong carbon price, a flexibility market has yet to emerge, and the implementation of capacity remuneration mechanisms are far from obvious and in general are widely criticised.

This shows there are substantial challenges to overcome. However, in the last decades technological development and economics of scale has given us the buildings blocks (solar PV, wind and electricity storage) for a sustainable system. The challenge has thereby moved from the technical realm to the policy realm: creating the right market incentives that allows the technologies to be deployed.

Methodologically, this study illustrates that the evaluation of electricity market designs in the light of specific policy targets (in this case sustainability concerns), requires the incorporation of agent behaviour. We have shown that modelling relatively simple, yet realistic agents can deliver strategic insights in the workings of electricity markets in the future. It is our experience in communicating with stakeholders that suggests that this form of modelling supports communication with policy makers and business decision makers as it allows for joint understanding of complex analysis.

7.2. Policy implications

The policy implications from this study are three-fold. Firstly, this study suggests that policy makers will need to shift their focus from the improvement of energy-only markets to developing appropriate capacity remuneration mechanisms in order to facilitate and ultimately enable this transition to a fully renewable electricity system in the coming decades.

Secondly, our model results suggest that flexibility markets, in which storage operators are able to pay for excess renewable power generation would need to be facilitated. This will give investors the incentive to generate excess renewable power which can be stored to use at other times.

Thirdly, we recommend policy makers to make use of models that explicitly incorporate investor behaviour, and limit overreliance on models that assume perfect information, perfect rationality, homogeneous actors and focus on lowest (system) costs. This study shows that embracing the complexities of electricity markets gives a different and richer perspective on the discussion around investor dynamics. Traditionally, the discussion on electricity market design has been framed by the choice between developing a perfect market under ideal agent assumptions, or requiring a central planner to develop an efficient market. We encourage policy makers to evaluate their design by incorporating realistic agent behaviour. They will need to work *with* the market and accept the complexities that these markets bring.

Acknowledgements

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