On the emergence of the energy transition

Kraan, O.D.E.

Citation

Kraan, O. D. E. (2019, April 25). *On the emergence of the energy transition*. Retrieved from https://hdl.handle.net/1887/71807

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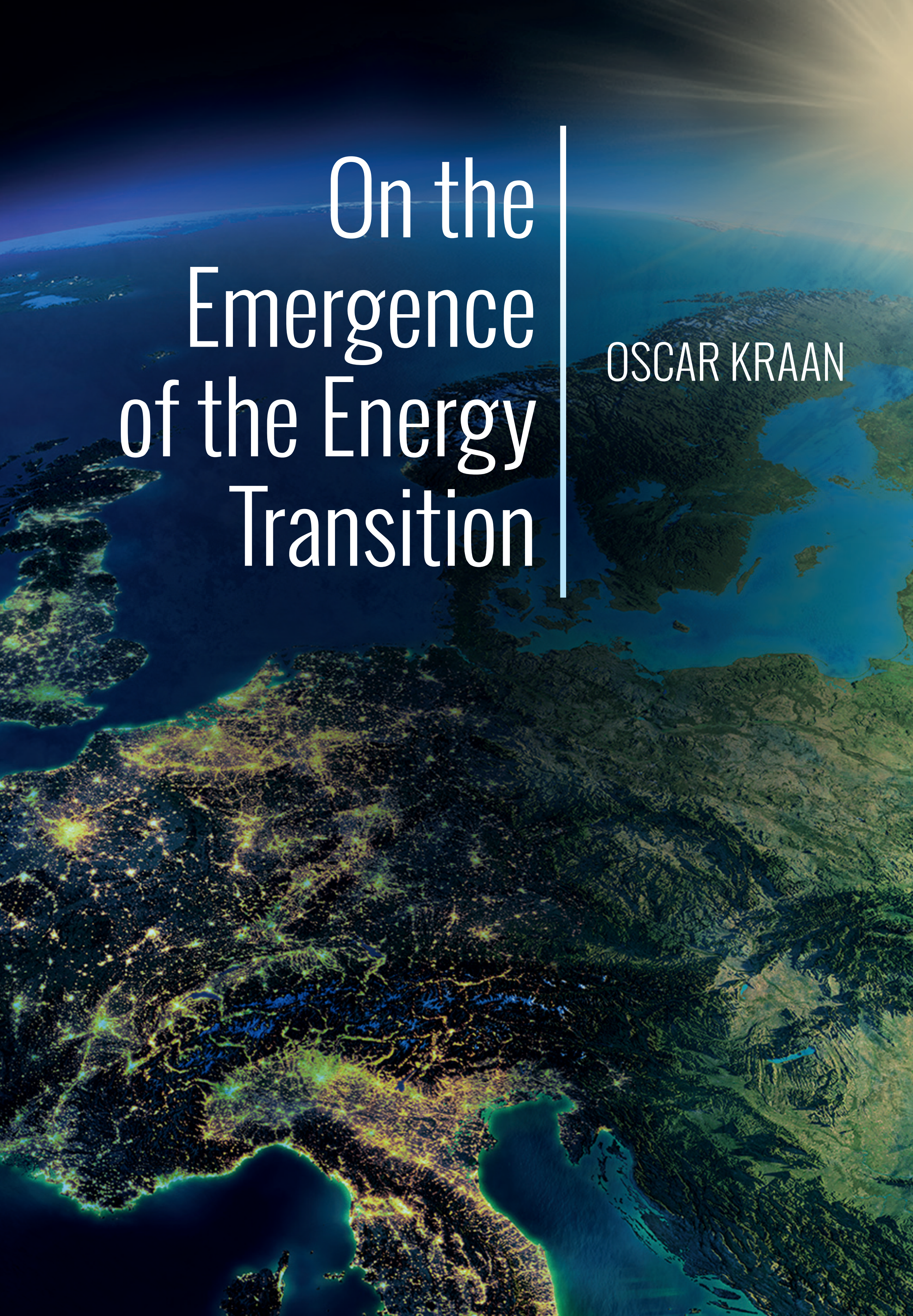
Author: Kraan, O.D.E.
Title: On the emergence of the energy transition
Issue Date: 2019-04-25



On the Emergence of the Energy Transition

OSCAR KRAAN

On the Emergence of the Energy Transition

Oscar Kraan

On the Emergence of the Energy Transition

Proefschrift

ter verkrijging van
de graad van Doctor aan de Universiteit Leiden,
op gezag van Rector Magnificus prof.mr. C.J.J.M. Stolker,
volgens besluit van het College voor Promoties
te verdedigen op donderdag 25 april 2019
klokke 16:15 uur

door

Oscar Dirk-Jan Eduard Kraan

geboren te 's-Gravenhage
in 1985

Promotores:

Prof. dr. G. J. Kramer	Utrecht University
Dr. ir. I. Nikolic	Delft University of Technology

Copromotor:

Dr. V. Koning	Utrecht University

Promotiecommissie:

Prof. dr. P. M. van Bodegom	Leiden University
Prof. dr. A. Tukker	Leiden University
Dr. R. Kleijn	Leiden University
Prof. dr. ir. P. Herder	Delft University of Technology
Prof. dr. B. de Vries	Utrecht University
Dr. E. M. Fumagalli	Utrecht University

This research has been funded by Royal Dutch Shell and has been carrier out in collaboration with Leiden University, Utrecht University and Delft University of Technology.

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Cover: Designed by Bright Brands
Produced with LaTeX
ISBN: 978-94-028-1299-2

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List of abbreviations

GHG	GreenHouse Gas
ABM	Agent-Based Modelling
BC	Base Case
BECCS	Bio-Energy Carbon Capture and Sequestration
CRM	Capacity Remuneration Mechanism
CCS	Carbon Capture and Sequestration
CPR	Common Pool Resource
CAS	Complex Adaptive System
CSP	Concentrated Solar Power
DAC	Direct Air Capture
DEM	Direct Equivalent Method
EGC	Electricity Generation Capacity
EE	Energy Efficiency
EI	Energy Intensity
ES	Energy Service
GHG	GreenHouse Gas
GDP	Gross Domestic Product
IEM	Incident Energy Method
KISS	Keep it Descriptive S.
KIDS	Keep it Simple S.
KPI	Key Performance Indicators
LtG	Limits to Growth
MFA	Mean-Field approach
NDC	National Determined Contributions
NPV	Net Present Value
OPEC	OPerating EXpenses
ODD	Overview, Design concepts, and Details
PSM	Partial Substitution Method
PV	PhotoVoltaic
PECM	Physical Energy Content Method
PNS	Post-Normal Science
SRMC	Short Run Marginal Costs
TFC	Total Final Consumption
TPE	Total Primary Energy
VOLL	Value Of Lost Load

1

Introduction

1.1 Climate change and the energy transition

1.1.1 The problem

Climate change is one of the largest challenges facing humanity in its current form [1]. The change of the earth's climate is caused by the accumulation of greenhouse gas emissions which have changed the heat balance of the earth causing the global average temperature to rise above the range of temperatures of the previous millennia (currently approximately 1 °C above pre-industrial levels at a CO_2 concentration level of 408 ppm, July 2018) [2, 3]. Although the climate of our planet has changed previously (over geological time scales), human activity for the first time has become the main cause for the current, potentially irreversible global warming. Without additional efforts earth's average surface temperature is expected to further increase to 3°C to 5°C warming [4] relative to pre-industrial levels. It involves however much more than temperature increase; loss of polar ice, melting of glaciers, sea level rise, changes in precipitation patterns will undoubtedly effect life of earth, triggering loss of biodiversity and social unrest [4].

To limit this change of our climate, in 2015 195 state parties committed in the Paris Agreement to limit the increase in global average temperature to well below a 2°C temperature rise from pre-industrial levels and to pursue efforts to limit the temperature increase even further to 1.5 degrees Celsius [5, 6].

The energy system is the single largest contributor to the emission of greenhouse gases, predominantly the result of the burning of fossil fuels [4]. Society therefore will have to engage in a transformative change of the energy system to limit the emission of these greenhouse gases; an energy transition. Climate change mitigation scenarios show that greenhouse gas emissions from the energy system will have to be diminished by 2070, giving the world society approximately five decades to complete this transformation to complete this transformation and have a 66% chance of complying with the Paris Agreement [7, 3]. At the same time, the energy system has an essential role in our current society as it fulfils the energy demand of households, businesses and the economy as a whole. The energy system therefore faces three simultaneous challenges; providing energy access and security, keeping energy affordable and making the system sustainable.

To describe what would be necessary to eliminate these greenhouse gas emissions we can look at an adapted version of the IPAT-equation [8], see Figure 1.1. The equation in this figure shows that the global emission of greenhouse gases, predominantly CO_2 is dependent on four factors; the number of people, the service demand (often expressed in GDP) per capita, the energy demand needed to supply these services and finally, the CO_2 emissions associated with delivering this energy demand[1]. To limit climate change and get the left-hand side of the equation in figure 1.1 down to zero, one of the factors on the right-hand side will have to become zero (or net-zero).

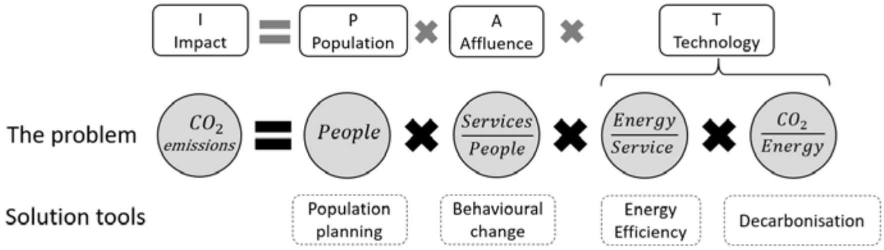

Figure 1.1 – A simple formula that summarises the challenge of mitigate climate change, adapted from [9]

.

Unfortunately, getting one of these factors to zero is not straightforward. The first factor, the number of people on earth, is expected to increase substantially in the decades ahead from 7.6 billion in 2017 to around 10 billion in 2050 after which growth is likely to flatten off [10]. Additionally, the second factor is expected to almost triple from now to 2050 as currently societies strive for economic growth to create a better life for their citizens [11]. Current solution directions are therefore directed at limiting growth of the first two factors and focus on decreasing the third and fourth factor; energy efficiency and decarbonisation.

Exploratory scenarios explore how the trends related to these factors will influence future emissions trajectories [12]. They are based on historical relationships between key drivers (e.g. demographic statistics and the relation between GDP and energy use, also known as energy ladders [13]). As these exploratory scenarios are based on empirically validated relationships, they form highly plausible narratives of how the future of the energy system may unfold. However, often these exploratory scenarios are ultimately unsustainable as they cross internationally agreed planetary boundaries thereby risking economic and/or environmental disruption [14].

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[1] Although there are other greenhouse gases (methane amongst others) the emission of CO_2 from burning fossil fuels has been the largest contributor to climate change since the industrial evolution, partly because of its long lifetime in the earth's atmosphere. [4]

1.1.2 Three directions towards a solution

Fortunately, the solution directions are generally well known; technically, economically as well as socially we know how to prevent crossing limits of even further warming of our planet.

Technical Normative scenarios from a broad range of actors such as Shell [7] and Greenpeace [15] depict what solution directions are possible. With regards to technical elements they refer to increased energy efficiency and the decarbonisation of the energy system. This will entail large scale electrification, deployment of hydrogen, deployment of more energy efficient technologies, large scale deployment of biomass and the application of carbon capture and sequestration to minimise CO_2 emissions. All of these options are available and rapid cost decline of a range of technologies in last decades [16] have made the technical part of the solution come into sight: Solar photovoltaic panels capturing solar radiation, wind turbines, batteries and electrolysers all have shown dramatic costs decline over the past decades, often surpassing main stream expectations [17].

Social It is also well known how social factors could decrease the size of the problem. Having less children would limit the first factor (population size) in Figure 1.1 and behavioural change to less energy intensive service demands could decrease the second factor. Flying less, vegetarianism and other lifestyle changes would have substantial impact. [18, 19, 20]

Economic As we know by now that mitigation of climate change will be cheaper than having to adapt to a new climate [21, 22, 23, 24, 25, 26], pursuing a energy transition thus makes economic sense. This will require that previously coupled factors (in general between I and PAT in Figure 1.1, e.g. between economic growth and GHG emission growth) will decouple resulting in green growth if possible at all [27, 28]. Economists even have laid out an incentive that could achieve it; a global price on carbon which will make polluters pay and internalise the social cost of carbon emissions [22].

1.2 The main research question

So, if the possible technical, social and economic solutions are known, what is then still the question? At this moment we do not know how and at what pace collective behaviour will emerge from individual behaviours and incentives as society develops towards a low carbon future.

Since the atmosphere is shared by all actors on this planet, mitigation efforts by one can be offset by increased emission by others. This makes that "effective mitigation will not be achieved if individual agents advance their own interests independently" [4] which highlights it will be essential to align individual incentives to the collective mitigation effort. Will I invest to mitigate climate change if my efforts can be offset by others? Therefore, the main question of this dissertation is:

How do individual incentives and their interaction influence the path and the pace of emergence of the energy transition?

The motivations and incentives that guide individual decisions will change overtime. Societal developments, population increase, affluence increase, technology development, political developments and a changing climate all will effect the alignment and dynamics of incentives. We are now at the stage where "we're the first generation to feel the impact of climate change, and the last generation that can do something about it" [29]. This gives mitigation efforts an individual rationale. Further alignment requires stakeholders to agree on the goal (which can be obscured by statistical artefacts see Chapter 4) and fortunately in some areas the alignment of individual incentives is starting to emergence: Technological development makes investments in mitigation efforts commercially attractive (see Chapter 3), but often market regulations are not yet ready to integrate large shares of new energy technology (see Chapter 6 and Chapter 7. With an increasingly changing change, the by societies perceived seriousness of the problem also increases (see Chapter 5), making studying these dynamics ever more urgent.

The combination of these questions is the narrative of Figure 1.2. Here we see the exploratory scenarios on the left, while on the right we see the result of normative scenarios. Normative scenarios describe pathways to a pre-specified future [30] which, in this case show how the emissions trajectory of the required energy transition might look like. The question however remains how we can connect these two types of scenarios. Essentially it will involve the everyday decisions of actors, individual consumers, business decision makers and policy makers.

How these actor interactions will work out is hard to comprehend but simulating these actor behaviours in computer models gives us the means to explore the dynamics of these actor interactions. Vice versa it gives the possibility to quantify narratives of how collective behaviour emerges from these actor interactions.

But how will these decisions be different from the empirical observed decision making structures of the past? Subsequently this leads to questions around how individual decision by actors may lead to collective behaviour and ultimately the emergence of an energy transition.

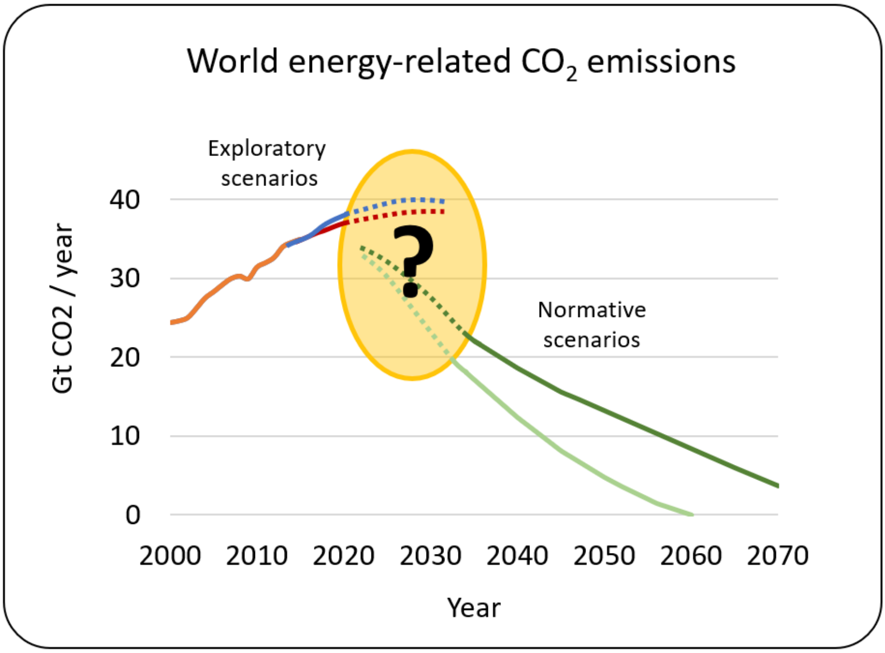


Figure 1.2 – World energy-related CO_2 emissions. Figure shows historical emissions [31], exploratory scenarios (indicatively shown in red and blue based on Shell New Lens Scenarios [32]) and normative scenarios (based on IEA 2°C scenario in light green and IEA Beyond 2°C scenario in dark green [33]). Yellow area with question mark indicates area where actor behaviour dynamics will be crucial to connect the scenarios. Adapted from Gert Jan Kramer, unpublished.

1.2.1 A complex question

The interaction between the social, economic, technical system elements on our planet makes the transition of the energy system a complex problem [34, 35, 36, 37, 38, 39, 40]. Complex here differentiates a problem from being simple or complicated. A simple problem such as making a cup of thee, is a problem for which it is relatively easy to determine whether a successful outcome has been achieved; there is a straightforward procedure to achieve a successful outcome and this procedure does not have to followed exactly to still achieve an acceptable outcome. A complicated problem such as solving a jigsaw puzzle, assembling a car engine or preparing a company's financial statement has more exact defined criteria for a successful outcome. Such a successful outcome can be achieved by following a comprehensive set of strict rules and this procedure is completely reproducible.

For complex problems such as the energy transition there is not such a well-defined procedure and the iterative interaction between many heterogeneous actors who possess human reflexivity (the ability to change or adapt their behaviour based on the action of others) make that the process is not reproducible. The outcome of such processes *emerges* from these actor interactions.

1.2.2 Emergence

Emergence is a key element of complex problems. It can be defined as being "stable macroscopic patterns arising from local interaction of agents" [41, 42]. Emergence occurs when interconnected system elements produce patterns or trends that are not guided by a central actor but evolve from the interactions themselves. Stock market dynamics, fashion trends and traffic jams are examples of emergent behaviour. In Section 1.3.3 we will see how we can model these emergent phenomena.

1.3 Research approach

The research approach to the aforementioned question, has been based on the development of narratives and their quantification by means of simulation models. They will be discussed subsequently.

1.3.1 Narratives

Narratives of the energy transition are plausible, internal consistent story-lines of how the energy transition may develop [43]. Narratives can be used to tackle complexity as narratives are not about objective reality, but are statements of what is significant [44].

A story of how the energy transition may develop requires us to understand what *pace* the emergence of the energy transition will have and what *path* it will take. In turn this requires us to create a better understanding of the mechanisms that influence the pace and the path of the energy transition. They will emergence from the decisions actors will take, how they are incentivised and how their interaction will play out. Eventually this will lead to a consistent story of how A will lead to B.

1.3.2 Quantification

Quantification of these narratives is important to facilitate stakeholder engagement. With *quantification* we understand the process of expression and/or determination of the amount of something. This quantification, involving the conceptualisation of system elements, is facilitated by energy system models. These models facilitate experimentation, promote rigorous analyses and provide a tool to communicate about findings [45, 46, 47]. The combination of narratives and their quantification, is known as scenario development or scenario planning [12, 48, 49, 50, 51, 52, 53, 54, 55].

Our approach to this quantification by means of energy system models involved the following elements:

Agent-based modelling as additional tooling Conventional energy system models are predominantly techno-economic in nature and rely on empirical observed relationships, rational agents and optimisation or equilibrium techniques [56]. By conceptualising actor behaviour in model-entities called "agents", narratives of realistic actor behaviour can be simulated. The application of agent-based modelling in this way gives additional tooling for the quantification of these narratives. This dissertation therefore makes a contribution to the methodological toolbox of scenario development, futuring and system thinking [57, 58].

Fundamental dynamics Given the nature and scale of the problem of climate change and the challenge of the energy transition, analysing the dynamics between individual incentives and collective behaviour in a meaningful manner, required us to concentrate our approach to the underlying, fundamental dynamics of the energy transition focusing on the root cause and effect of these dynamics.

Transdisciplinary Our approach has focused on bridging the gap between qualitative approaches to scenario making by means of narratives and the quantification of these narratives by means of simulation models; facilitating collaboration between *story tellers* and *modellers*. This required our approach to be receptive for scientists from various backgrounds, which resulted in a combination of insights from these diverse scientific fields. This makes this research truly transdisciplinary [59].

The past and the future Bridging the gap between story tellers and modellers means uniting historical derived patterns which drive exploratory scenarios with the behaviour of actors in the unknown future. In how far will the future look like the past? This requires us to constantly make judgements on what drives the actors' behaviours. In Chapter 2 specifically selected intellectual framings whose relevance was prompted by our research questions and which have been used throughout this thesis to inform the agent conceptualisations, will be discussed in more detail.

Stakeholder engagement Since climate change has to be tackled by societal actors (politicians, firms, and citizens) and given the limited time frame to tackle the problem of climate change, it is the scientists' responsibility to engage with these societal actors to find the appropriate response to these problems. This required our approach to facilitate stakeholder engagement, between scientists and policy makers, between scientists and business decision makers and between scientists and the general public.

Validation As explored more elaborately in Chapter 5, large-scale complex simulation models suffer from the large parameter space for which values cannot be determined within a reasonable amount of time, if measurable at all [60, 61]. A common solution is to *fit* the model predictions to empirical data which often lead to impressively good results [62]. However, a good fit does not guarantee any realism of parameter values or model structure. True validation of these large simulation models, some argue, is therefore simply impossible [62, 63, 64, 65]. Simulation modelling therefore requires balancing the complexity of the simulation model instigated by the research question at hand, with the challenge to maintain transparency, reproducibility and tractability; the ultimate challenge of agent-based modelling [66, 67, 68]. More fundamentally these simulation models are self-invalidating as they are aimed at actors that can change their behaviour based on the provided insights. Fortunately, these models are not meant as forecasts but as exploration of actor interactions.

A minimal representation These discussed elements; i) to address the scale of the problem of climate change (with regards to time and space), ii) to facilitate stakeholder engagement, iii) to face the challenges of agent-based modelling and iv) to bridge the gap between story tellers and modellers, has lead us to our general research approach. This approach has focused on finding a minimal representation of the relevant system elements with a minimum set of assumptions that still did right to the complexities of the problem. This makes that, in the wide spectrum of modelling approaches with regards to the detail of the model conceptualisation [69] and in contrast to following a descriptive, KIDS approach (Keep It Descriptive) [70, 42, 69], our approach to agent-based modelling can be characterised as following a KISS (Keep It Simple) approach [42].

Post-normal science This research approach can be characterised as being post-normal science (as will be elaborated on in Chapter 2). Our approach recognised that researching the problem of climate change and the energy transition brings us to the border of science as uncertainties are large, decisions stakes are high, choices have to be made and values are in dispute. To increase transparency, reproducibility and tractability all the presented models in this dissertation are open source and can be found online accompanied by model descriptions following the The ODD (Overview, Design concepts, and Details) protocol [71, 72]. Our research has resulted in various scientific journals as well as in publication and presentation in various other media for the general public (see the list of Publications).

1.3.3 Agent-based modelling

As described in our research approach, we have used a relative new modelling method called agent-based modelling (ABM) to explore the emerging mechanisms between individual incentives and collective action. Agent based modelling has gained increased attention since the beginning of the century [73] as these models that work on the basis of realistic behaviour have the unique possibility to make the story teller's "who does what to whom, when and how" amendable to quantitative modelling.

The fact that models based on the assumption of neoclassical economics with its associated idealised rational agents have their limitations, was already recognised by economists in the 1950s [74, 75]. This resulted in efforts to increase the realism of economic theory by incorporating findings from psychology in what we now know as behavioural economics. With agent-based modelling, computer scientists, psychologists, sociologists and ecologists now have the opportunity to model (human) decisions making more realistically and simulate collective, emergent behaviour which other modelling methods are not able to reproduce [41, 76].

Also in the energy domain, there is recognition of the fact that the next generation energy system models should incorporate the complexity of the energy system with its many interacting system elements [77, 78, 34]. However, traditionally energy system models were dominated by techno-economic considerations. They are generally based on neoclassical economics and rational agents and struggle to capture transformative change and dynamics such as disruption, innovation, and non-linear change in human behaviour [79]. Therefore the importance of simulating the actual behaviour and interaction of different actors (company's, governments, consumers) is increasingly being recognised [56, 80, 81, 54].

Consequently, researchers increasingly focus on the fact that the energy system is a complex, non-linear system with dynamic changes of structural drivers, which are in part formed by collective behaviour at lower system levels. The application of agent-based modelling (ABM) to model the energy transition can subsequently complement the knowledge about the energy transition because it allows us to model the complex non-linear properties of the energy system. [77, 78, 34, 82]

The basics of ABM

ABM is a modelling method to simulate systems from the complex adaptive systems (CAS) perspective [83]. This system perspective emphasises the fact that a system is composed by many heterogeneous and autonomous agents that interact which each other. These interacting agents endogenously develop emergent system behaviour through constant interaction over time within a specific environment. These agents, software entities representing actors in the system, often represent people or groups of people but can also represent entities such as companies or governments. [84]

In contrast to top-down exploratory models that focus on past relationships between key-drivers and rational decision making (in general based on costs), in agent-based models the behavioural rules of the agents determine the system dynamics. The decision-making process of agents can therefore be extended with bounded rational behaviour. The determination of these rules in the conceptualisation of the model is essential. In this dissertation the agent-based models are based on multiple perspectives provided by specifically selected intellectual framings of the energy transition, which will be discussed in Chapter 2.

Results from ABM typically show probability distributions and several attractors of possible outcomes and in this way ABMs give a more nuanced story about possible scenarios. Often there is no single possible pathway, but there is a range of possible outcomes based on the chaotic nature of recursive interaction among actors in the system which is in line with our understanding of the real world. This reflects the fact that the system at hand is inherently complex and sensitive to small changes in the initial settings. This is in contrast to conventional techno-economic modelling studies which focus on techno-economic considerations and can give the impression we know much more than we really do about societal systems [85].

Common applications can be classified in five areas: modelling flows (e.g. traffic), markets (e.g. stock markets), several kinds of diffusion processes (e.g. innovations [86, 87, 88], epidemics) and formalising social theories [89].

One of the many simple examples to illustrate the use of ABM is a highway with car drivers which by their interaction (acceleration, deceleration, overtaking) can form a collective emergent system state, a traffic jam which could not be reduced to individual behaviour of agent but stems from the collective interaction between the agents.

Many of the mentioned examples have used Netlogo as software tool. Netlogo is a free and open source software tool [90] and includes a modelling library with several example models in different areas of research. Other modelling tools are Repast [91] and Swarm [92] amongst others.

The ABM community has steadily grown the last two decades and there has been efforts to standardise the modelling practise [93] and there is a well-rooted protocol to report agent-based models [71, 72]. For a further introduction to agent-based modelling we refer the reader to [94, 67, 84, 89].

1.4 Relevance

The relevance for the research presented in this dissertation is twofold; societal and scientific.

1.4.1 Scientific

The scientific relevance of this research comes from the understanding that the complex problem of the energy transition requires multiple perspectives to get a grasp of the dynamics of this transition. By applying agent-based modelling, a different perspective to various problems around the energy transition can been given which enabled us to depart from the traditional perspective of rational agents. With this approach we could focus on the simulation of a more realistic actor behaviour from which potentially collective behaviour emerges. As we will see throughout this dissertation, this perspective has given additional insight in the possible narratives of the energy transition, in the design of electricity markets and in societal dynamics influencing the pace of emergence of the energy transition.

The application of agent-based modelling also has proven to be an important additional methodological tool for scenario development as it gives researchers the means to bridge the gap between narratives and the quantification of these narratives. Applied to the energy transition, this has given a new perspective of how the energy transition could develop.

To facilitate stakeholder engagement and combine insights from various scientific disciplines a transdisciplinary research approach is vital to generate scientific insight and the successful application thereof. But vice versa, as we will see in Chapter 2, facilitating transdisciplinary research requires an application of agent-based modelling that is still understandable for the various scientific, business and societal actors involved. This resulted in a unique application of agent-based modelling focused on a minimal representation while encompassing the fundamental complexities of the energy transition.

1.4.2 Societal

The energy transition will have to emerge from the collective action of various heterogeneous actors, citizens, policy makers, business decision makers amongst others. With regards to policy makers, this dissertation gives an additional perspective to the design of policies for the energy transition. By simulating the realistic behaviour of agents, we will see that insights from the developed models give an important additional perspective to policy design when evaluating policies have a specific purpose, in this case CO_2 reduction.

The use of models and scenario development already has a strong foundation in strategic business decision making [95]. We will see how the application of agent-based modelling can be used as additional tooling for this scenario development as it gives business decision makers a new perspective on how the energy transition may develop.

1.5 Aim and outline

This dissertation is intended to bring a deeper understanding to the fundamental dynamics of the energy transition. The application of agent-based modelling will give an additional perspective and tooling to scenario development. It has the potential to bridge the gap between qualitative story tellers and the modellers that focus on the quantification of these narratives. Insights obtained by simulating realistic actor behaviour will provide insight in the dynamics between individual incentives and collective action and will put current and possible future developments into perspective. These simulations are aimed at facilitating transdiscipinary research and stakeholder engagement while doing justice to the complex dynamics. Ultimately the insights from these studies can subsequently be used to support strategic decisions making by public as well as private actors and to anticipate the consequences of their (future) decisions.

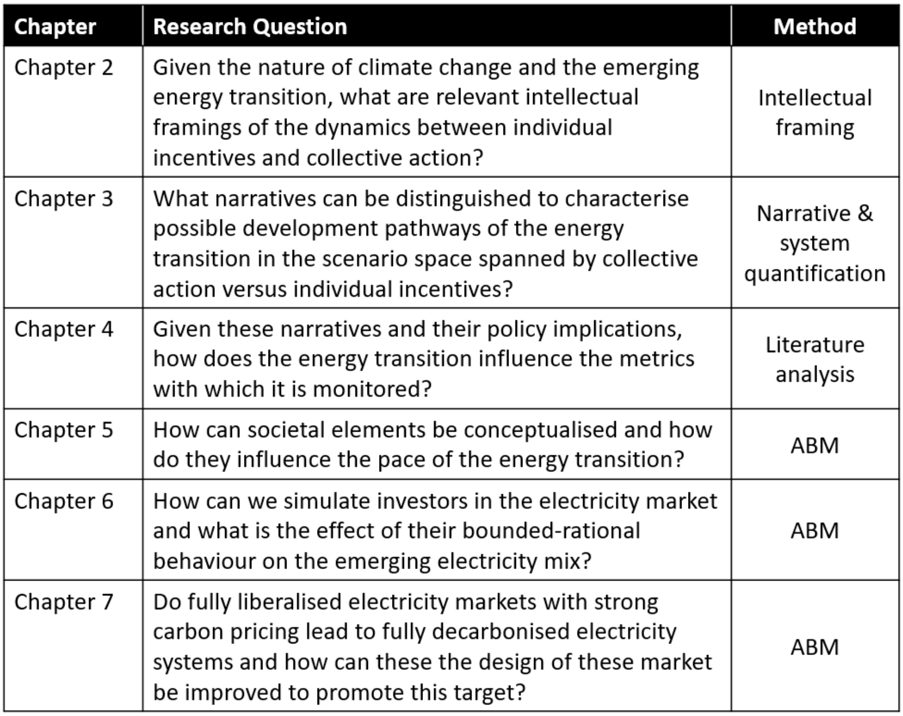
1.5.1 Research questions

The main research question in this dissertation is:

How do individual incentives and their interaction influence the path and the pace of emergence of the energy transition?

This is the research theme of this dissertation. We can never hope to answer this question in its full form but it did guide our research endeavours. It has led to a sequence of more specific question which are addressed in Chapter 2 to 7, see table 1.1. The logical sequential order of these questions will become clear in the next section, Section 1.5.2.

Table 1.1 – Research questions by chapter. Right-hand column indicates the used research method.



Chapter	Research Question	Method
Chapter 2	Given the nature of climate change and the emerging energy transition, what are relevant intellectual framings of the dynamics between individual incentives and collective action?	Intellectual framing
Chapter 3	What narratives can be distinguished to characterise possible development pathways of the energy transition in the scenario space spanned by collective action versus individual incentives?	Narrative & system quantification
Chapter 4	Given these narratives and their policy implications, how does the energy transition influence the metrics with which it is monitored?	Literature analysis
Chapter 5	How can societal elements be conceptualised and how do they influence the pace of the energy transition?	ABM
Chapter 6	How can we simulate investors in the electricity market and what is the effect of their bounded-rational behaviour on the emerging electricity mix?	ABM
Chapter 7	Do fully liberalised electricity markets with strong carbon pricing lead to fully decarbonised electricity systems and how can these the design of these market be improved to promote this target?	ABM

1.5.2 Structure of this dissertation

These research questions are addressed in Chapter 2 to 7 and conclusions are formulated in Chapter 8.

Chapter 2 The transition of the energy system will have to emerge from the interaction between many societal actors. This chapter presents selected relevant intellectual frameworks to come to grips with the different incentives of these actors. It gives background to the fundamental dynamics underlying the energy transition and has been used to inform the conceptualisation of the various models which are presented in this dissertation.

Chapter 3 Narratives of the energy transition give us a perspective on the possible pathways in which the energy transition may develop. This chapter presents two of these narratives. *All Renewable* and *Balancing Act* show the possibilities society has to tackle climate change and transition the energy system. Both narratives start from the notion that today the energy transition progresses with the build-out of electric renewables and sector electrification. But these developments will run into limits as some sectors are hard to electrify and therefore, a demand for hydro-carbon based fuels will persist. That demand could either be met by balancing remaining emissions with negative emissions which would require overcoming the associated collective action problems, or by producing a new type of renewables-based fuel, a Solar Fuel which deployment could provide an individual incentive for investors. This chapter puts current and future development into perspective, and shows what one needs to believe in for these narratives to become reality.

Chapter 4 Aligning individual incentives to collectively engage in an energy transition along the pathways described in Chapter 3 and building models to study these dynamics requires thorough understanding of energy metrics. These energy metrics are the building blocks of policy targets and energy scenarios. This chapter shows that two fundamental dynamics of the energy transition, electrification and decarbonisation make that key energy metrics such as Total Primary Energy and Electricity Generation Capacity become unrepresentative, ambiguous, difficult to interpret and ultimately, misleading. This is problematic as these metrics potentially steer climate policy and investment decisions based on statistical artefacts, rather than valid representation of the energy system. To overcome these problem recommendations for decision makers and energy modellers are presented.

Chapter 5 Now we know what solution possibilities there are, how fast will this transition develop? Critical transitions are fast and strong system changes triggered by relatively small changes in external conditions. In this chapter this concept is applied to the energy transition to explore how social dynamics around the energy system influence the pace of its transition. By applying this concept in an agent-based model, this chapter will explore various social aspects of the energy transition to explore the role of human behaviour on the possible pace of emergence of this transition.

Chapter 6 Although Chapter 3 focuses on how the demand for fuels can be met with net-zero emissions, it somewhat implicitly assumes that the electricity system will be fully decarbonised. This decarbonisation of the electricity system will actually be key to the transition of the energy system as a whole. Now that technology developments and costs reductions have given investors an individual incentives to deploy these technologies, this chapter explores whether market regulations are ready to integrate ever larger shares of these new technologies and whether a full decarbonisation emerges if the realistic behaviour of investors is taken into account. To explore these dynamics the realistic behaviours of heterogeneous investors are simulated in an agent-based model. With this model the influence of the design of the liberalised electricity market on the emerging electricity mix has been analysed.

Chapter 7 As shown in Chapter 6, the full decarbonisation of the electricity system will require increased flexibility (provided by, for example electricity storage) to incorporate increasing shares of intermittent non-dispatchable electricity generation from wind and solar radiation. By simulating investor behaviour and building on findings presented in Chapter 6, this chapter explores whether current electricity markets designed as liberalised markets in combination with strong carbon pricing will incentivise investors to invest in the required mix of storage and renewable electricity generation assets to attain a full renewable, reliable and affordable energy system in the second half of the century. Possible alternatives for these fully liberalised markets in which the capacity requirement of the system is institutionalised via capacity remuneration mechanisms are explored.

Chapter 8 In previous chapters the complexity energy transition have been explored; intellectual frameworks have been presented, possible pathways have been displayed and findings from simulation models have been described. In this chapter the conclusions of more than four years of research on the simulation of the energy transition are brought together. Moreover, this chapter reflects on findings and the approach taken.

2

Intellectual framing of the energy transition

2.1 The pace and the path of the energy transition

The transition of the energy system will have to emerge from the interaction between a wide set of actors. In democratic and capitalistic organised societies, people (in theory) will have a choice, in the ballot box and in the shopping street. However, it is an illusion to think they have a completely free will and are the only actors influencing the path the energy transition takes. As long as politicians, investors, policy makers, journalists, and even scientist have sufficient societal support they can (try to) steer the system in a particular direction. Moreover, these actors are part of social structures; companies for which they work, political party on which they vote, that potentially act differently from the actor in solitude.

Next to societal players the energy system involves many technical elements. Resourcing primary energy carriers, crude oil, natural gas, coal but also wind and solar radiation require large scale infrastructures; oil rigs, wind farms and coal mines amongst others. The distribution of large flows of mass and energy involves large scale infrastructures; electricity networks, pipelines and tankers to name a few. Additionally, processing these flows involves refineries and converter stations. Large energy consuming industries also involves large scale infrastructure, e.g. the steel industry. The size of these infrastructures makes that the return on investment of these large scale infrastructures is distributed over decades. The combination of the social system with this physical system is often referred to as being a socio-technical system [96, 97].

Next to the socio-technical system elements the energy system has an influence on the earth's ecosystem. Greenhouse gas emissions resulting from the use of the fossil resources have influenced the earth's climate [4]. It has and will warm the atmosphere, with various adverse effects on the ecosystems of the planet of which we humans are part.[1]

The interaction between all these different societal actors, the technical energy system as well as earth's ecosystem will determine the pace and the path of the energy transition. The dynamics of how such collective behaviour emerges from individual actor behaviour has been studied in many different scientific disciplines. It is the common thread of this chapter. This chapter will give the reader background to the fundamental dynamics of the energy transition as well as give an introduction to the foundations on which the chapters in this dissertation are built.

In this chapter we discuss the theoretical background, our transdisciplinary perspective on the nature of the problem of climate change and we present the associated relevant intellectual framings of the decision making structure of actors

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[1] The connection between the social system and the technical system is also referred to as *the economy* and its physical counterpart is referred to as *the technosphere* [98, 99].

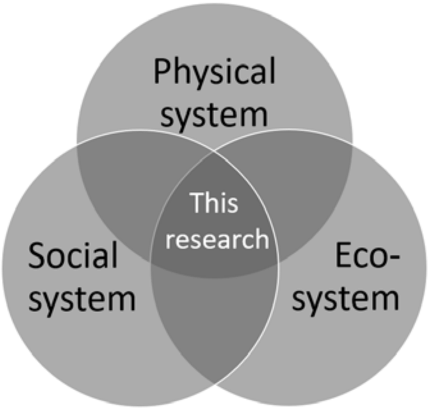

Figure 2.1 – Three systems. This research is located at the intersection of the physical, social and ecosystem.

in the energy transition. Starting from the fundamental nature of climate change, perspectives from economics, psychology and sociology will be discussed. These intellectual framings serve as starting point to the analysis in the subsequent chapters in this dissertation.

Section 2.2.1 will discuss the traditional paradigm of neo-classical economics and subsequently this chapter will show that the problem of climate change requires additional perspectives to be able to appreciate the full complexity of the dynamics around the energy transition.

2.2 Economic decision making

2.2.1 Rational choice

Although various definitions exist, economics can be seen as the science of choice in cases of scarcity [100]. The problem of climate change can be seen as such a case of scarcity: limiting climate change sets an upper limit to the emission of greenhouse gasses [101].

A particular branch of economics, neoclassical economics and its associated assumption on rationality has a long academic tradition as basis for reasoning about the collective behaviour of humans in the economy. Although it can be seen as meta-theory (a set of implicit rules or understandings for constructing satisfactory theories), its fundamental assumptions are generally accepted even though its empirical basis is very limited [102]. It is based on the following three assumptions: i) People have rational preferences among outcomes; ii) Individuals maximise utility and firms maximise profits; and iii) People act independently on the basis of full and relevant information. [103]

Based on these assumptions economic theories show that in an ideal economy, where property rights are defined and protected and every activity has a price, efficient pricing emerges from the balance between supply and demand. Based on these axioms, Adam Smith's argued that self-interested individuals will be led, as by invisible hand to an efficient outcome [104].

Put together, the assumptions of neoclassical economics and rational choice theory bring about theories on how these individual choices lead to the behaviour of the group of individuals. Additionally, they serve as basis for the development of fair, liberalised markets. The study of cases in which the axioms of neo-classical economics do not hold, sometimes framed as market failures, lead to the study of several types of collective goods, one of which is the common pool resource. [105]

2.2.2 The common pool resource dilemma

As the internationally agreed limit to keep climate change well-below 2 °C requires the world's society to transform the energy transition within the coming decades, climate change will be the ultimate driver for the energy transition.[2] As we will see, this driver will bring about a dilemma between individual incentives and collective behaviour which can be conceptualised as common pool resource dilemma.

Figure 2.2 shows a perspective on the various drivers for the energy transition. Climate change influences economic decision making; the interaction between individual choices and collective action, ultimately resulting in an investment decision in the energy system. Technology here functions as enabler and creates decision possibilities.

Climate change has two aspects that make it a common pool resource dilemma. First, the atmosphere can be seen as resource and the problem of climate change limiting our unimpeded use of this resource. We can even think about a carbon budget that is available to us before we hit limits of dangerous climate change articulated in internationally agreed goals to limit global warming. The crucial element is that our atmosphere is shared by all of us and that physical exclusion of potential users is impossible (low excludability). Secondly, the problem of climate change has the element of rivalry to it; collectively limiting global warming will mean that emissions of greenhouse gasses by one will limit the availability of carbon budget to others. These two aspects differentiate types of goods, shown in the matrix given in Figure 2.3. [107]

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[2] This in contrast to the problem of the expected depletion of resources which has a longer time scale [106].

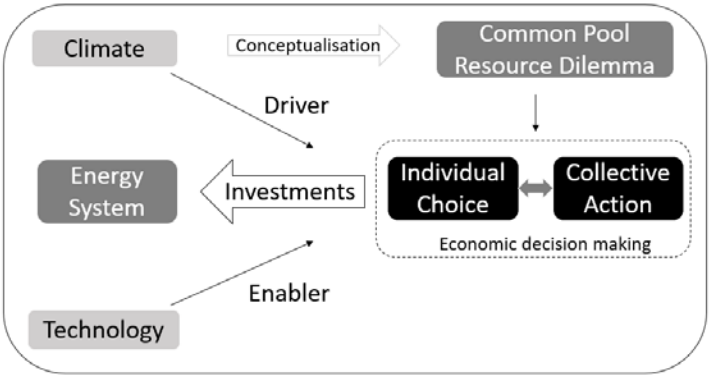


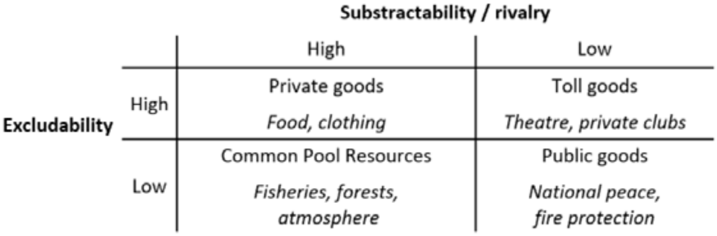
Figure 2.2 – A perspective on the energy transition. Figure shows climate change conceptualised as common pool resources dilemma. It is the ultimate driver for the decision-making process that may lead to the required investments to transition the energy system. Technology here creates decision possibilities and in that sense can be understood as enabler for this transition.

As the problem of climate change can be seen as common pool resource dilemma, the transition of the energy system entails the dilemma of the management of this resource-type. This framework can help us understand how different driving forces work out on individual and collective level.

Several examples of common pool resources situations have shown how successful management of these resources can come about. Examples include local irrigation systems, various fishing grounds, the Montreal Protocol to limit ozone depletion amongst others. Section 2.2.3 will cover the identified design principles for success.

The tragedy of the commons

In the tragedy of the commons, Garrett Hardin [108] articulated the most famous example of a common pool resource dilemma. He describes a situation in which individual herdsman acting on their own self-interest have an incentive to increase the number of sheep grazing on a common pasture as it brings personal benefits (wool, milk etc) while increasing the number of sheep abridges the collectively owned pasture, ultimately leading to a depletion of the resource. It shows the misalignment of incentives in these type of problems; in CPR situations there is an individual incentive that is contrary to the common good. Successful management of these resources therefore requires effective regulating the behaviour of beneficiaries. However, in practice the danger of free-riders



Substractability / rivalry

Excludability		High	Low
	High	Private goods *Food, clothing*	Toll goods *Theatre, private clubs*
	Low	Common Pool Resources *Fisheries, forests, atmosphere*	Public goods *National peace, fire protection*

Figure 2.3 – Types of goods can be differentiated with regards to their excludability of potential users and the rivalry of the resource. Potential users for CPR are difficult to exclude and the use by one influences the availability to others. Public goods such as global peace, public radio differ from CPR as the use of pure public good does not influence the availability to others, while with toll goods, potential users can be excluded such as is the case with theaters or private clubs.

(because of the low excludability of CPRs) often make it difficult to negotiate a successful agreement between users [107].

Climate change is often seen as a tragedy of the commons as there is individual benefit of using fossil fuels (delivering energy services) while the emissions are affecting the commonly owned atmosphere, ultimately changing the climate.

Formalised games can highlight the (mis)-alignment of incentives between individuals and the collective. Game theory provides this formalisation with which the alignment of incentives can be analysed [109]. One of these games is the "prisoner's dilemma".

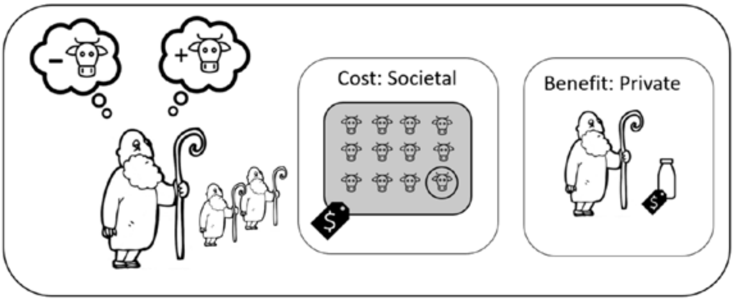
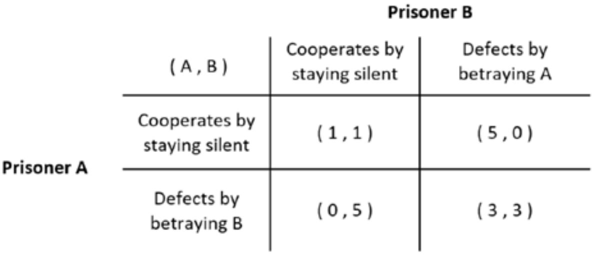


Figure 2.4 – The tragedy of the commons. Individual herdsmen have the incentive to increase the number of cattle on a commonly owned pasture because the costs are bore societal while there are individual benefits

The prisoner's dilemma can be seen as formalisation of the tragedy of the commons in a game theoretic model with a small number of participants. In 1950 most presumably Albert Tucker gave the name and interpretation "Prisoner's Dilemma" to the most well-known game theoretic paradox [110].

The paradox involves two separately imprisoned suspects that are offered a deal to betray each other. The deal structure (see Figure 2.5) gives an individual incentive for betrayal while cooperation (by both staying silent) would effectuate to the lowest conviction.



		Prisoner B	
	(A , B)	Cooperates by staying silent	Defects by betraying A
Prisoner A	Cooperates by staying silent	(1 , 1)	(5 , 0)
	Defects by betraying B	(0 , 5)	(3 , 3)

Figure 2.5 – A prisoner's dilemma. Table shows the sentence prisoners face in various scenarios; there is an individual incentive for betrayal while cooperation (by both staying silent) would effectuate to the lowest conviction.

The dilemmas the prisoners are facing is another example of a situation where the self-interest of actors will lead to an inefficient outcome. The example inductively shows that in some situations the assumptions of rational choice do not hold, but also defies Adam Smith's invisible hand as following individual incentives does not lead to the best outcome for the collective [107].

However, slight modifications to the game showed that cooperation "can" emerge. Nobel prize winner Robert Axelrod started to transform the prisoner's dilemma into an iterated prisoner's dilemma, an experiment in which players were faced with the same problem repeatedly. To find the best strategy he organised a competition between different research groups and found that "tit for tat" was the most optimal strategy for the individual to achieve an optimal outcome for the group. Tit for tat is merely the strategy of starting cooperation and thereafter doing what the other actor did on the previous move. This showed that social norms and especially reciprocity are key factors to support cooperation between actors. [110]

Outside the field of game theory, researchers in the field tried to deduce how individual behaviour in CPR dilemmas can lead to collective cooperative behaviour [111]. These findings will be discussed in the next section, Section 2.2.3.

2.2.3 The successful management of CPRs

The management of private goods (with their high excludability and substactability) is relatively easy in comparison with managing CPR's because the property right holder (owner) will have the incentive to sustainable manage the private good as he or she is the only user. However, even in situations where property rights are absent, successful governance has been observed [107]. Examples of such successful management of CPR in the field can helps us understand the dynamics between individual incentives and collective action in the context of the energy transition.

In last decades, case studies collected and analysed by, amongst others Nobel prize winner Elinor Ostrom have built up evidence that successful self-governance of common pool resources can evolve and that the tragedy of the commons in CPR situations can be omitted [112, 113]. The origins of such social behaviour are still debated but Ostrom's findings are backed-up by evolutionary studies that have shown that humans, as one of few species that have evolved to show social behaviour, are subject to two different kinds of rationality: Group rationality defending the interest of the group; and individual rationality defending the interest of the individual [114].

Ostrom isolates the free-rider problem as central to the successful management of CPR dilemmas [107]. Actors who cannot be excluded from the resource and are without incentive to act in the common interest, will tend to take advantage on the efforts of other users. However, by restricting access and creating incentives for users to put effort in the management of the resource, cooperative behaviour can emerge.

The large body of literature among many different scientific disciplines have resulted in identification of a large number of variables that increase the likelihood of cooperation in social dilemmas. As articulated by Ostrom [111, 107], among the most important are the following:

Information Informal monitoring is feasible and reliable information is available about the immediate and long- term costs and benefits of actions.

Individual motivation The individuals involved see the common resource as important for their own achievements and have a long-term time horizon.

Reputation Gaining a reputation for being a trustworthy reciprocator is important to those involved.

Communication Individuals can communicate with at least some of the others involved.

Sanctioning When individuals and groups face rules and sanctions imposed by external authorities, these are viewed as legitimate and enforced equitably on all.

Leadership Social capital and leadership exist, related to previous successes in solving joint problems.

Unfortunately, these conditions are in reality rarely met simultaneously. They mostly refer to local case studies with few participants. This has resulted in one essential insight from the CPR field of research: there is no single panacea for the management of CPR's, every situation has its characteristic features and thus problems and solutions [115, 107]. The mentioned variables however give a hint about what factors should be monitored in CPR dilemmas. They are therefore also relevant in models that focus on CPR problems.

Global CPR dilemmas are even more difficult to manage given their scale. Two examples of successful management of a global CPR dilemma give hope for societies ability to tackle the problem of climate change: the phase out of leaded gasoline [116] and the phase out of ozone depleting substances [105]. Were leaded gasoline harmed public health, the emission of ozone depleting gasses harmed the environment. Without too much elaboration, both were possible because there were viable technological solutions to the problem, and there were commercial gains for substitutes (for more detailed comparisons see [105, 117]).

By modelling these global CPR dilemmas, the interaction between individual incentives of actors and their collective emergent behaviour can be studied to find successful management interventions. Agent-based modelling is a natural fit for the analysis of CPR dilemmas as they involve the interaction between various heterogeneous actors [111]. The application of ABM has given researchers a way to simulate these dynamics in relative simple computer models [118, 119, 120, 115, 121, 122].

2.2.4 What makes Climate Change a special CPR dilemma

As we have seen in Section 2.2.2, the problem of climate change can be seen as CPR dilemma given the non-excludability of actors to the resource (our atmosphere) and the adverse effect of individual GHG emissions on the common pool resource (high substractability). Looking at the mentioned variables that increase likelihood of cooperation, it is not surprising that society so far has been slow to effectively respond to the threats of climate change. In fact, the problem of climate change has several elements to it that make it especially challenging to successfully overcome the common pool resource dilemma.

Time scale of climate change The consequences of the problem of climate change are exposed at long timescales (intergenerational)[4] due to the long timescales of climate feedback loops. The benefits of increased mitigation effort to limit the CPR problem, in this case the climate change problem, are therefore also exposed at long time scales. The actors that bear the costs of mitigating climate change therefore do not necessary gain all (or any) benefits from their efforts which make them less likely to bear the costs in the first place. This explains the interest in and focus on ancillary benefits of mitigation measures such as reduced air pollution which gives benefits give on shorter time scales and therefore changes actor's incentives. It also explains the fundamental difference between mitigation and adaptation; adaptation would almost immediately be effective giving an actor a direct incentive while mitigation efforts face long feedback times and involve more indirect incentives.

The fact that the underlying energy infrastructures (economic, social and physical) can only be developed and improved over decades [123] means that we shape them in their continuous development process. Therefore, the energy transition is complex in the sense that it contains huge numbers of elements that interact during long time spans. The underlying systems are affected by all sorts of actions taken and decisions made by various actors that are part of the same energy system. This iterative interaction can result in non-linear behaviour [105].

Geographical scale Next to the long time scales, the consequences of climate change are also exposed at large geographical scales (international) [4]. Although climate change is intrinsically a global issue, impacts will be unequally spread around the planet. Some nations will likely experience more adverse effects than others and there will even be countries (on the short term) benefiting from climate changes influencing the distribution of incentives. Therefore, the problem of climate change is in fact a *global* common pool resource problem facing a global collective action problem, simply because the resource, the atmosphere, is of global scale. This global character also means that the number of actors influencing the system is at a global scale. This in contrast with classic common pool resource problems such as irrigation systems and fisheries that usually have a more local character.

Unpredictability While the basic science of global warming is simple, the causes and likely impact of climate change are highly complex as they involve processes with considerable uncertainty [4]. As has been explored earlier, the overall impact of climate change depends on the relationship between GHG emissions and climate change (the climate sensitivity) and the effect of a changing climate on the economic system (the welfare sensitivity), see Figure 2.6. Although decreasing, these uncertainties are still inevitably large especially with regards to local effects.

Figure 2.6 – Climate and welfare sensitivity. Figures shows that the economic impact of GHG emissions depends on the climate and welfare sensitivity.

The fact that the effects of climate change are hard to predict with regards to time and space, is one of the reasons that significant proportions of society doubt the cause and effects relationship of climate change (as we will see in Section 2.3) [124]. This climate change related uncertainty, as in generic CPR dilemmas, leads actors to favour self-interest [125].

2.2.5 Application in this dissertation

Economic decision making gives a view on individual decision making in times of scarcity. Within this field, the concept of the common pool resource dilemma has served as base for analysis and several actor formalisations throughout this dissertation.

The application of an agent-based modelling approach enabled us to depart from the conventional policy perspectives on economic decision making which is grounded in the neoclassical economics paradigm, i.e. that people are profit maximising rational decision makers in a perfect market, see Figure 2.7. In this paradigm policy makers are aware a particular market may be imperfect, but the general notion is that a fair and optimal market design needs to reason from rational actors (as we have seen in Section 2.2.1). Conventional policy making therefore, focuses on perfecting this market by removing market failures. However, the application of agent-based modelling enables policy making that accepts the notion of imperfect markets and bounded rationality of actors. In Chapter 7 an idealised market with bounded rational agents is simulated which shows that removing a market failure (by applying a carbon tax) is not enough to achieve a successful policy outcome.

The CPR dilemma comes back in several parts of this dissertation. In Chapter 3 the management of this dilemma is used to differentiate two narratives of the possible path of the energy transition. In Chapter 5 the CPR dilemma is used to inform the agent behaviour within the concept of critical transitions. Chapter 6 and 7 indirectly refer to the dilemma; in the agent-based simulations of investor behaviour in electricity markets investors characteristics and future decisions depend on their performance in the electricity market, which subsequently depend on decisions by competing investors.

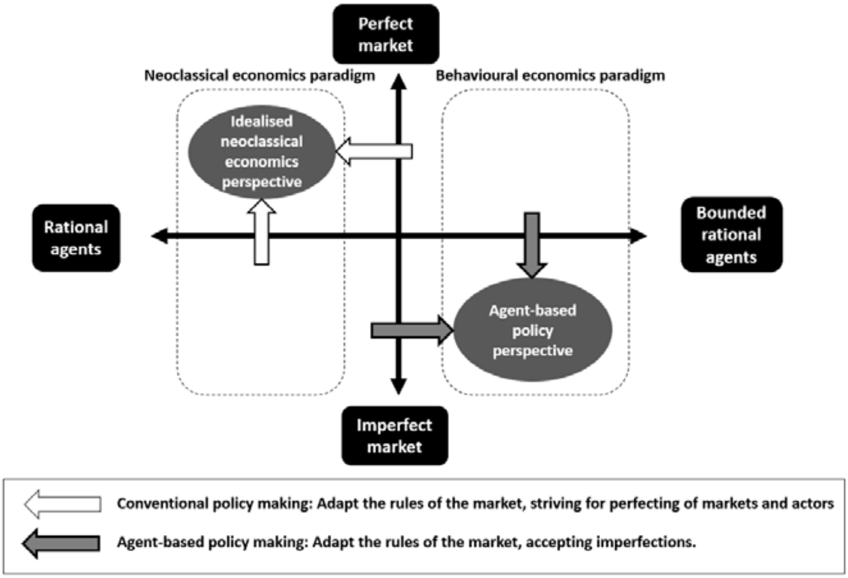


Figure 2.7 – Policy perspective matrix. The application of agent-based modelling enables modellers to depart from the conventional perspectives on economic decision making which is ground in the neoclassical economics paradigm. In this perspective policy makers are aware a particular market may be imperfect, but the general notion is that a fair and optimal market design needs to reason from rational actors. Conventional policy making therefore, focuses on perfecting this market by removing market failures. However, the application of agent-based modelling enable policy making that accepts the notion of imperfect markets and bounded rationality of actors.

As discussed, the successful management of global CPR dilemmas in the past often involved a viable technological solution. With regards to the technological solution to the problem of climate change; in Chapter 3 we will see that the technological solutions have shown substantial cost reductions and their deployment is gaining pace (electrification, solar PV and wind). Focus now increasingly goes into integration of these technologies. We will see one part of that story in Chapter 3: for a large part of the energy service demand, the technical solutions (CCS and BECCS) are not commercially attractive and deployment only allows for a license to operate that has to be mandated. This chapter shows what one needs to believe for a carbon-neutral substitute for fossil fuels (a Solar Fuel) to become commercially attractive. Chapter 6 and 7 tell the other part of the story, the actor dynamics involving integration of ever larger shares of renewable resources in the electricity mix.

2.3 What's on the agent's mind?

From the 1950's on-wards insights from psychology and sociology have been used to increase realism to economic decision making. This branch of economics is now known as behaviour economics [126]. How are we different from the rational self-interested actor as assumed in neo-classical economics?

Psychologists as well as sociologists have defined several factors that influence the action level of individuals, often formulated with help of different frameworks, models or theories (e.g. theory of planned behaviour, value-belief-norm model). They can be differentiated into three groups; awareness of the problem, world views and values, and behavioural factors [127, 125, 128, 129, 130]. They will be discussed subsequently.

2.3.1 Awareness

Firstly, the awareness people have of the problem of climate change is important [127, 129]. However, being aware of the problem is not enough; to take effective action one also needs to understand the cause and effect and *how* to take action. This is not obvious. Although awareness has been increasing [131], best practices are not always clear nor universal. What is the best way to lower your climate change impact? Life-cycle assessments [132], in theory the most comprehensive analysis to compare options, are technically complex and full of large uncertainties (climate sensitivity and welfare sensitivity or a broad range of environmental impact categories). These uncertainties, especially in cases of CPR-dilemmas lead people to favour self-interest [127, 133].

One of the sources of information is media and journalism. In liberalised markets where media rival each other for the attention of the consumer, eye-catching, notable news stands out. This is a long-ingrained characteristic that is based on our animal instinct to look out for the unusual as it can anticipate danger. In the case of climate change that is often the climate denier or the conspiracy thinker which play into gut feel disproportionately influencing the awareness and action level of society. [127]

2.3.2 World views & values

One's world view also influences one's decisions. Where moral and ethical values as intergenerational and international equity can be a reason to act, there are also worldviews and values that can result into inaction. Whether you believe in supra-human powers, Gaia, God or techno-salvation it can all be a reason to decrease the relevance of one's individual choices [127, 128, 134, 135, 136]. Another worldview that can play part can be described as system justification; the tendency to defend the societal status quo [137]. This is best exemplified by a quote from former U.S. president George H. W. Bush: "The American way of life is not up for negotiation" [138]. This also relates to the resistance to change. The famous NIMBY: *Not In My Backyard* characterises the resistance to a proposed development in an actors local area while they would support or tolerate development further away from them.

What makes things more difficult is that the various values people have, are potentially conflicting [139, 140, 141]. A biologically raised chicken is more CO_2 intensive than an intensively farmed chicken but has had a happier life [142]. So what do you prioritise, your appetite for chicken, animal welfare or climate change impact?

Also political world views can influence peoples incentives. Economic liberalism prioritises the freedom of choice and efficient markets, limiting governmental interventions to prioritise on only the most basic collective goods [143].

But these world views and values tend to be flexible. Cognitive dissonance is the term attached to the mental discomfort people experience when multiple beliefs, ideas or values contradict [144]. People tend to try to decrease this dissonance by bending the earlier hold beliefs, ideas and values; feeling inadequate to prevent the problem makes me justify my actions, for example by making myself believe the problem is less severe than I thought previously. Ultimately this can lead to climate change denial [145].

2.3.3 Behaviour

With regards to the behaviour of actors in the context of climate change, several behavioural elements have been distinguished by psychologists that differentiates actors' behaviour from the assumptions of rationality [75, 146]:

Optimism bias There is considerable evidence that suggests that people discount their personal exposure to environmental risks. For example, although global citizens do expect that environmental conditions will worsen in the coming decades, they expect that people in other places will be worse off than themselves [127, 147, 148].

Discounting People tend to discount the future and undervalue distant or future risk [149, 147]. They do so heterogeneously and dynamic over time. For example Kahneman showed that people who would choose one candy bar now over two tomorrow, at the same time would choose two candy bars 101 days from now over one candy bar 100 days from now. This phenomenon is also known as hyperbolic discounting [150].

Comparisons People are very social and tend to compare actions of other continuously with themselves, subsequently influencing future decisions [144]. Social norms, informal understandings that govern the behaviour of members of a society, can encourage certain behaviours [151]. These norms can spread through social or physical networks. A well-known example is the spread of photovoltaic (PV) panels through neighbourhoods; the visibility of these PV panels make neighbours more inclined to invest in these panels themselves [152, 153].

Fear of inequity The fear for free-riders, common in open resource situation such as climate change, can lead to fear of inequity. This fear ultimately can lead to in-action and stall progress [154, 107, 155].

Loss averse Although rationally investments should be regarded as sunk costs after they have been made, in reality people are loss averse. This makes dispensing of a good after investment more difficult than it would have been if one had not invested in it [156, 157]. This makes investments in old technology, a car on personal level or industrial processes on corporate level, difficult to replace.

Pricing Putting a price on something has the potential to remove morality and ethical arguments from the decision-making process [158].

Low-cost hypothesis Once the decision to take action has been taken, the low-cost hypothesis says people are more inclined to take the easy option rather than the more effective option [128, 159].

Rebound-effect When people have made a decision the rebound-effect, the effect that peoples gains of action are diminished by a subsequent action, will decrease the overall effect of action [160, 161]. For example, the decrease of time that people shower can raise enough social capital to justify an extra flight to the other side of the world, eventually increasing climate impact.

These insights from psychology have initiated policy experiments to encourage climate change mitigation measures that make use of these insights under the theme *nudging*. Several successful examples have shown their positive effects [162]. For examples, subsidies to isolate attics in the UK became successful only after they were offered in combination with providing services to clean these attics. Other examples include changing the default choice, whether it is printing 1 or 2 sided, or providing a vegetarian versus omnivore menu.

Although the effect of these nudging experiments are proven, the question remains whether these relatively small-scale experiments will bring about the drastic and large scale transition the world will need. They do however add an extra effective policy design option to encourage the energy transition.

2.3.4 Application in this dissertation

These insights have been used at various location in this dissertation. The fact that actors show bounded rational behaviour comes back in Chapter 5, 6 and 7. Insights about the differing world views and discounting have been applied in 6 and 7. In these two chapters investors are modelled in the electricity market which have different world views and discount investment heterogeneously. Social behaviour of actors, especially with regards to comparisons and network effects comes back in Chapter 5. In this chapter the influence of these aspects has been explored by modelling agents that influence each other to become active or in-active with regards to the energy transition. The point about awareness comes back in Chapter 4; awareness of the problem of climate change begins by monitoring the system in an effective way by using a representative set of (energy) metrics. The core of Chapter 3 turns around differing world views, in this case of the reader; what pathways can be laid out based on different world views?

2.4 Critical transitions

The successful management of CPR often requires a regime shift to sustainable manage the CPR. Therefore, the analysis of CPR dilemmas is closely related to the analysis of regime shifts or *critical transitions* in socio-ecological systems. Historical energy transition as well as fairly recent ones such as the “Energie wende”, the German energy transition, have been described in the context of such a critical transition [163].

With the concept of critical transitions system characteristics can be explored that may lead a fast, disruptive transition of the average public attitude with regards to a problem. Such a transition can be triggered by small changes to the perceived seriousness of the problem (based on changes of the external environment). These small changes can lead a bifurcation point that makes a previously stable system show a critical transition to another system state.

Originally derived from ecological case studies, Scheffer et al. [164] have formalised the concept and applied it to societal problems. In this way social aspects such as peer pressure, the absence of leaders and the complexity of the problem could be explored. They have been distinguished as critical aspects that can influence the type of transition the average public attitude of a society will take with regards to the perceived seriousness of the problem (see Figure 2.8) [164].

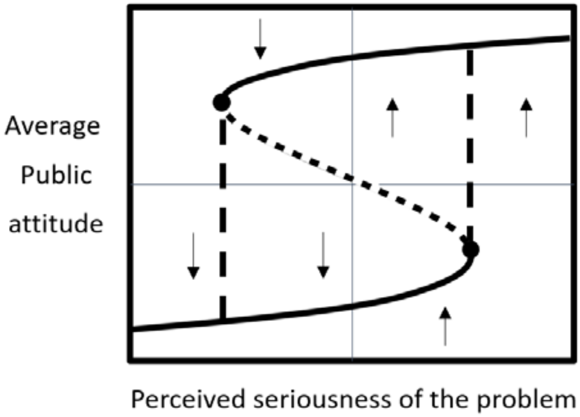


Figure 2.8 – The concept of critical transitions. Figures shows a situation in which the average public attitude to a problem increases slowly with the perceived seriousness of the problem. When a bifurcation point is reached, a critical transition can occur to a state with an higher average public attitude to a problem.

2.4.1 Application in this dissertation

In Chapter 5 this concept will be explored in more detail. It will serve as basis for an agent-based exploration of this concept in which the dynamics between agent-interactions can be further studied. Social aspects such as interaction via networks, heterogeneity of the population and the effect of leaders have been incorporated to analyse their effect on the emergence of collective action to engage in an energy transition.

2.5 Dealing with uncertainty and high-impact

The energy transition is an urgent multi-dimensional complex process across large time and geographical scales that involves the interaction of many different societal and physical elements which faces large uncertainties [165]. It is an illusion we can possibly and meaningfully simulate all these elements in an (agent-based) model, even more so as the iterative actor interactions in combination with human reflexivity (the circular relationship between cause and effect of human action) makes the social system fundamentally unpredictable. Choices have to be made on what to include and what to exclude and on the boundaries of the model. Given these choices, when can we still be certain that the generated scientific insights actually represent the truth?

Traditionally there are two ways of doing science to generate scientific insights; induction and deduction. Where deduction starts from a set of axioms (explicit assumptions) to derive a logically certain conclusion, induction starts from specific observation of reality to derive general conclusions. Arguably agent-based modelling is a third way of doing science (also known as generative science [41]); from deductive generated model data produced by models based on explicit assumptions from various frameworks, inductive analysis generates insights [42]. The presented framing in this chapter, which relevance was triggered by our research questions gave us guidance on the importance elements to include in simulation models.

Generally model validation ensures that the model is correctly representing reality but models designed to simulate the energy transition are impossible to validate completely as they simulate fundamentally unpredictable systems into the unknown future [63]. Post-normal science (PNS) is a novel approach to science which give guidance to the scientific method in these type of cases [166, 167].

PNS differentiates itself from what Thomas Kuhn articulated to be *normal* science [168]. While normal science relies on a common set of rules either provided by inductive or deductive analysis, Silvio Funtowicz and Jerome R. Ravetz, the developers of this approach, argued that in cases where facts are uncertain, values in dispute, stakes high and decisions urgent a different approach is necessary. In these cases "speaking value-free truth to political power" is impossible as scientists have considerable room to make choices in the assumption of their analyses [169, 170]. Therefore, these decisions are increasingly politicized and require politicians to weight the arguments and make a decision based on their political worldview.

To put PNS in perspective, three styles of analysis are distinguished to deal with specific problems; applied science, professional consultancy and PNS which can be differentiated in figure 2.9 in the space spanned by two axes, decision stakes on the vertical axis and system uncertainties on the horizontal axis. While in the applied sciences, the normal peer-review process is sufficient, professional consultancy is considered appropriate for analyses that cannot be peer-reviewed and where decisions are pressing [166]. When uncertainties are even larger and decision stakes are higher we enter the space of PNS. PNS refers to three key elements to deal with these kinds of scientific problems.

Uncertainty management Different methodological perspectives to the same problem give additional insight.

Plurality of perspectives Multidisciplinary, transdisciplinary and interdisciplinary teamwork within science makes collaborative teamwork with policy makers, business and society possible.

Extension of peer community The extension of the peer community could bring in insights from representatives from social, political and economic domains.

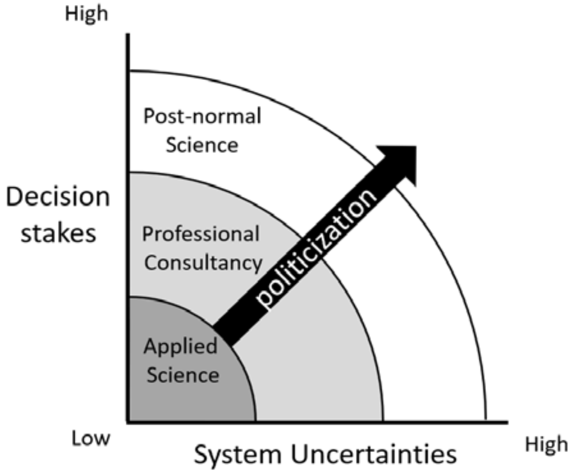


Figure 2.9 – A diagram differentiating Applied Science, Professional Consultancy and Post-normal Science. Figure shows that when decisions stakes are uncertainties large, we enter the space of Post-normal science. During this process decision are increasingly political in nature as scientific research increasingly delivers insights by means of perspectives rather than "the truth". Adapted from [171].

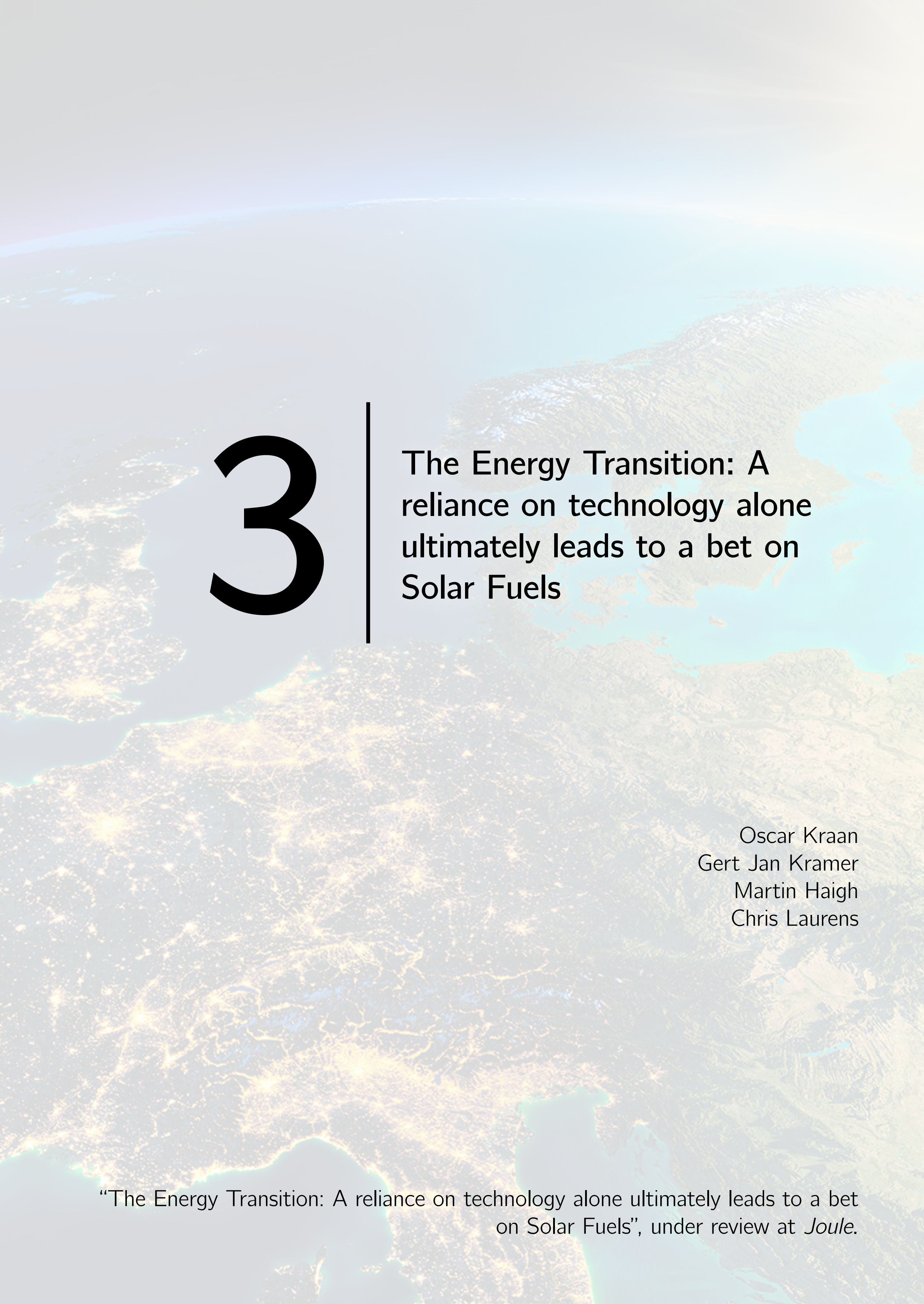
2.5.1 Application in this dissertation

The problem of climate change is often described as being post-normal science (e.g. [172, 173, 169, 174]). PNS also provides the best description of our research approach. Referring to the three elements of PNS:

An additional methodological perspective The application of agent-based modelling to the various questions in this dissertation has provided an additional methodological perspective to the discussed problems. In Chapter 5 the idea of PNS will be explored in more detail but the application of ABM to electricity market modelling in Chapter6 and 7 clearly has provided a new perspective on the most effective design of these markets.

Transdiciplinary This dissertation describes truly transdiciplinary research and in the process deliberately involved stakeholders from different domains. Firstly, by combining insights from different scientific disciplines. Insights from economics, psychology, sociology and biology provided insights into actor behaviour; computer science and physics provided insights into how to model these social phenomena. Secondly, this research has been conducted at three universities in The Netherlands; in Leiden at the Institute of Environmental Sciences, in Utrecht at the Copernicus of Sustainable Development and the Technical University in Delft, at the faculty of Technology, Policy and Management.

Extension of peer community Next to the various research institute, this research was carried out in collaboration with the industry, the R&D department within Shell, Shell's scenario team and Shell's New Energies business. Additionally, results have been discussed at several occasions with policy makers, specifically at the Dutch Environmental Assessment Agency (PBL).



3

The Energy Transition: A reliance on technology alone ultimately leads to a bet on Solar Fuels

Oscar Kraan
Gert Jan Kramer
Martin Haigh
Chris Laurens

"The Energy Transition: A reliance on technology alone ultimately leads to a bet on Solar Fuels", under review at *Joule*.

Abstract

Today the energy transition progresses with the build-out of electric renewables and increased electrification of end-use. However, significant demand for hydrocarbon fuels will persist. That demand could be met by capturing and storing fossil fuel emissions and balancing remaining emissions with negative emissions by deploying existing technologies. This requires active government involvement to orchestrate and support the transition. A radical alternative exists in the form of Solar Fuels, carbon-neutral fuels produced from renewable electricity, water and the circular use of CO2. If and when Solar Fuels could be produced at affordable cost and scaled, their market introduction could be market-led needing no more than price-protection in the form of a carbon price. We give a specific target for the future viability of solar hydrocarbon fuels of 200 US$ per barrel. While this is potentially achievable in the long run, policy reliance on it is a significant bet.

Keywords

Energy transition, Energy scenario, Solar fuels, Collective action.

3.1 The choice at the heart of the energy transition

The task to build-out and reshape the world's energy system is central to two of the greatest challenges for the 21st century: fulfilling the economic aspirations of a growing world population while drastically reducing CO_2 emissions to limit global warming. Since 2000, the world has tried to make progress on these challenges by the rapid deployment of "new renewables", notably solar PV and wind [175]. This expansion appears likely to continue apace as costs continue to fall and decarbonisation efforts increase under the pressure of "Paris" [5]. Any future scenario therefore includes large-scale electrification with significant contributions of solar PV and wind electricity, which will continue to be the workhorses of energy-sector CO_2 mitigation in the decades ahead. There is no alternative. Even when electrification is pushed to its limits, however, demand for fuels will persist – often in the form of hydrocarbons. How these fuels will be supplied while committing to climate targets is a societal choice for which the world has yet to make up its mind.

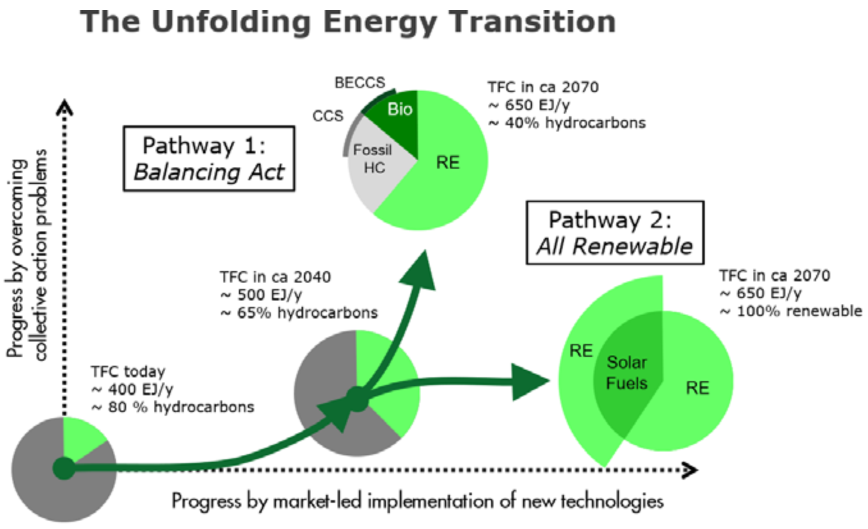


Figure 3.1 – A paradigm for the two dimensions of progress in the energy transition. Second circle in Pathway 2 shows energy going into solar fuel production process (580 EJ/y). The 2070 date given is consistent with the Paris Agreement. Total Final consumption (TFC), Fossil hydrocarbons (Fossil HC), Renewable, non-hydrocarbon-based electricity (RE), Bio-Energy with CCS (BECCS).

In our view, two fundamental directions in the pursuit of 'progress' are possible, see Figure 3.1. One is progress that requires overcoming co-ordination and planning hurdles, such as through active government involvement This pathway, *Balancing Act*, has several aspects. It requires orchestrating the roll-out of new infrastructure: long-distance electricity transmission, hydrogen distribution networks and the deployment of carbon capture and storage (CCS). It also requires coherent policy actions across countries, for bio-energy to grow to its full potential in an environmentally responsible manner.

Many commentators are sceptical that we can overcome these collective action problems. Instead, they put their faith in the possibility of developing new technology [176] with just a limited government role just to get the ball rolling. This leads us to Pathway 2, *All Renewable*, that relies on unpredictable technical progress. Most of the progress we see today is of this type: renewable technologies (wind, solar), vehicle electrification and efficiency measures, helped initially and when needed by substantial subsidies or mandates, but eventually becoming completely market-led once their costs are competitive. Taken to its logical conclusion, this ultimately will become a bet on solar fuels: the making of everyday hydrocarbon fuels like methane, gasoline and jet fuel from solar and wind energy, water, and the circular use of CO_2.

Balancing Act and *All Renewable* differ in one other crucial manner. *Balancing Act*'s reliance on biomass and carbon storage will eventually constrain the world's total fuel supply, which may eventually raise difficult questions around lifestyle-change and limits to growth [20]. *All Renewable* with its reliance on solar and wind, at least in theory, offers scope for an unlimited supply of renewable fuels. As history time and again shows, this is an enduring aspiration, see box [177].

> *"[I]t would be highly desirable to have an efficient and economical way of directly converting and storing solar energy as a chemical fuel".*
>
> J. Bolton - Science (1978)

3.2 Current and future energy demand

Our current energy system, responsible for 70% of all greenhouse gas (GHG) emissions, has an annual take-in of 590 EJ primary energy. 80% is of fossil origin, a percentage that has hardly changed since the 1960s. Another 10% is biomass (most of it traditional), hence a full 90% of the world's energy supply is hydrocarbon-based. After conversion losses two-thirds of this primary energy reaches the end-user, with some 20% in the form of electricity. Fuels and chemicals feedstock account for 70%, while biomass and heat make up the remaining 10% of consumption by end-users [31].

A recent Shell scenario, Sky [7], depicts a transition pathway that is consistent with the Paris agreement but at the same time acknowledges that energy demand will grow as the non-OECD develops and billions more enter the global middle class. In this world the demand for energy services (lighting, heating, transport kilometres, tonnes of steel produced, etc) will grow substantially. Even under optimistic assumptions that energy efficiency will improve (by a factor of between two and six in the Sky scenario, across different sectors), total final energy will increase by 60% to 2100. This would equate to around 650 EJ / year, or 65 GJ / person / year, half the level of demand per person in the OECD today.

How can the broad range of energy services be met with net-zero CO_2 emissions? What are our options to meet Paris? In what follows we will follow the logic of Figure 3.1; electrification pushed to its inevitable limits leading to a branching point of how to deal with the remaining fuel demand.

3.3 Renewable electricity and electrification: immediate push to inevitable limits

Since the beginning of the century, we have seen that solar PV and wind industries have grown from insignificance to US$ 300 billion per year, adding 150 GW every year [178, 179]. Yet such is the scale of the world's energy system, that between them they still comprise less than 1% of the global energy supply today and so further very substantial growth will be needed. In the coming decades these technologies will increasingly have to be paired with storage and ongoing electrification of sectors which traditionally relied on fuels, specifically transport (by introducing electric vehicles) and heating of the built environment (by applying heat pumps). In short, the transition is gathering pace and the list of near-term options for change is impressive. But at the same time, it is one-sided, heavily leaning on electric renewables, electrification of demand and strong efficiency improvement. It leaves the fuels half of the energy transition still to be done.

This includes industrial sectors where GHG emissions are inherently difficult to strip from the production process such as in steel and cement making. Also, while recognising the electrification potential of passenger road transport, the decarbonisation of the heavy-duty transport (ships, aeroplanes, lorries) will be limited. These sectors must be expected to remain significant reliant on energy-dense, portable fuels for a long time. Another critical aspect is that at least 15% of the total energy demand, 100 EJ / year, will need to meet feedstock needs for the chemical and materials industry. This "non-energy use" is dominated by oil and natural gas today, and may have increasing shares of coal or biomass, but it fundamentally relies on carbon.

Hydrogen is the natural – one might say preferred – fuel in a decarbonised world, for it contains no carbon. But the slow progress over the last decades makes clear how great the infrastructural challenges are. There can be no doubt that hydrogen will play a role, but only in regions and sectors where the infrastructure challenge can be overcome. This is specifically the case in large industrial clusters. Transport and the built environment are sectors where the hurdle for introduction is much greater, and hydrogen's future in those sectors is both uncertain and globally limited. This leads us to the view that also in a net-zero emissions-world, hydrocarbons are likely to continue to be the mainstay of fuel provision.

Our best estimate, in line with Sky, is that at least a third of the energy supply will require some sort of carbon-based 'fuel', or some 225 EJ per year.[1] This will lead societies to a choice as to how to proceed to make these fuels carbon-neutral: to face up to the difficult organisational challenges (as in *Balancing Act*) or to bet on uncertain technological advances (as in *All Renewable*).

3.4 The orthodox energy transition for fuels: efficiency, bio-energy and offsets

Pathway 1, *Balancing Act*, would seek to deliver the 225 EJ of fuel through a combination of bio-energy and fossil fuels, and is similar to Sky Scenario assumptions. Following the current views on the sustainable resource base for biomass, between 100 and 200 EJ primary energy could be supplied by biomass as feedstock for biofuels and bioplastics [181]. After converting the woody biomass, we could expect biofuels to deliver up to 80 EJ / y of final energy. This would leave 145 EJ, or 25% of the system, relying on fossil resources.

The use of fossil fuels however entails emissions. To get to a balance of "sources and removals by sinks" [5], the ubiquitous use of CCS will be essential, but those emissions that cannot be captured and sequestrated centrally (such as from the transport sector) will need to be offset by negative emissions. To attain these negative emissions, most major long-term outlooks [182] including Sky rely on the capturing and sequestration of point sources bio-energy emissions currently seen as the most promising option to deliver negative emissions at the required scale.[2]

None of this requires transformational technological breakthroughs. The

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[1] This is in line with experts that showed that a mid-century, low-cost 100% decarbonisation scenario for the energy system using only electric renewables is in-feasible. [180]

[2] Importantly, this calculation relies on the hydrocarbons (fossil and biomass) that are used to make materials being properly disposed of after use. If waste plastics, for example, cannot be recycled, and if they are burnt to provide electricity and heat, then those emissions in turn will need to be captured with CCS.

technologies exist today and large-scale CCS projects have already stored more than 200 million tonnes of CO_2 [183]. At a long-term cost of 50 US$/t$CO_2$ [183], CCS would add about 3 US$ / GJ to the average energy costs of a mix of coal, gas, oil, and biomass combined, giving a total of 15 US$ / GJ (of which CCS is 20%). Further deployment will bring CCS cost down, but further deployment will need better alignment of incentives. Societal support for strong policy signals will be required to trigger the appropriate investments, alongside a clear legislative framework and a planning of co_2 infrastructure. Only by overcoming these coordination hurdles will large scale deployment of CCS arise.

3.5 The technology leap: what one needs to believe for solar fuels

Pathway 2, *All Renewable*, by contrast, supplies the demand for hydrocarbon fuels with a new, carbon neutral fuel, a Solar Fuel, produced by capturing co_2 directly from air. Such fuels have recently gained much attention under the headings of Power-to-X (X being gas, liquid or product) and electricity-based fuels [184, 185, 186, 187, 188, 189].

Production of these solar fuels banks on the integration of a suite of technologies, that individually need both greatly improved performance and cost reductions to make it into an economic and scalable option. But when hydrocarbon fuels can be synthesised at an affordable cost from renewables and co_2 in circular use from the atmosphere, the prospect offers a practically unlimited supply of carbon-neutral (high energy density) fuels.

Although in both pathways the energy industry would be completely transformed, what sets *All Renewable* apart from *Balancing Act* is that, though the technology challenges are harder, the public policy challenge may be a great deal easier. Consumers can continue using energy exactly as they do today, but without affecting the climate as any consumption would simply be returning co_2 to the atmosphere that had been drawn from it to make the fuels. Starting with R&D incentives, the transition would proceed by entrepreneurs and large companies making use of market mechanisms, since they do not need to rely on any new infrastructure. In addition, the resource base for all practical needs is unconstrained and most countries could choose to produce solar fuels locally if they wished. Therefore, *All Renewable* depends on the ability to develop and deploy key technologies well beyond their current pilot stage but thereafter only on its affordability.

We suggest a reasonable target to be 200 US$ / barrel (bbl). The cost of crude oil has typically ranged between 50 and 100 US$ / bbl in recent years, but solar fuels are in the form of useable fuels, for which retail prices can be much higher. For example, gasoline in Germany typically sells for the equivalent of 250 US$ / bbl today. As such, this does suppose societies are willing to pay a premium for one or all of the attractions above. Yet it would still be affordable, particularly in time and as economies grow. In our outline assessment here, we find that when assumptions from technology experts in different fields are combined, and optimistic yet plausible values are used, an overall cost of around 200 US$ / bbl comes into sight. Although some elements are only at pilot stage today, a first order indication is that the cost today could be around 850 US$ / bbl. With regards to the energetic and economic costs, what do we need to believe in order for solar fuel to become reality?

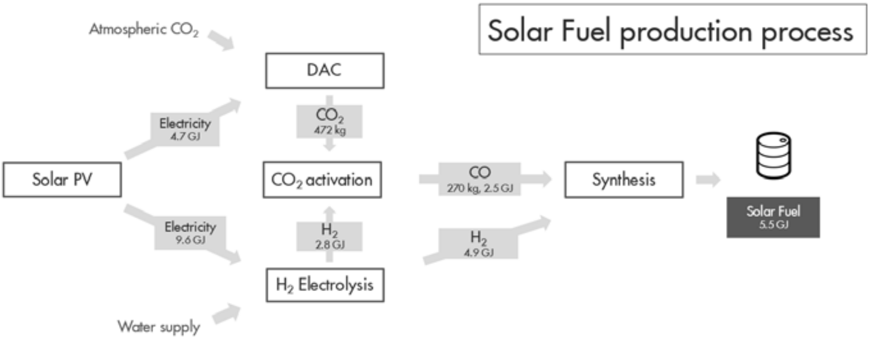

Figure 3.2 – The five principal elements of solar fuels production: Solar Photovoltaics (Solar PV), Direct Air Capture of CO_2 (DAC), Hydrogen (H2), Activation of CO_2 to CO, and Synthesis (e.g. via Fischer-Tropsch) of the fuels.

Using an engineering process that we can conceive today, there are five principal elements to manufacturing solar fuels, see Figure 3.2. A barrel of fuel products, like gasoline or diesel, contains 5.5 GJ of energy, with a little over 100 kg of embedded carbon. As such, the production process of a barrel of solar fuel would need to draw about 0.5 tonne of CO_2 from the atmosphere.[3] Around 5 GJ would be needed to run this Direct Air Capture (DAC)process [191] and an additional 9.6 GJ would be required to produce hydrogen and upgrade the captured CO_2 to CO [192]. Together with the produced hydrogen, this CO can be synthesised to a fuel. As such, the energy efficiency could be close to 40%, requiring 14.3 GJ of electricity to produce 5.5 GJ of solar fuel. Based on current projections [193, 194], it is reasonable to expect that in favourable locations, the cost of solar PV (or other renewable) electricity can fall from typical values of

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[3] Some scientists have put forward work on artificial photosynthesis as an alternative, but the theory as well as the technology is at an earlier and more speculative stage [190].

around 50 US$ / MWh today [195] to 15 US$ / MWh. This would equate to 60 US$ / bbl for the electricity costs. Recently, engineers have put forward a pathway for developing DAC at a cost of 100 US$ / t CO_2 [196, 197, 198]. As a result, this contributes nearly 50 US$ for the cost of our barrel. Previously, the comprehensive analysis by the American Physical Society in 2011 [199] estimated a cost of 600 US$ / t CO_2. This is the greatest contribution to the change in the economics of solar fuels from today.

Electrolysis of water to produce hydrogen is established but limited in scale. IEA estimate [200] the current cost of electrolysers at around 1200 US$ / kW (input electricity). There are substantial efforts to reduce the cost from today, targeting 300 US$ / kW [201]. At that level, the equipment would add around 50US$ to the tally.

Finally, the Fischer-Tropsch process for synthesis is used in full-scale industrial production today for converting natural gas or coal to liquid fuels. Here it would take the activated CO_2 as carbon feedstock. The costs of this activation - for which several alternative technologies exist[4] [203] - are still speculative but let us assume it could be done for 10 US$ / bbl. With further development and economies of scale of these processes, the final Fischer - Tropsch synthesis would cost around 20 US$ per barrel [204].

There would inevitably be other costs for processes such as the water handling and gas transport, and for other equipment such as the hydrogen storage tanks. If the combined cost of these could be no more than 5% of the total costs, then alongside the other progress, the 200 US$ target could be realised (see Figure 3.3 for summary of the calculation).

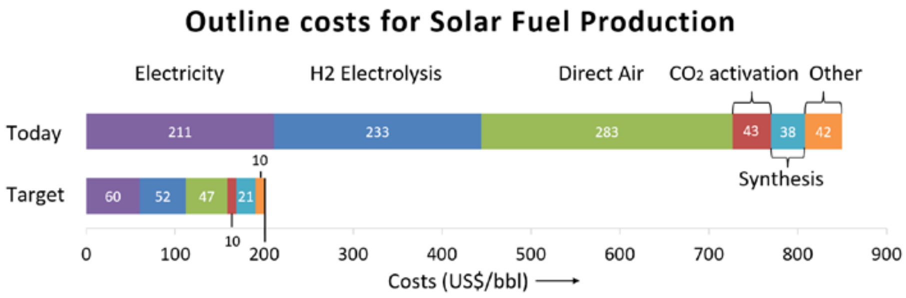

Figure 3.3 – Outline costs for solar fuels production

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[4] The leading options for converting CO_2 to CO are the reverse water-gas shift reaction [202] or electrolysis of CO_2 [203]

3.6 Conclusion

A fifty percent increase in energy consumption in about 50 years, combined with increasing environmental stresses will bring the world to uncharted territory. Even if wind and solar PV succeed in replacing half of the existing energy system, as well as meeting the significant demand growth in the decades ahead, they will run into the systems limits of electrification. Close to a half of the energy system will need a fuel from one source or another. That is where the path forks.

The world can either choose to rely on the policy and infrastructure coordination, necessary to bring CCS, bioenergy and BECCS to the required scale. This is the path of *Balancing Act*, a development trajectory for which the technologies are ready to be scaled. However, for decades now, nations have hesitated to make a start, as with CCS, or have struggled with the governance and co-ordination, as with biofuels. Nevertheless, the Paris Agreement may offer a resilient global architecture and it remains a plausible approach.

However, the scepticism over the world's ability to overcome these collective action problems and the reluctance to embrace technologies such as CCS and BECCS [205, 191], has created space for an alternative narrative. In turn, that relies on technologies that are at a lower level of readiness, but that offer the promise of less hindrance from the problems that have held back the deployment of CCS and biofuels. This narrative, *All Renewable*, explores the rapid technological progress to make solar fuels affordable and scalable over an unprecedentedly short time period [123]. It presents a daunting technical challenge. While affordable, *All Renewable* is still a significantly more expensive route than *Balancing Act*. Furthermore, *Balancing Act* is more resilient: *All Renewable* will only work if all its five components make great technological advances. Yet if solving the co-ordination problems of *Balancing Act* proves insurmountable, the world may be forced to commit to *All Renewable* to address climate change, whether it wants to or not.

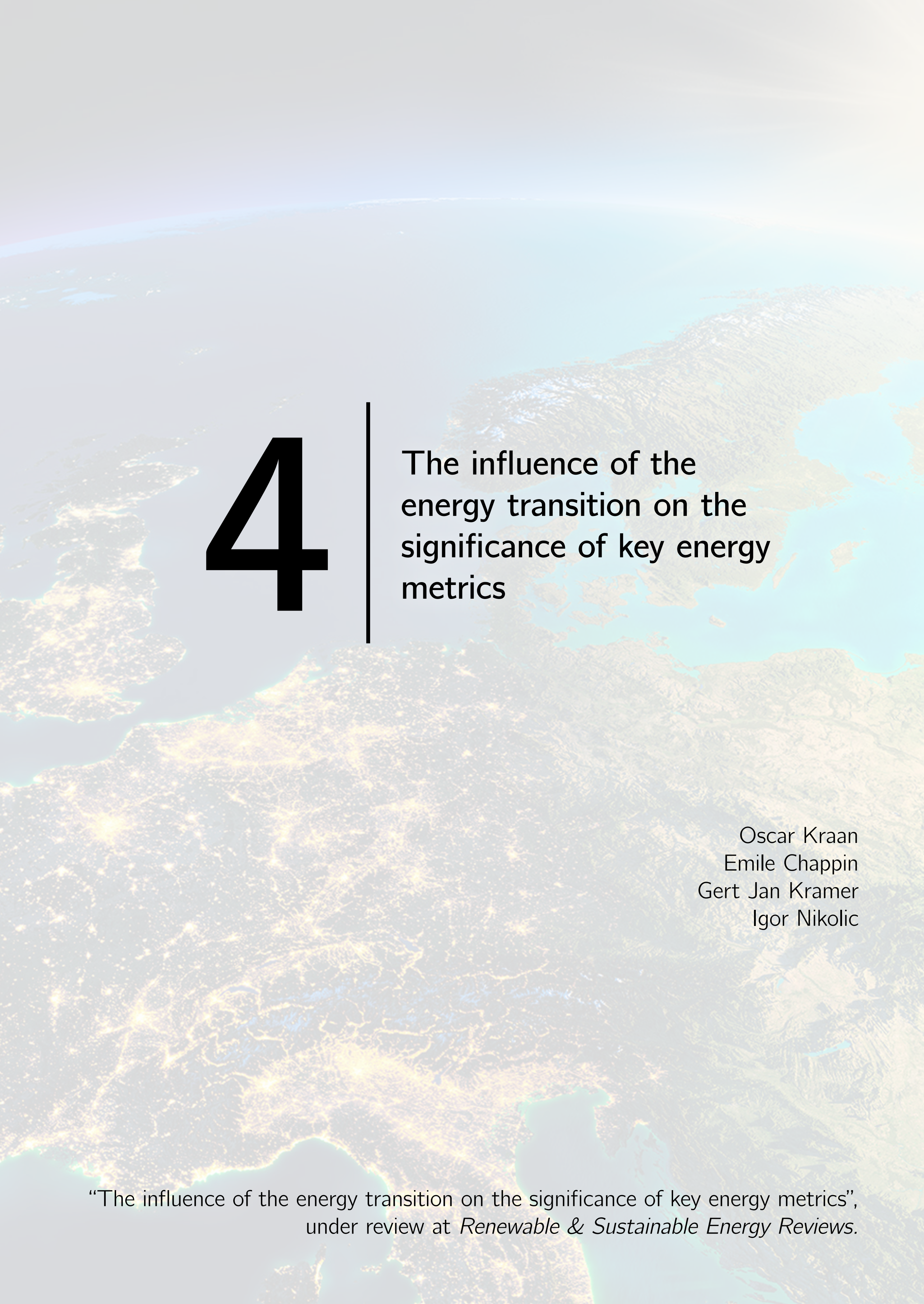
In order to avoid postponing action and hence making a late, risky bet on *All Renewable* by default, we recommend that it would be prudent policy to stimulate developments along both pathways simultaneously. And if only some of the elements of *All Renewable* prove successful, then they are likely to benefit *Balancing Act* anyway.

Acknowledgements

The authors would like to thank Mark Klokkenburg, Ajay Mehta, Katharina Gruenberg, Wim Thomas and Jeremy Bentham for their insights, helpful suggestions and comments.

Affiliations

Oscar Kraan is PhD candidate at The Copernicus Institute of Sustainable Development at Utrecht University, The Netherlands and Institute of Environment Sciences of Leiden University.
Gert Jan Kramer is Professor of Sustainable Energy Supply Systems at The Copernicus Institute of Sustainable Development at Utrecht University, The Netherlands.
Martin Haigh is Senior Energy Adviser in the Shell Scenarios Team, London, UK
Chris Laurens is Vice President Strategy & Innovation at Shell, The Netherlands. Currently Senior Vice President Group Strategy & Performance at ANSOC, Abu Dabi, UAE.



4

The influence of the energy transition on the significance of key energy metrics

Oscar Kraan
Emile Chappin
Gert Jan Kramer
Igor Nikolic

“The influence of the energy transition on the significance of key energy metrics”,
under review at *Renewable & Sustainable Energy Reviews.*

Abstract

Transparent, consistent accounting of climate-related energy targets is a fundamental building block to the architecture of international climate agreements. Many of these climate targets focus on the transition of the energy system which has led to the development of various energy transition scenarios. Now that fossil resources are being replaced by non-combustible and renewable energy sources a re-assessment of the applicability of the current set of metrics on which these energy scenarios are based is necessary.

Now that energy derived from renewable and non-combustible resources with abundant availability but limited instantaneous availability becomes more prominent the ongoing electrification of the energy system combined with the decarbonisation of the electricity system has caused the current set of energy scenario metrics to become ambiguous. More specifically we show that Total Primary Energy (TPE) and its related indicators, Energy Efficiency (EE), Energy Intensity (EI) as well as the key metric Electricity Generation Capacity (EGC) have become unrepresentative, potentially misleading and for a large part irrelevant. This is problematic as these metrics steer climate policy and investment decisions based on statistical artefacts rather than valid representation of the energy system. This study concludes with a set of requirements on energy scenarios to overcome these problem that will lead energy scenarios to focus on Total Final Consumption within a mix of related energy metrics.

Keywords

Energy transition, Energy metrics, Decarbonisation, Electrification.

4.1 Introduction

Since the energy system is the largest contributer to the world's greenhouse gas emissions [206], decarbonisation of the energy system is key to limit global warming to 2 °C. Especially now that international negotiations [207] to limit global warming depend on National Determined Contributions (NDCs) [208], consistent, transparent accounting of these different targets and commitments becomes increasingly important.

Many of these NDCs depend on or make reference to (energy) scenarios [209] which are quantified narratives of future pathways [210]. These scenarios are often based on extrapolations of historical relationships collected in energy balances. Only four organisations [106, 211, 31, 212] publish these (historic) energy balances [213], whereas many more publish scenarios (e.g. Shell [7], Greenpeace [15], International Institute for Applied System Analysis [214], World Energy Council [215]). These scenarios help policy makers and many different societal stakeholders to debate policy options, monitor policy effectiveness and discuss trade-offs between various technology, system and value chains. Moreover, they support investors to make informed strategic decisions in an uncertain future.

These policy targets as well as scenarios are based on various metrics, such as *Total Primary Energy* and *Total Final Consumption* amongst others. An adequate, relevant and representative set of these metrics is of vital importance; they must be sufficiently broad to characterise the system, relevant for policy and business decision making and concise enough to facilitate smooth communication with and between (non-)experts. Here two kinds of metrics can be distinguished. The first are primary metrics which are absolute values (e.g. Total Primary Energy and Total Final Consumption). The second are indicators which are relative, typically ratios of primary metrics (e.g. Energy Intensity, Energy Efficiency).

4.1.1 Metrics and transition dynamics

With the effect of climate change becoming more evident, stakeholder's interests (i.e. objectives of policy makers, opportunities and risks for businesses and the general public) have changed. Where previously policy targets and business strategies were focused on the depletion of (fossil) resources, in the last decades there is increased focus on the impact of the use of resources. Moreover, where previously the total resource availability was of concern (i.e. oil, gas and coal reserves), presently the instantaneous energy availability is of primary concern (wind and solar radiation), marking a shift from Joules of primary energy to Watt hours of final energy.

Now that the energy transition progresses, the resource mix of the energy system changes and energy from non-combustible sources (i.e. wind, solar) becomes more prominent. These "new" resources are different from fossil fuels in two fundamental aspects: they are abundant rather than scarce but their instantaneous availability is limited, rather than being dispatchable on demand. Furthermore, two major developments in the energy system are ongoing: i) ongoing electrification of end use and ii) the decarbonisation of the energy system. We will show that these developments in combination with the fundamental differences with regards to the resources they rely upon, cause two key primary metrics to become impaired: Total Primary Energy (TPE) and Electricity Generation Capacity (EGC). Related indicators derived from these primary metrics, i.e. Energy Efficiency (EE) and Energy Intensity (EI) are also affected.

The source of these problems lies in the difficulty of finding a representative quantification of the energy system via an appropriate accounting method while the system is structurally changing. How do you account for the Joules contained in a barrel of crude oil and the kWh of electricity from a solar panel in a single metric?

Although often the explanation of the different possible accounting methods used for these quantifications are buried away in appendices [213, 216, 217, 218, 219], several researchers have mentioned the associated problems of accounting of energy metrics. Giampietro and Sorman [220] question the overall usefulness of energy statistics, and subsequently [221] argue to focus on a broader set of metrics instead of a "one size fits all" approach. Also Wang et al. [222] mention the difficulty of accounting for primary energy. Segers [223] advocate the use of an accounting method that compares renewable energy sources with typical conventional energy sources using a substitution method. Harmsen et al. [224] discuss the relationship between two policy targets, Europe's 2020 renewable energy target and it's 2020 energy efficiency target, and show that, depending on the accounting method used, renewable energy contributes very differently to the energy efficiency targets. Ligtfoot [225] also recognised the different accounting methods and concluded that primary energy values from various organisations are not comparable and the IPCC has insufficiently addressed this issue. In a comprehensive review Macknick [226] analysed discrepancies between data sources and recognised the differences resulting from different accounting methods. Also various reports from consultancies [227], governmental bodies [228] and other independent organisations [229, 230] including the IPCC [218] highlight the difficulty of comparing data from sources that use different accounting methods. To overcome these problems the United Nations in 2011 have published the International Recommendations for Energy Statistics [219] but universal implementation of these recommendations is far from reality.

Building on these long-recognised concerns of energy accounting, in this article these problems are put in the context of the fundamental dynamics of the global energy transition. We highlight statistical artefacts of the various (recommended) accounting methods that should be of concern to those that work with these metrics. We show how these developments relate to the architecture of climate change negations, and show how expected future developments will increase these problems. We furthermore make the connection between various energy metrics that are affected and show how set policy targets can interfere with international agreed goals to limit global warming.

This analysis is relevant as the consequences of these identified problems can be large. Many international regulations and targets depend on these metrics (e.g. European Directives [231, 232] and NDCs [208]): Thirty-five countries have set their NDC targets for climate change mitigation in terms of energy metrics [233]. For example, China, the singles largest emitter in the world [210] has set it's NDC in terms of TPE, India, the third largest contributor, has set its target in terms of EGC. Moreover, 143 of the 162 submitted NDCs mention energy efficiency [233]. In addition, many NDC targets are set relative to a baseline scenario. Which bring us to energy scenarios; although comparisons from different sources gives depth to the discussion on the different assumptions in these scenarios and to the robustness of results, comparing scenarios has become a near impossible. Together the in-transparency of documentation and unfamiliarity with this issue can lead to misinformed arguments and misguided policy choices. An assessment of an adequate set of metrics therefore becomes increasingly important.

We argue that the complex transition of the energy system, will need a diverse set of metrics to represent the system and build policy upon. However, adverse effects of accounting artefacts have to be prevented. Therefore, whereas previously energy scenarios focused on resource availability and thus on TPE within such as set, we propose to focus on Total Final Consumption instead as we will show that this metric gives a better representation of the current and future system, is more relevant with regards to policy targets and most importantly, thus not faces the issues of un-representativeness of TPE.

The organisation of this article is as follows, the use of Total Primary Energy and its related indicators Energy Efficiency and Energy Intensity will be discussed in Section 4.2. In Section 4.3 Electricity Generation Capacity will be discussed. A reflection on our findings is presented in Section 4.4 and conclusions are laid out in Section4.5.

4.2 The use of Total Primary Energy

To introduce the different ways to represent the energy system let's look at the main metrics of energy scenarios. Energy scenarios are composed of three main metrics:

Energy Services (ES): The demand for a particular energy service such as passenger kilometres, tonnes of steel etc.,

Total Final Consumption (TFC): The consumption of energy carriers such as solid, liquid or gaseous fuels and electricity to fulfil this service demand

Total Primary Energy (TPE): the primary energy required to produce these energy carriers.

These three metrics are connected subsequently by the energy service efficiency and the production efficiency, see Figure 4.1.

Figure 4.1 – Primary energy metrics and efficiency indicators. Energy services by sector need to be supplied by energy carriers which need to be produced from energy sources.

TPE has long been central to energy scenarios as the availability of energy resources was of main concern to policy makers and business decision makers. During the last decades in which the energy system was dominated by the use of combustible resources such as fossil fuels and biomass, its definition was relatively straightforward: "energy that has not been subjected to any conversion or transformation process" [234]. This was supported by the fact that the primary energy content for combustible resources such as fossil fuels and biomass, is easily measured and commonly tracked.

Calculating the primary energy equivalent for non-combustible resources such as wind, solar photovoltaic (PV), nuclear, hydro and other marine-based technologies, is not self-evident because it's primary energy equivalent is not consistently defined and not widely measured. Figure 4.2 shows the different energy sources and how they can be differentiated over renewable versus non-renewable energy sources, and combustible versus non-combustible sources. The dark grey area indicates sources that produce electricity; the lighter grey area indicate sources that produce heat as an intermediate step.

Different organisations use different approaches to calculate the primary

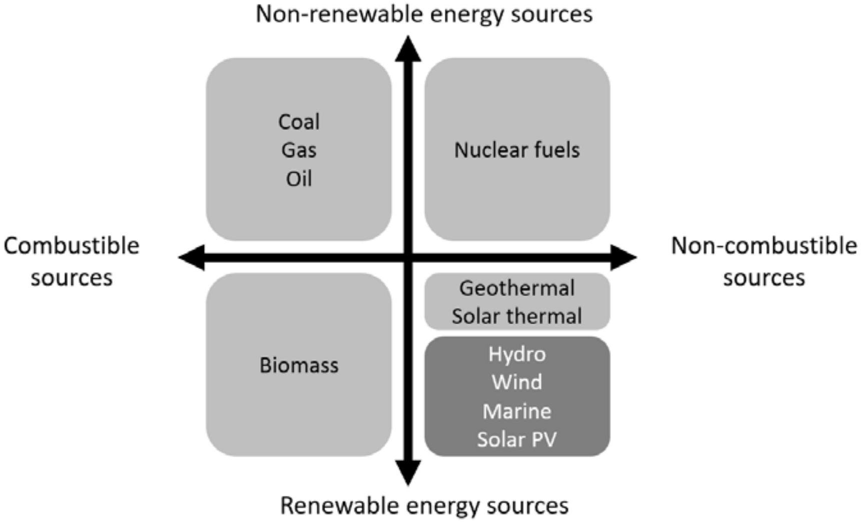


Figure 4.2 – Primary energy sources. Light grey areas indicates sources with heat as conversion step. Dark grey indicates sources that directly produce electricity. Marine includes wave and tidal energy, Wind includes off- and on-shore wind, Solar PV (Solar Photovoltaic).

energy equivalent of non-combustible energy sources, but in general four approaches can be distinguished (see Table 4.1).

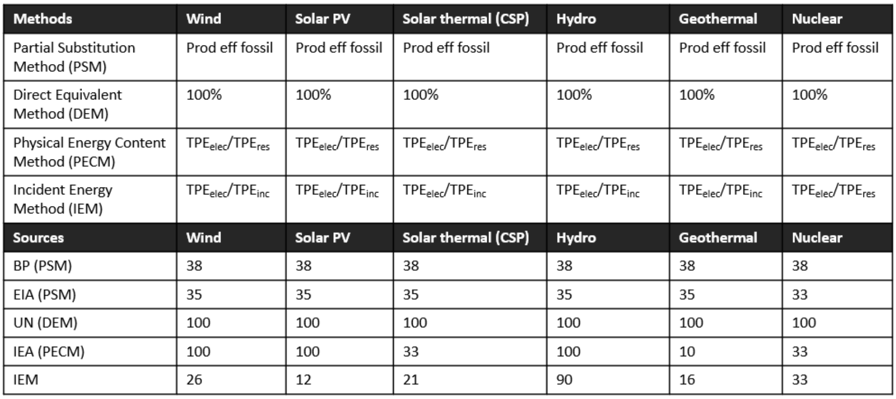
Partial Substitution Method (PSM); EIA, WEC, IIASA, BP. With this method the primary energy equivalent for non-combustible energy sources that produce electricity, is defined by the hypothetical amount of energy it would require, on average, to produce an equivalent amount of electricity in a thermal power station using combustible resources. In practice this means that a representative efficiency of thermal power stations is used to calculate the primary energy equivalent for non-combustible resources. This method is widely used by for example BP [106] the World Energy Council [235] and IIASA [213]. The fundamental difficulty with the partial substitution method is that it does not have a physical basis, does not represent any real market quantity and assumes a hypothetical and arbitrary defined conversion loss. This method is even more problematic when renewables begin to displace other renewables (instead of fossil fuels). Moreover, in energy system that are dominated by renewables, (e.g. hydro-electricity dominated countries such as Norway), this method gives a distorted view on the reality of the system as its representation is based on thermal generation (with relative low conversion efficiencies) while in reality the system is based on non-combustible sources.

Direct Equivalent Method (DEM); UN, IPCC. With this method the primary energy for non-combustible energy sources is set equal to the energy contained in the produced electricity. This approach excludes the production efficiency of conversion technologies such as solar panels (from solar radiation to electricity) or wind turbines (from wind to electricity) and implies that the conversion of non-combustible renewable energy is 100% efficient. This method is also often used, for example by the United Nations Statistical Bureau [217] and in IPCC reports [218]. The problem that arises from the use of this method is that a statistical defined 100% efficient production efficiencies makes primary energy for these sources a statistical artefact. It does not measure a characteristic of reality, but gives a statistical representation of reality to be able to add up the many different sources the energy system relies upon.

Physical Energy Content Method (PECM); IEA, OECD, Eurostat This method differentiates the non-combustible resources in resources that produce heat as intermediate step (i.e. nuclear, solar thermal and geothermal energy sources) and those that do not (wind, photovolataic), see Figure 4.2. For technologies that produce electricity directly, the method accounts for the generated electricity while for technologies that produce heat it accounts for the produced heat. Again, this method is widely used by various organisation, for example the OECD, IEA [236] and Eurostat [237] and is the basis of the International Recommendations of Energy Statistics [219]. This method can be confusing: for some technologies (i.e. solar PV, wind and hydro) the production efficiency is set to an arbitrary 100%, while for others (i.e. solar thermal, geothermal and nuclear) much lower efficiencies (as low as 10%) are used although both are based on renewable resources that produce electricity. Additionally, for resources with an 100% production efficiency the same difficulties hold as described in the Direct Equivalent Method. Moreover, in this approach the share of renewable technologies that produces heat is over-emphasised as their primary energy equivalent is multiplied by their production efficiency and estimated at, in the case of solar thermal (i.e. concentrated solar power), ten times its electricity output. The same problem holds for electricity from nuclear for which primary energy equivalent is set at three times its electricity output. For some resources (i.e. wind, solar and hydro) this accounting method downplays their share in Total Primary Energy and an argument could be made that renewables may not be mature enough to deploy on larger scale.

Incident energy method (IEM) With this method the primary energy for non-combustible energy sources is defined as the energy that enters an energy conversion device. For solar this would be the energy that enters the surface of the photovoltaic panel or mirror, for wind the energy that passes the rotor disc, or in the case of geothermal, the energy contained in the hot fluid at the surface of the bored well. The difficulty with the incident energy approach is that renewable energy plants almost exclusively track electricity output and therefore this metric is not widely reported by organisations that produce energy balances.

Table 4.1 – Production efficiencies of non-combustible energy sources. Data from [106, 229, 210, 217, 216]



Methods	Wind	Solar PV	Solar thermal (CSP)	Hydro	Geothermal	Nuclear
Partial Substitution Method (PSM)	Prod eff fossil	Prod eff fossil	Prod eff fossil	Prod eff fossil	Prod eff fossil	Prod eff fossil
Direct Equivalent Method (DEM)	100%	100%	100%	100%	100%	100%
Physical Energy Content Method (PECM)	TPE_{elec}/TPE_{res}	TPE_{elec}/TPE_{res}	TPE_{elec}/TPE_{res}	TPE_{elec}/TPE_{res}	TPE_{elec}/TPE_{res}	TPE_{elec}/TPE_{res}
Incident Energy Method (IEM)	TPE_{elec}/TPE_{inc}	TPE_{elec}/TPE_{inc}	TPE_{elec}/TPE_{inc}	TPE_{elec}/TPE_{inc}	TPE_{elec}/TPE_{inc}	TPE_{elec}/TPE_{res}
Sources	**Wind**	**Solar PV**	**Solar thermal (CSP)**	**Hydro**	**Geothermal**	**Nuclear**
BP (PSM)	38	38	38	38	38	38
EIA (PSM)	35	35	35	35	35	33
UN (DEM)	100	100	100	100	100	100
IEA (PECM)	100	100	33	100	10	33
IEM	26	12	21	90	16	33

To illustrate the effect of these diverse definitions, Figure 4.3 shows the development of total primary energy under a single energy transition scenario but under different accounting methods, PSM, DEM and PECM. It's base scenario is Sky, Shell latest energy transition scenario [7] (compatible with the Paris Agreement). It is based on the World Energy Model [238] which uses IEA standards of measurement for all energy sources and carriers, and thus follows the PECM.

The figure shows that, although differences today are relatively modest, these differences are expected to increase in the future as increasing electrification and decarbonisation of the energy system make non-combustible zero-emission energy sources more prominent.

Figure 4.4 illustrates the effect on a country level. The figure shows the TPE figures for three countries with different energy system structures; France, The Netherlands and Norway. France in 2015 was dominated by nuclear energy (see pie charts), while The Netherlands was dominated by fossil fuels and Norway was dominated by renewables (especially hydro). The Figure shows that there are large differences between TPE figures, which also effects the relative share in the energy mix, especially for non-fossil dominated countries such as France

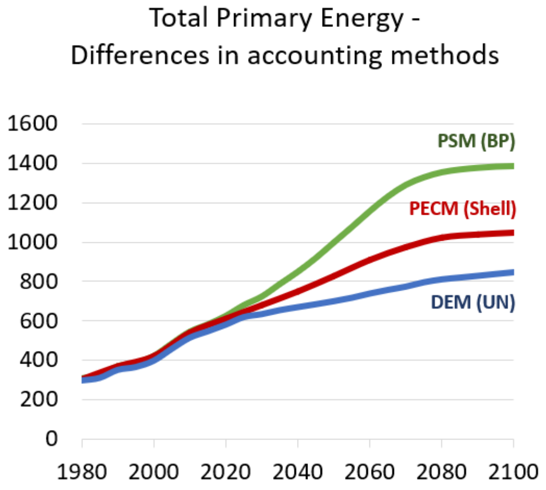


Figure 4.3 – Total primary energy of Shell's Sky scenario under different accounting methods. Comparison is made with production efficiencies from Table 4.1. Data from [7]

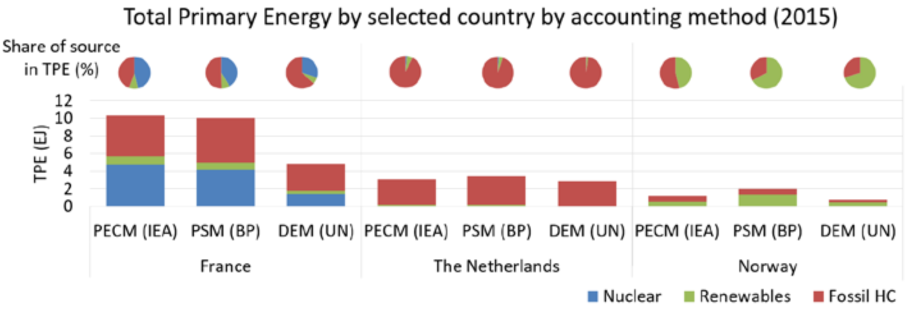


Figure 4.4 – Total Primary Energy by selected country by accounting method in 2015. Data from [31]

and Norway. Of course these differences originate from the different production efficiencies given in Table 4.1.

4.2.1 Direct effect

From this analysis we conclude that different TPE definitions lead to increasing ambiguity because of the following six reasons.

1. The use of production efficiencies of 100% for non-combustible energy

resources by many organisations makes primary energy for these sources a statistical artefact. It does not measure a characteristic of reality, but gives a statistical representation of reality to be able to add up the many different sources the energy system relies upon.

2. Now that abundant renewable resources are replacing finite fossil resources, the primary energy demand becomes increasingly less relevant.
3. TPE values depend largely on the applied accounting method which all face difficulties.
4. Within these approaches, organisations use various figures that are likely to change over time with technology improvement and system integration.
5. These problems are expected to increase over time as decarbonisation and electrification of the energy system will ensure that non-combustible resources will increase their share in the energy mix.
6. Climate change mitigation targets expressed as a reduction of TPE can result in an *increase* of GHG emissions under certain accounting methods (PECM) while they don't incentivise the use of renewable resources in others (PSM). Under PECM, an TPE reduction target would disincentivise the replacement of fossil generation by low efficiency, zero-emissions alternatives (i.e. replacing geothermal, solar thermal or nuclear with fossil generation).

The difficulty of defining TPE unambiguously makes it a misleading metric now that the energy transition progresses and stakeholders can choose an accounting method that is most attractive to them. This has significant adverse effect on the value of ability to set quantitative targets and the ability to compare them. Together this makes appreciations of targets, ambitions and progress defined in TPE difficult. Specifically, difficulty with comparisons arise with respect to the following:

1. **Scenarios** become difficult to compare when each scenario uses a different accounting method. This makes the discussion on underlying assumptions and narratives near impossible which impairs one of its main purposes; communication with and between stakeholders.
2. Comparing the efforts and targets of **countries** and the progress towards them becomes difficult as countries with a particular dominant energy source (e.g Norway with hydro) can be very differently represented under different accounting methods. This makes comparisons of these countries

with other countries depended on the used accounting method. As comparing countries becomes difficult, comparing policy targets such as NDCs also becomes difficult when different accounting methods are used. Ultimately this hinders progress on international climate negotiations.

3. The comparison of different **technologies** also becomes difficult. Various production efficiencies across technologies in the different account methods make the share of these technologies in the energy mix dependent on the accounting method. For example, TPE figures for concentrated solar power (solar thermal) using PECM or PSM give these technologies a much larger share compared to solar PV then if one would use the DEM. This can have consequences as targets set on TPE can lead to policy incentivising deployment of technologies based on a superficial representation of reality. From a climate-based policy target in general it us undesirable that one zero-emission technology will be promoted over another zero-emission technology solely based on accounting artefacts.

The number of different approaches combined with the expected increase of difficulties each approach faces, shows that TPE is at best an irrelevant and potentially a misleading metric to represent the energy system given the expected decarbonisation and electrification of the energy system.

4.2.2 Indirect effects on related indicators: Energy Efficiency & Energy Intensity

The consequence of the inconsistent definition of TPE is that related indicators, specifically, Energy Efficiency and Energy Intensity are also affected. This has consequences as EE and EI are both indicators that are widely reported, intensively studied and subject to various policy targets and business considerations. As mentioned in Section 4.1, almost 90% of the submitted NDCs mention energy efficiency [239].

Energy efficiency

Energy efficiency (EE) is defined as:

$$EE = \frac{Energy\ Service}{TPE} \tag{4.1}$$

Now that TPE becomes ambiguous, the indicator energy efficiency now also becomes difficult to appreciate. This becomes evident when the energy efficiency of a normal gasoline car is compared with an electric vehicle driving on electricity derived from non-combustible energy sources. Changing the supply of the energy service (in this case vehicle kilometres driven) from using a thermal power train to one without heat conversion can make relatively small differences (using a fossil equivalent efficiency for the production of renewable-based electricity via PSM) or dramatically increase the efficiency (using a 100% production efficiency of the renewable-based electricity via PECM & DEM). The same holds for electrifying heat demand in buildings (e.g through heat pumps); depending on the accounting method this can dramatically increase (using PECM & DEM) or barely change (PSM) energy efficiency of the building. In a general context this is relevant as efficiency targets are more or less easy to reach depending on the used accounting method.

Energy Intensity

The same argument holds for the indicator Energy Intensity. It measures the amount of energy that is used to produce an unit of GDP and is defined as:

$$EI = \frac{TPE}{GDP} \tag{4.2}$$

The energy intensity of a country can differ substantially depending on what accounting method is used. Iceland for example, is a leader in several energy savings programs but its energy intensity remains high in energy balances that use the PECM [240]. This can be explained by understanding that in PECM the production efficiency of electricity generation from geothermal sources which are increasingly deployed in Iceland, is relatively low (10%). Using a different, much higher production efficiency of up to 100% in DEM would lower its energy intensity dramatically.

Let's us consider again the three cases discussed in Section 4.2, France, The Netherlands and Norway. Figure 4.5 shows the energy intensity figures for these three countries in 2015. It shows that comparing these three countries, three different conclusions could be possible, dependent on the accounting method used. Either France, or The Netherlands or Norway has the worst energy intensity. In the next section we will argue that EI based on Total Final Consumption instead of Total Primary Energy is a better expression of energy intensity which is shown on the right-hand three columns in Figure 4.5.

4.2.3 Recommendations on the use of TPE, EE and EI

Given the shift of focus from resource use to climate change impact, policy targets have changed. To address climate change impact, a complex and comprehensive system transformation that covers many sectors and locations will be required. Setting, comparing and monitoring of targets relating to this transition therefore

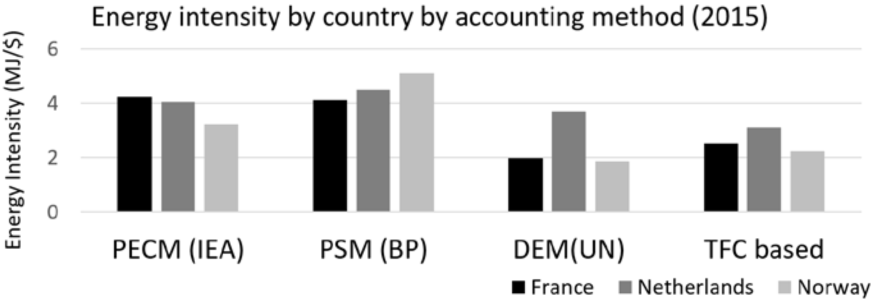


Figure 4.5 – Energy Intensity by selected country by accounting method in 2015. Data from [31, 241]

will require a diverse set of metrics. Based on the above considerations the following set of recommendations for the use of TPE, EE and EI can be made:

1. As a minimum, when TPE targets are set, data are supplied or scenarios are displayed, the energy accounting method should be explicitly given. Preferably, it should also highlight possible consequences of the used approach on the interpretation of the reader such that conclusions based on statistical artefacts are prevented.

2. Although climate related policy targets set with regards to energy metrics can make these policy targets more concrete, they should be subsidiary and serviceable to the target of lowering GHG emissions. Therefore, targets set relative to TPE, EE and EI should include an additional premise to prevent interference with GHG reduction.

3. Given the difficulties surrounding TPE, together with ongoing developments that decreases it significance and the shift of focus from resource availability to the impact of consumption, we would recommend, to focus on Total Final Consumption. TFC, being the energy as used (consumed) is free of definitional ambiguity: it is the sum of the Joules as consumed. Shifting from TPE to TFC would mean that the indicators energy efficiency and energy intensity would also be better expressed in terms of consumption. This would mean that energy efficiency would in practice be equal to energy service efficiency, i.e. the energy consumption needed to deliver a certain kind of service, see Equation 4.3. This can be expressed as passenger km / GJ for personal transport, tonne km / GJ for freight transport, heating and lighting requirement per GJ for the building sector etc. The same holds for Energy Intensity, which would be better expressed in TFC to prevent the mentioned problems with TPE, see Equation 4.4. Figure 4.5 shows the

effect of using a TFC in the calculation of EI in the three discussed cases.

$$EE = \frac{EnergyService}{TFC} \tag{4.3}$$

$$EI = \frac{TFC}{GDP} \tag{4.4}$$

The disadvantage of the use of TFC is of course that some information is lost as the efficiency of production of non-renewable energy carriers is neglected in this metric. However, now that the energy transition unfolds, focus has shifted from the availability of primary energy resources to the effect of consumption of these resources. Moreover, since the renewable-share of the energy mix is expected to increase as the energy transition unfolds, this problem, in comparison to the ambiguities surrounding TPE is expected to decrease.

4.3 The use of Electricity Generation Capacity

Next to primary energy and its related indicators, another important metric of which the meaning changes and becomes increasingly ambiguous with increasing shares of renewable resources, is electricity generation capacity (EGC). EGC figures are widely reported to show e.g. how much generation capacity a specific country has added or will be adding from a specific technology. In general, organisations report this metric to show the development of the electricity generation capacity mix, accompanied by headlines such as *renewables accounted for almost two-thirds of net new power capacity around the world in 2016* [242, 243] Moreover, India has framed one of its targets in these terms: "To achieve about 40 percent cumulative electric power installed capacity from non-fossil fuel based energy resources by 2030" [208].

Whereas TPE has become difficult to appreciate because the focus of stakeholders has changed from total resource availability to the impact of energy consumption, the interpretation of EGC has become difficult for a different reason. Whereas previously the total resource availability was of concern (i.e. oil, gas or coal reserves), now the momentary resource availability is of concern, i.e. solar radiation and wind. The intermittent character of these renewable resources make the availability of these resources on a second to second scale relevant. Capacity factors, the ratio of the average actually power production over the maximum power production, expresses this intermittent character of technologies (see Figure 4.6).

Previously the actual production of dispatchable thermal generation depended on the electricity demand. EGC values therefore where comparable as they

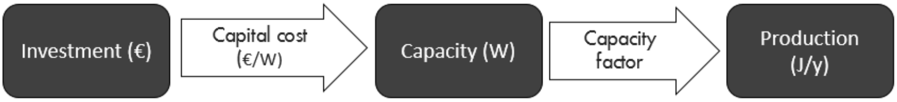
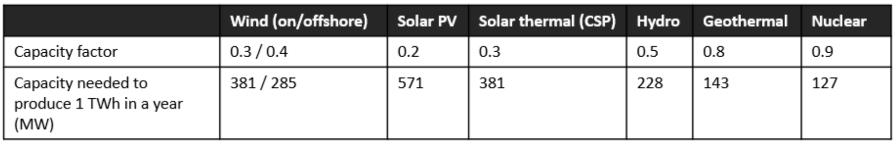


Figure 4.6 – Relationship between investments, capacity factors and actual production.

referred to their actual achievable maximum capacity. The production of renewable power generation however is predominantly depended on the availability of resources. This is illustrated with Table 4.2. It gives an overview of capacity factors reported by the IRENA [244] and EIA [245]. It shows that a similar sized electricity generator that is used for base-load electricity can have capacity factors of ca 90%, while solar PV panels have an average capacity factor of ca 20% (although very dependable on geographical location of the plant). Table 4.2 also shows how much capacity would need to be added to produce a similar amount of electricity around the year.

Since these capacity factor differ across (renewable) technologies, the metric EGC becomes technology dependent and its aggregate value becomes meaningless, as does comparison between technologies. Appreciation of progress on climate related policy targets is impossible from the reporting of bare EGC numbers. Moreover, targets set on (renewable) EGC, by all means do not guarantee to decrease the impact of the energy system on climate change; if electricity demand increases faster than the expected production from renewable EGC (multiplying EGC with the associated capacity factors per technology), emissions can de facto increase.

Table 4.2 – Average capacity factors of renewable generators in 2017, rounded to one decimal. Data from IRENA [244] and EIA [245]



	Wind (on/offshore)	Solar PV	Solar thermal (CSP)	Hydro	Geothermal	Nuclear
Capacity factor	0.3 / 0.4	0.2	0.3	0.5	0.8	0.9
Capacity needed to produce 1 TWh in a year (MW)	381 / 285	571	381	228	143	127

4.3.1 Recommendations on the use of EGC

If one wants to establish an appreciation of the renewable power industry or define targets in NDCs, newly added EGC does not give an un-ambiguous representation of the target or industry. Therefore, we would give the users of this metrics the following three recommendations:

1. Reporting EGC accompanied by the expected capacity factor would improvement the appreciation of the reported development as it would show how much product (electricity) actually would be expected to be produced.
2. Next to EGC the size of the involved investment would provide relevant information to assess the development of the industry (see Figure 4.6). As the world is moving from a world where the value of energy is embedded in the resource to a world where the technology is essentially the resource, additionally reporting on the associated investment gives a better representation of the system.
3. Targets set on (renewable) EGC should be avoided as policy interference is difficult to prevent. Targets set on the share of actual electricity production from renewable, zero-carbon resources using a similar production efficiency across these resources would already be an improvement.

In conclusion, appreciating EGC gives severe difficulties as referring to EGC in solitude gives a distorted view on the reality of the energy system. These difficulties can be overcome by simultaneously reporting other relevant and related metrics e.g. capacity factor, investment size.

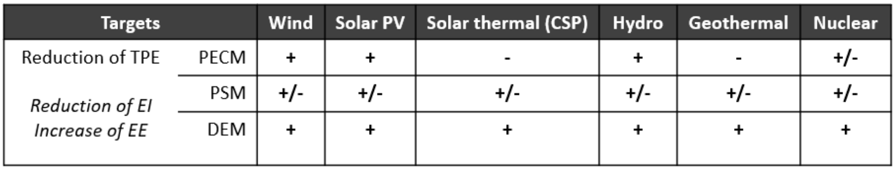
4.4 Reflection on findings and consequences for policy design

It has been shown that appreciation of TPE and its related indicators EE and EI as well as the metric EGC becomes increasingly difficult now that the energy transition progresses. Tables 4.3 and 4.4 show that various policy targets, generally used in NDCs, can potentially steer investments based on statistical artefacts.

Table 4.3 shows a qualitative assessment of the effect of policy targets set in terms of TPE (in the different accounting methods) on the attractiveness of a specific energy resources. The table indicates that although replacement of a fossil resource with one of the listed sources in reality reduces CO_2, in various superficial accounting realities they do not. Minuses indicate that a specific resource is less attractive than a fossil alternative when policy is steered on the mentioned targets.

Policy targets set in EGC give similar difficulties. Policy design aimed at increasing the share of renewable power capacity in reality is an in-effective policy tool to steer investment. Table 4.4 gives a qualitative assessment of the effect of a policy target combined with the deployment of a specific technology on the mitigation of climate change. Minus signs are given when the capacity factor of

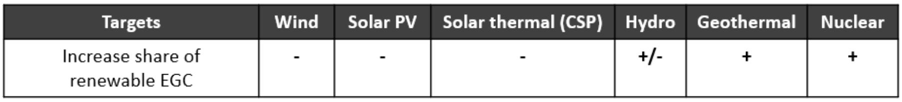
Table 4.3 – Qualitative assessment of the effect of policy targets set in TPE or related indicators (in the different accounting methods) on the attractiveness of a specific energy resource relative to the use of a fossil equivalent.



Targets		Wind	Solar PV	Solar thermal (CSP)	Hydro	Geothermal	Nuclear
Reduction of TPE	PECM	+	+	-	+	-	+/-
Reduction of EI *Increase of EE*	PSM	+/-	+/-	+/-	+/-	+/-	+/-
	DEM	+	+	+	+	+	+

EGC with a specific resource is lower than that of a fossil, thermal power station and plus signs vice versa. Table shows that with a given electricity demand, increasing the share of renewable capacity with, relative to fossil resources [246], low capacity factors, actually leads to an increased use of fossil resources.

Table 4.4 – Qualitative assessment of the effect of policy targets set in EGC on the reduction of climate change impact relative to the use of an fossil equivalent.



Targets	Wind	Solar PV	Solar thermal (CSP)	Hydro	Geothermal	Nuclear
Increase share of renewable EGC	-	-	-	+/-	+	+

In general it undesirable that energy related policy targets interfere with the overarching climate related policy targets. Moreover, it is undesirable that one zero-emission technology will be promoted over another zero-emission technology solely based on accounting artefacts.

Based on these considerations, and the recommendations stated in Section 4.2.3 and 4.3.1 we would argue that climate policy targets such as the National Determined Contributions (NDCs) submitted as part of the process initiated by the Conference of Parties in Paris 2016, should be set in terms of CO_2 to prevent policy interference. These targets could subsequently be supported by energy-related measures, which as we have argued are best expressed in terms of consumption (Total Final Consumption).

4.5 Conclusion

Now that climate policies focus more and more on the deployment of renewable, non-combustible energy sources (e.g. wind and solar radiation) the way these non-combustible energy sources are represented in energy data becomes increasingly important. Especially now that international climate negotiations are based on National Determined Contributions (NDCs), the appreciation and monitoring of progress on these targets needs transparent and consistently defined metrics.

However, as has been shown, key metrics often used in these NDCs, (Total Primary Energy and its related indicator Energy Efficiency and Energy Intensity as well as Electricity Generation Capacity) are becoming unrepresentative with large scale electrification and decarbonisation of the electricity system. Given the inconsistencies of the various accounting rules these metrics at best become confusing and at worst are derailing climate mitigation efforts.

In this paper it has been shown that these inconsistencies matter. Metrics influence outcomes of scientific research, political decisions and investment by private parties. Unfamiliarity of these inconsistencies on the part of policy makers or the general public can lead to adverse effects. It can potentially steer climate policy and investment decisions based on statistical artefacts, rather than a valid representation of the energy system.

Therefore, we argued, that both for policy development as well as for monitoring, a different set of energy metric is needed. As the overall objective of climate policy is to decrease greenhouse gas emissions, policy targets should be expressed in metrics that support this target.

Therefore, we recommend to have a clear overall target set in terms of emissions. For energy policy targets in support of these, we recommend to shift from Total Primary Energy to Total Final Consumption. Although not a panacea, we have argued that, as policy concern has shifted from total resource availability to the impact of resources, Total Final Consumption is a more relevant energy metric to track the development of the energy transition. With regards to renewable electricity we recommend focus on a broader set of metrics and not on EGC in solitude.

Our advice for energy modellers would be to be explicit about assumptions going into the energy scenarios. This holds especially on the definition of TPE as we have argued that a clear mentioning of this accounting issue, and its potential effect on the interpretation of these scenarios, would greatly improve understanding.

Building effective policy, making investment decisions and studying the energy transition, requires clear understanding of the building blocks of such analyses. This paper has given business decision makers, scientific researchers and policy developers essential background to appreciate these key energy metrics.

5

Jumping to a better world: An agent-based exploration of criticality in low-carbon energy transitions

Oscar Kraan
Steven Dalderop
Gert Jan Kramer
Igor Nikolic

"Jumping to a better world: An agent-based exploration of criticality in low-carbon energy transitions", published in *Energy Research & Social Science* 47 (156-165).

Abstract

Understanding the possible transition pathways of the energy system requires the integration of human behaviour in energy system models. In order to model the influence of actor behaviour we have developed ACT (Agent-Based Model of Critical Transitions), an agent-based model inspired by an existing conceptualisation of critical transitions. ACT allows us to depart from the current mean-field approach and explicitly explore the effects of heterogeneity, leaders, and networks on the transition. Two key finding are (1) the importance of local communities and (2) leaders can both encourage and discourage the energy transition; a finding that nuances existing literature on critical transitions. We conclude with a reflection on the strengths and weaknesses of our modelling approach.

Keywords

Energy transition, Simulation, Critical transitions, Agent-based modelling.

5.1 Introduction

Energy system models and their resulting scenarios are used to understand the transformation of the energy system. They offer us a possibility to meaningful assess future developments, facilitate experimentation, promote rigorous analyses and provide a tool to communication about findings [247, 248, 46, 249]. We observe that most energy models designed to analyse the energy system are techno-economic in their nature [56] and that conceptual models that focus on societal elements [250] are heavily criticised [251].

5.1.1 Modelling the role of human behaviour in the energy transition

Internationally agreed goals to limit climate change by decarbonisation of the energy system require that the world will have to engage in transformative change of the system; an energy transition [252]. Although there is scientific consensus on the severity of climate change, it is uncertain whether society will act accordingly. A better understanding of the role of human behaviour in the transition of the energy system is therefore of vital importance to improve our understanding of this transition. [253, 254, 255, 256, 257, 258]

Traditionally, energy system models are dominated by techno-economic considerations and are generally based on neo-classical economics, equilibria, and the assumption of rationality of decision making agents (which are not explicitly modelled). These models are not able to capture the change in energy system structure and dynamics of disruption, innovation and non-linear change in human behaviour [79]. This has led to the recognition of the importance of simulating the more realistic behaviour and interaction of different actors (companies, governments, consumers) [56, 252, 259].

At the same time, the field of sociology and psychology has produced a wealth of knowledge about the decision-making process of groups and individuals which led economists already in the 1950's to conclude that the core assumptions of neo-classical economics (perfectly informed and perfectly rational agents) has its limitations as basis of systems modelling and analysis. This resulted in efforts to increase the realism of economic theory by incorporating findings from psychology in what we now know as behaviour economics [61]. In sociology, the increase in computer power and tools to encompass social behaviour led to the development of social simulation with agent-based models (ABMs). The development of the complex adaptive system perspective has bundled these findings in a general system perspective that focuses on actor behaviour which can be used in simulation models of the energy system. [41]

5.1.2 The role of simulation models

In the broad spectrum of modelling approaches for the simulation of energy transitions, we can distinguish two types of simulation models, empirical models and conceptual models. Empirical models of the energy transition often focus on a specific case, e.g. a relatively small-scale transition in specific industries (e.g. [260, 261, 262, 263, 264]). These empirical models have shown important insights and have highlighted the importance of simulation of realistic actor behaviour to explain historical transitions and future concerns [41, 265].

Although global energy transitions have occurred in the past [266], the scale of dealing with global warming makes the world move into uncharted territory. The global energy transition under the influence of global warming therefore has little empirical evidence to relate to. Conceptual models, i.e. those not necessarily fitted to empirical data but based on general concepts and theories and frameworks [267] that capture relevant parts of the energy transition dynamics can help to give insight. These conceptual models are based on metaphors, narratives and images that provide insight and are important instruments that engage public and politicians and bridge different disciplines.

The combination of these qualitative story-lines (narratives) and quantified models is a way to come to grips with a understanding of how this energy transition will unfold [268]. This process is known as scenario development [269]. The scenarios developed by Royal Dutch Shell are a well-known example of this scenario practice [95, 32]. In these studies, scenarios (combinations of narratives and quantification of these narratives) are used to communicate results of energy models. The combination of qualitative narratives and quantifications of these narratives strengthens the communication about the transitions. The continuous interaction between the quantitative model and the qualitative narrative increases the fundamental understanding of the system at hand.

We recognise the tension between conceptual models that can be characterised as following a KISS (Keep It Simple) approach [42] versus more complicated models following a KIDS approach (Keep It Descriptive) [70, 42]. However, large-scale complex simulation models, following a KIDS approach, that describe the system in more detail, suffer from the subsequent large parameter space for which values cannot be determined within a reasonable amount of time, if measurable at all. A common solution is to *fit* the model predictions to empirical data which often lead to impressively good results [62]. However, a good fit does not guarantee any realism of parameter values or model structure. True validation of these large simulation models, some argue, is therefore simply impossible [62, 63, 64]. Based on this argumentation, this paper will take a KISS approach but deliberately includes descriptive relevant actor behaviour.

5.1.3 Research objective and structure of the paper

The importance of the integration of human behaviour in simulation models (as discussed in Section 5.1.1), combined with the drive for conceptual models with a quantitative basis (as discussed in Section 5.1.2), brings the concept of critical transitions [250] into focus. This concept, which we will explore in more detail in Section 5.2, gives us the possibility to integrate relevant aspects of human behaviour in a conceptual model with quantitative basis. With an agent-based modelling approach we studied the question what the concept of critical transitions can tell us about the influence of relevant behavioural dynamics of actors in the energy transition.

Before we develop such a agent-based model, we must explore the key dynamics of the energy transition in the light of the concept of critical transitions focusing on the role of human behaviour. This we will do in the next section, Section 5.2. In the subsequent section, Section 5.3, we present the model design followed by a presentation of the model results in Section 5.4. We then discuss the model results in Section 5.5. To put our modelling approach and results in context, we reflected on our modelling approach in Section 5.6. Specifically, we discuss whether this approach is suited not just to gain understanding, but also to *communicate* about the challenges of the energy transition. In Section 5.7 we lay out our main conclusions.

5.2 Critical transitions

5.2.1 The energy transition and critical transitions

Historically, the energy system has undergone several shifts of dominant energy sources (e.g. from wood to coal and from coal to oil) [266]. Understanding the timescales of these historical transition [270, 271] as well as possible future transitions pathways have resulted in the study of *regime shifts* [163], *critical transitions* [250] and several other closely-related fields of research (e.g. [35, 36, 272, 273]). Currently, the most pressing question is the pace of the transition from non-renewable CO_2 energy sources to renewable, decarbonised energy sources in the coming decades [270]. Why is society slow in its response to climate change, and will the required energy transition consist of a fast structural change or will it follow a more gradual and smooth trajectory? These questions on system transition types can be related to the concept of critical transitions and more general to bifurcation theory [274, 250].

The concept of critical transitions [250] explores which system characteristics may lead to different types of transitions. It shows the development of a catastrophe fold; when external condition change, a bifurcation point can be passed that makes a previously stable system show a critical transition to another system state (see Figure 5.1.

Scheffer et al. [250] show several aspects of actor behaviour that are relevant to the analysis of critical transitions. Social aspects such as peer pressure, the absence of leaders, the complexity of the problem and homogeneity of the population can decrease the pace in which society acts to a certain problem (see Section 5.1). Because of its focus on actor behaviour in transitions this concept is relevant to address the point we made in Section 5.1.1: the importance of including actor behaviour in models of the energy transition.

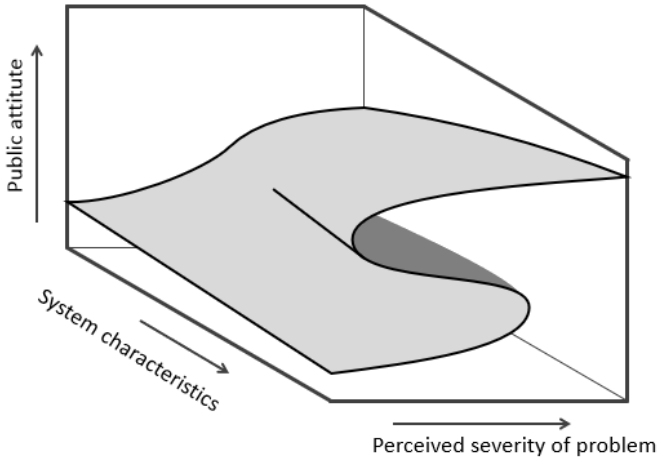


Figure 5.1 – The catastrophe fold. System characteristics can lead to different types of transitions.

An existing conceptualisation of critical transitions focuses on overall system behaviour by using a mean-field approach. Throughout this paper we will refer to this mean-field approach by Scheffer et al. as *existing* or *original* model. The acronym for mean-field-approach, MFA, has been added to these references to increase transparency on what model has been meant. A complementation of this conceptualisation that focuses on relevant *actor* behaviour would give a richer understanding on the role of human behaviour in the energy transition. But what is the relevant actor behaviour from which the different types of the energy transition emerges? This we will explore in the next section, Section 5.2.2.

5.2.2 Relevant actor behaviour in the energy transition

The relevant actor behaviour to be captured by a model is determined by the context in which we want to study this actor behaviour. In this case we are interested in what actor behaviour can lead to different types of transitions in the context of the energy transition.

The ability of the atmosphere to absorb greenhouse gases can be understood as a *common pool resource dilemma* [112, 272]. Common pool resources (CPRs) are defined as open resources for which the physical exclusion of potential users of the resource is difficult (low excludability), while the increased consumption of a user implies that less resource is available for others (high substractability / rivalry).

The relevant actor behaviour is thus decision-making process in CPR-dilemmas. Work of Elinor Ostrom [275] has highlighted conditions under which a Tragedy of the Commons [108] can be overcome without requiring top-down regulation. Two key aspects that can be distinguished from these conditions and which we will use as model requirements are the following:

1. Actor interaction. Reciprocal cooperation can be used to overcome social dilemmas. Because groups of people who can identify one another are more likely than groups of strangers to overcome CPR dilemmas, the existence and type of social or physical networks via which actor interaction can take place is of importance. The same holds for the influence of actors being thought of as being trustworthy.
2. Heterogeneity. The ability of a society to overcome the CPR dilemma is closely related to the heterogeneity between actors managing a CPR. Heterogeneity is related to their willingness to act and to the perceived severity of the problem, especially in cases where the common pool is a *global* common such as the problem of climate change. The latter has mainly to do with the fact that actors have incomplete information about the state of the resource.

Closely related to the analysis of CPR dilemmas is the analysis of regime shifts and (critical) transitions, our system behaviour of interest. Often the successful management of CPRs requires a transition to sustainable manage the CPR. It is therefore not surprising that climate change and the related necessary energy transition are framed as both a CPR dilemma and (critical) transition.

5.2.3 Modelling critical transitions

Phase transitions in physics, *critical transitions* in ecology, *non-marginal change* and *regime shifts* in socio-economic literature all share the feature of structural change, often with a perceived sense of abruptness [276]. Although these concepts are discussed in different contexts with different vocabulary, the models that study these dynamics are closely related to each other.

While researchers are usually aware of the limitations, there is a long tradition in applying insights from these different fields of research to structural change in response to societal problems. As a first approximation, Ball [277] showed with examples ranging from ecology, social choice, to (business) economics and political science, that modelling these systems from the viewpoint of statistical physics does seem capable of capturing some of the important features of these social systems.

Several ecologists have applied concepts from ecology to study structural change in socio-ecological systems [278, 250, 279, 280]. One of these, Scheffer and his colleagues, presented the concept of critical transitions and devised a mathematically simple but conceptual rich model of the dynamics of opinion in a society. This concept has been the subject of several influential studies [250, 281, 282, 62, 283, 284] and has been applied in various other fields such as finance and medicine [285, 286]. Although the model is based on ecological dynamics and there is recognition of the difference between societal systems and ecological systems, Scheffer et al. argue that fundamentally these dynamics are similar to processes that determine the character of societal transitions.

Scheffer et al. characterise three types of transitions in the relationship between public attitude about the need to take action against a problem and the perceived severity of the problem: i) an almost linearly responding system, ii) a non-linear but continuous response of public attitude and iii) an abruptly, discontinuous shift to a predominantly active attitude when the perceived severity of the problem has grown sufficiently to reach a critical point and engages in a critical transition. Scheffer et al. distinguish four properties of society that determine what kind of transition takes place: peer pressure, absence of leaders, complexity of the problem and homogeneity of the population.

All these models are based on an application of bifurcation theory, [274] which has its foundation in mathematics. They also share the same sort of conclusion; the reaction of system to its changing external conditions can be slow, resulting in hysteresis, a discontinuous shift from one regime to another [277, 250].

These conceptual models have been criticised in various reviews stating that these kinds of models “impose over-simple behaviour ... and don’t validate strongly against unseen data. Thus, whilst such models may have interesting behaviour there is little reason to suppose that they do in fact represent observed social behaviour.” [287] and that “the problem is that they treat social influence in a trivial way” [288].

Although we recognise that conceptual models simplify the complex reality of human behaviour, in standard (techno-economic) energy models they are not treated at all. In Section 5.6 we will come back to this discussion, discuss critiques in more detail and reflect whether these models can be possibly valued differently. For now we will show in the next section how an existing conceptualisation (MFA) of the concept of critical transitions that focuses on overall system dynamics can be extended and enhanced by incorporating relevant actor behaviour.

5.3 Methods

Inspired by the existing conceptualisation (MFA) of the concept of critical transitions by Scheffer et al. [250] and the requirements identified in Section 5.2 we developed ACT: Agent-based model of Critical Transitions. With ACT, we altered, extended and implemented, the existing conceptualisation (MFA) to develop an actor approach of the concept of critical transitions. It is conceptual in nature; it is not focused on a specific location, situation or isolated case but is centererd around a conceptual framework (the concept of critical transitions) to reason about the role of human behaviour in the energy transition.

To include this actor behaviour, we designed ACT as an agent-based model. Agent-based modelling (ABM) is a modelling method with which actors, agents in a particular system, can be modelled. In these systems the overall system behaviour emerges from the behaviour and interaction of constituent heterogeneous agents. By applying ABM we could include the relevant actor behaviour and study its influence on the overall system dynamics. [96] With ACT we could depart from the mean-field approach (the assumption that the average attitude of all individual agents influences the action-level of the individual) by simulating more realistic and relevant actor behaviour.

The model is written in the software environment of Netlogo and is accessible online[1] together with a more detailed model description following the ODD protocol [71, 72].

5.3.1 Model conceptualisation

In ACT agents represent actors in the energy system that face the problem of climate change. The relevant actor behaviour with which we extended the existing model conceptualisation (MFA) is based on the described actor behaviour which we deduced from actor behaviour in global CPR dilemmas as described in Section 5.2. This relevant actor behaviour was conceptualised as follows:

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[1] https://www.comses.net/codebases/5836/releases/1.1.0/

Interaction To depart from the mean-field approach we modelled individual agents and their interaction via social and physical networks. In this way we could model actors in the energy system which are not (only) influenced by the average public action-level, but (also) by their individual peers; be it via social or physical networks.

Heterogeneity Heterogeneity in ACT consists of two elements:

1. Perceived severity. Actors in the energy system have a heterogeneous view of the severity of the problem climate change and the corresponding need to transition the energy system. In ACT the heterogeneity of agents is modelled explicitly by giving agents a uniform distribution of the perceived severity of the problem.

2. Influence. In the energy system we can see the effect of different types of leaders in the world. Political leaders, business leaders, and influencers all have their effect on the energy transition. Although Scheffer et al. predict the effects of heterogeneity of individuals to influence the transition trajectory, it is not explicitly modelled in their model. Therefore, in ACT leaders are explicitly modelled as agents with more influence over their peers. These leaders are randomly distributed in the system and have a larger influence on the mean field interaction of the agents. They act in the public arena and in this way, influence all agents evenly, but with a larger weight factor than normal agents do. Leaders themselves are influenced by their constituency and thus change over time. By explicitly modelling leaders, the effect of leaders can be analysed and checked for consistency between model results. This gives the opportunity to translate these results into an analysis of the effects of leaders.

Non-binary action-level The original model (MFA) assumes that individuals have a binary action level regarding a problem; they are either active or passive. Arguably real individuals have a more continuous distribution of action-level. Therefore, ACT does also have the option of a neutral attitude. Although we don't claim to represent all complexities of human behaviour, it is a closer representation of reality.

These model elements are well suited to represent relevant elements in the energy system. Table 5.1 shows how the mentioned elements subsequently are related to the energy transition, the mean-field approach and ACT.

5.3.2 Model design

The conceptualisation translated in the following model design. Discussing this model design we stay close to the original model (MFA) description, and focus

Table 5.1 – The relationship between the energy transition and elements with which ACT was extended in comparison with the model developed by Scheffer et al.

Energy transition	Scheffer et al. (MFA)	ACT
Heterogeneity in perceived seriousness of climate change	Heterogeneity in attitude using law of large numbers	Heterogeneity in action level between agents
Social influences by peers	Mean-field interaction	Interaction via networks
Leaders in the energy transition	Not explicitly modelled	Explicit modelled leaders
Continuus action level	Binary action level	Non-binary action level
Uncertainty about climate change	Complete information	Heterogeneous perceived severity of the problem

Table 5.2 – Application of mean-field model to the energy transition in ACT.

Abbreviation	Scheffer et al. (MFA)	ACT
$U_i(t)$	"Utility of being active or passive"	Concern about climate change of individual *i*
$A_{system}(t)$	"Overall tendency for action"	The tendency of the system as a whole to engage in an energy transition
$A_i(t)$	$A_i(t) = A_{system}(t)$	The average tendency of peers of an individual *i* to engage in an energy transition
$V_i(t)$	"Perceived utility of individual I at time *t* to become active or passive"	Preference of being either active or passive based on agents' *i* concern and that of its peers
$P(t)$	"Probability of action *a*"	Probability of becoming active or passive
$h(t)$	"Perceived severity of the problem"	Perceived severity of climate change
c	"Cost of taking a deviating position"	Factor that scales social aspects

ACT consists of individuals (agents) that can have two action levels (a) with regards to climate change; an agent i, can either be active and engage in the energy transition ($a = +1$) or passive ($a = -1$) and do nothing. (In the non-binary action level experiment a neutral action level as been introduced ($a = 0$)) Whether an agent becomes active of passive, depends on its preference V_i of being either active or passive. We assume that this preference of an individual agent depends on three factors; their current concern about climate change $U_i(t)$, the average concern of its peers ($A_i(t)$), and the cost c that scales the costs of deviating from this average concern following Equation 5.1.

$$V(a_i) = U(a_i(t)) - c(a_i(t) - A_i(t))^2 \tag{5.1}$$

In the mean-field approach, agents are influenced by the average public opinion, $A(t)$; the overall tendency for action. When we introduce interaction via networks, $A(t)$ becomes an individual attribute $A_i(t)$ and agents are influenced by the average opinion of their connections. The network that has been implemented and has been experimented with is the nearest neighbour network with different radii r, simulating energy communities as physical neighbourhoods.

To explore the effect of leaders, we introduced leaders which action level is determined by its constituency; the agents in its area of influence determined by radius r. Subsequently these leaders have a larger influence l_i then normal individuals on the overall system expressed in the weight factor w_i. Their own action level thus depends on their connected agents while they influence other agents by influencing the overall action level of the system $A(t)$.

When networks or leaders are introduced, the overall influence of agents is normalised following Equation 5.2 in which n is the number of agents within an exogenous determined radius r of the agent (i.e. $r = \infty$ for mean-field) and the weight factor w_{ij} normalises the influence on an agent.

$$A_i(t) = \sum_{j=1}^{n} a_j * w_{ij} \tag{5.2}$$

Following Scheffer et al. [250] the probability P of an agent becoming either active or passive (a) is defined as:

$$P(a) = \frac{e^{\frac{U(a)}{s}}}{e^{\frac{U(+1)}{s}} + e^{\frac{U(-1)}{s}}} \tag{5.3}$$

The perceived severity of climate change h_t defines the action level of an agent when it is either active or passive; $U(+1)$ and $U(-1)$. This parameter follows an exogenously set scenario (linear increase or decrease), reflecting the concern by scientists about climate change.

$$h_t = \frac{U_t(+1) - U_t(-1)}{2} \tag{5.4}$$

In the original model (MFA) a parameter s was defined to incorporate heterogeneity on the perceived severity of the problem. In ACT heterogeneity has been modelled directly via a uniform distribution on h with bandwidth b_h to explore the effect of heterogeneity in the perceptions on the severity of climate change (in Equation 5.3, $s = 1$). By substituting the current action level of an agent

($U(a)$) with its individual preference of being either active or passive (which is partly based on its peers ($V(a_i)$) in Equation 5.3, the average tendency for action of the system $A_{system}(t)$ becomes:

$$A_{system,t} = \tanh\left(h(t) + 2cA_{system,t-1}\right) \tag{5.5}$$

Then solving Equation 5.5 for $A_{system,t} = A_{system,t-1}$; giving all the agents the possibility to balance their own concerns with that of their peers, gives the equilibrium overall tendency for action as a function of the severity of climate change $h(t)$. Figure 5.2 shows a graphical representation of the model structure.

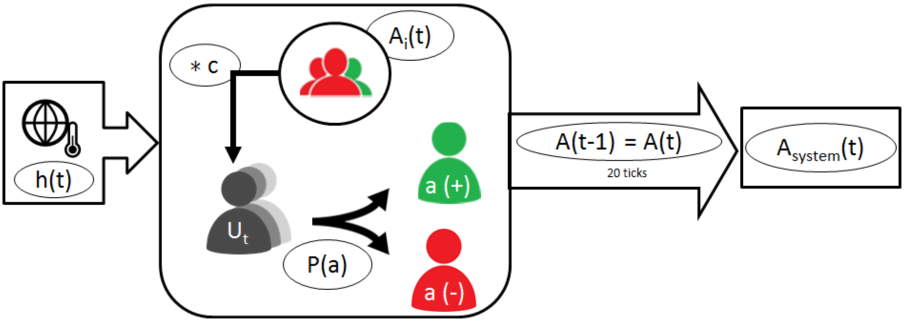


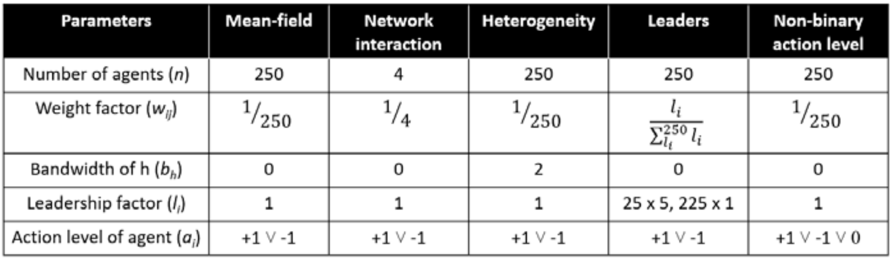
Figure 5.2 – Model structure. The chance ($P(a)$) of an agent becoming active or passive depends on their current concern about the climate ($U_i(t)$), the perceived severity of climate change (h), the average tendency of its peers ($A_i(t)$) and c, an factor that scales social aspects. Each agent makes a choice to be become active or passive which results in a new equilibrium $A_{system}(t)$

5.4 Experiments & results

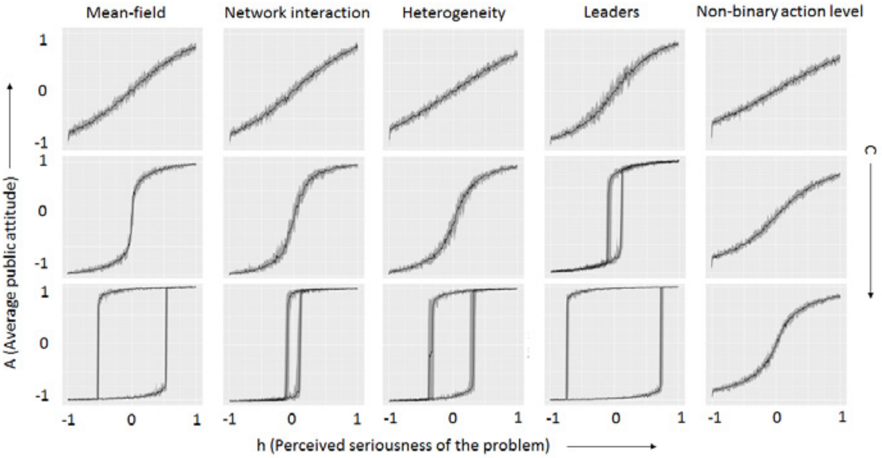
With ACT several experiments have been conducted with regards to the described relevant actor behaviour. Experiments were conducted with the parameter setting given by Table 5.3.

Results from these experiments are depicted in Figure 5.3. In the three rows of figures, the peer pressure c between agents has been increased. Figures show the results of 30 model runs. The experimentation of a selection of experiments with 100 runs showed that the experimentation with 30 runs was sufficiently representative with regards to the median and standard deviation of the model outcomes. Depicted are the first and second quartile on both sides of the median (shaded) while the thick lines show the median. Figures were obtained with two scenarios to show the hysteresis of the system behaviour; the perceived seriousness of the problem h, is exogenously and linearly increased in steps of

Table 5.3 – Experimental design



Parameters	Mean-field	Network interaction	Heterogeneity	Leaders	Non-binary action level
Number of agents (n)	250	4	250	250	250
Weight factor (w_{ij})	$^1/_{250}$	$^1/_4$	$^1/_{250}$	$\frac{l_i}{\sum_{l_i}^{250} l_i}$	$^1/_{250}$
Bandwidth of h (b_h)	0	0	2	0	0
Leadership factor (l_i)	1	1	1	25 x 5, 225 x 1	1
Action level of agent (a_i)	+1 ∨ -1	+1 ∨ -1	+1 ∨ -1	+1 ∨ -1	+1 ∨ -1 ∨ 0



0.05, from -1 to 1 and subsequently decreased back to -1, waiting for 20 ticks to reach equilibrium.

Figure 5.3 – Results of the ACT model. The most left column shows the replication of the mean-field experiment. Subsequently the results for network interaction, heterogeneity, leaders and non-binary action level experiment are depicted.

Table 5.4 gives a quantification of the difference between the original mean-field approach and the experimental results. In this table we compared the experimental results (for all h) with the mean-field approach, and show the value of c (in steps of 0.05) at which σ_e is minimal following Equation 5.6 in which $A_{system,mf}$ is the result of the mean-field experiment and $A_{system,e}$ the result of the subsequent experiments

$$\sigma_e = \sum_{h \in H} (A_{system,mf} - A_{system,e})^2 \tag{5.6}$$

Mean-field Our first results showed that with ACT, in which we paramet-

Table 5.4 – Comparison between mean-field experiment and subsequent experimental results

C_{mf}	$C_{network}$	$C_{heterogeneity}$	$C_{leaders}$	$C_{non\text{-}binary}$
0	0	0	0.15	0
0.5	0.40	0.35	0.65	0
1	0.65	0.85	1.15	0.25

erised the actor interaction as a mean-field, we could replicate the results from the original conceptualisation (MFA) as described by Scheffer's [250]. With ACT we could explore the effect of additional elements that will be subsequently discussed.

Network interaction A key element we distinguished in Section 5.2.2 is actor interaction. Departing from mean-field interaction, we experimented with nearest neighbour interaction ($n = 4$) as this network is the largest deviation from the MFA with regards to the number of connected agents. The weight-factor w_i normalised the influence, simulating energy communities as physical neighbourhoods. Results show the system reacts faster and that a critical transition is less likely but is still possible. Similar results were obtained when experimenting with interaction within the small-world network.

Heterogeneity Experiments have been carried out with regards to heterogeneity in the perceived severity of the problem. Agents were given an individual perceived severity of the problem h, based on a uniform distribution with bandwidth b_h. Results from these experiments show that heterogeneity of agent opinions has an influence on model outcomes if we compare those results with the mean-field experiment. Heterogeneity makes the system react faster to a worsening problem and a critical transition is less likely but still possible. This reflect the fact that allowing for a larger heterogeneity, actors are included that change relatively early from inactive to active (or vice versa).

Influence of leaders The second aspect of heterogeneity we explored is the influence of leaders. We experimented with the heterogeneous influence l_i of agents in the system which were normalised with the weight factor w_i (see Table 5.3). Results show the experiment where 10% of agents are leaders with 5 times ($l_i = 5$) as much influence as normal agents. These results show that leaders cause inertia; a critical transition is then more likely. This result contradicts existing literature on the effect of leaders with regards to critical transitions concept. This is due to a difference in conceptualisation of leaders. We will come back to this issue in Section 5.5.

Non-binary action level To explore the effect of the restriction to a binary action level, we experimented with the possibility for a non-binary action level by allowing for a third option $a = 0$. Results show that if we allow for a neutral action-level the critical transition disappears completely.

5.5 Reflection on model results

The concept of critical transitions highlights several aspects of the energy transition. It argues why society so far has been slow to respond to the dangers of climate change and highlights aspects we should keep an eye on as they can trigger a future critical transition. The model results as they have been presented in Section 5.4 give rise for the following observations:

Complexity of the problem Scheffer et al. argue that the increased complexity of a problem decreases the pace in which society will take action. When a problem is very complex, the perception of individuals of that problem is diffuse and the perceived effectiveness of action is low. This makes that individual's opinion will depend more on the opinion of its peers and authorities [250]. Modelling the increase of complexity thus boils down to modelling an increase in peer pressure. Increasing peer pressure in ACT confirms this view; a slow response to an increasing worsening of the problem and a higher change for a critical transition.

Influence of leaders Scheffer et al. [250] argue that in highly centralised / more authoritarian decision-making structures, leaders are a positive driving force for the prevention of a critical transition. Our research however nuances this view. With the use of a richer model, results show that the "real world" emergence of champions of change will naturally bring forth champions of status quo representing vested interests. Either leaders can be understood as actors that initiate action (as Scheffer et al. argue, "once the central authority is convinced of the need for change"), or as simply more influential actors that can possibly represent vested interests and can obstruct action. We therefore conclude that when the role of leaders in the energy transition is discussed, an clearer understanding of the role of leaders is necessary.

Collective action problem and the importance of energy communities Model results from our network experiments confirm insights from economists [275] and game theoretic modellers (e.g. [42]) that address the collective action problem. They distinguish *noticeability* as important aspects to promote action in groups. This also relates to *observability* of innovations, as Rogers [289] suggests that “the observability of an innovation as perceived by members of a social system, is positively related to its rate of adoption”. Our model results are in line with this thinking; decreasing the radius of peer-influence increases the ability of the whole system to take early action. In societies where decision making power is decentralised the existence and action readiness of local communities therefore become a critical element [290]. Relating this to an observed practise in the energy transition we have seen that in Germany local communities triggered the German *Energiewende* [291, 163, 292, 293, 294]. Copying this success has shown to be difficult [295] but has highlighted the importance of specific aimed policies [296] and the need for time to build up momentum [291]. This is recognised in the concept of critical transitions; it highlights the problem of slow response of society to the problem of climate change. In decentralised systems, local communities however, have proven to be able to initiate a positive shift to a more sustainable system [297, 298, 294].

Polarization Several key players (i.e. the United States and Western Europe) in the energy transition have shown increased polarization of their society not in the least on the issue of global warming and climate change [299, 300]. It can be argued that polarizing societies will have less heterogeneity of opinions, the result of which we showed in experiments looking at heterogeneity. Decreased heterogeneity can lead to group-think. The effect of group-think in problems such as climate change has been explained as cognitive dissonance; the tendency to ignore contradictory information from an individual’s own opinion [301, 257]. Our results confirm the idea that polarised societies will decrease their ability to act upon problems such climate change and the need for an energy transition.

5.5.1 Modelling critical transitions

Modelling non-linearity in the energy system We distinguish three sources of non-linearity in the energy system. Firstly, there is the cost decline of technology due to technical progress and economies of scale. This leads to so-called tipping points where new technologies outperform incumbent technologies, leading to accelerated (non-linear) change. Secondly, there are ’events’ that change – in colloquial terms – the rules of the game, i.e. from one moment to the next the actor’s outlooks have changed as do (consequently) behaviours. Related to climate change, such events are for instance (climate induced) natural disasters and pivotal political moments (the signing of the Paris accord might be a candidate). Thirdly, there is the iterative bi-directional interplay between system elements such as actors. Simulating the non-linear character of the energy system and the energy transition would require modelling these three elements.

Modelling of 'events' is illusive; this can only be brought in exogenously, and must be supported by a narrative. The second element is outside of the scope of this paper. But our model and the concept of critical transition gives us the mathematical as well as qualitative construct to simulate the last point: how iterative actor interaction influences their behaviour, changing over time as the external environment develops. This goes a long way to model the emergent behaviour in this complex system.

Energy scenarios The results of such experiments and the experiments in this paper can be related to energy scenario studies. In the latest New Lens Scenarios [32], earlier described as example of scenario development studies, a qualitative story line is shown to which we can relate to with ACT. The study presented two possible pathway lenses: Room to Manoeuvre where an early crisis leads to punctuated reform, and a Trapped Transition where no action is taken until an existential crisis leads to either 'write-off reset' or 'decay/collapse'. These abstract narratives were the basis for the two scenarios Mountains and Oceans that apply these narratives to assumptions on the possible evolution of the energy system. Figure 5.4 shows a summary of the results of the experiments and how the critical transition theory would be applicable to the Shell's pathway lenses.

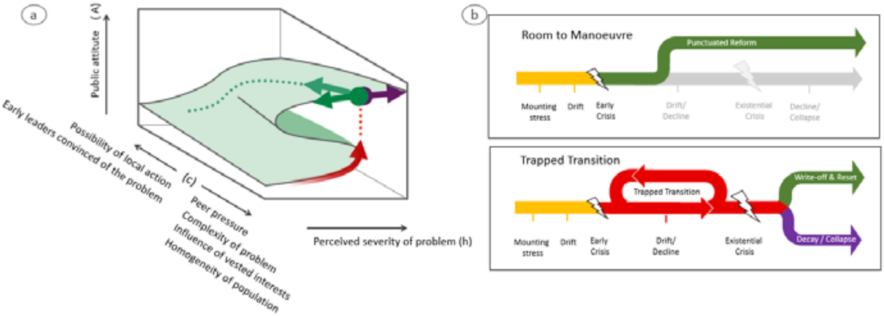


Figure 5.4 – Summary of results and comparison with the Shell Scenarios. Figure a. shows relationship between average public attitude ((A_t), the perceived seriousness of the problem (h) and social aspects described by the parameter c. Figure shows relationship between critical transition theory and Shells "Pathway Lenses" (Figure b) as building blocks for energy scenarios (adapted from [32])

5.6 Reflection on modelling approach

The energy system is a multi-dimensional complex system that consists of many interacting subsystems. ACT on the other hand is a simple conceptual model which is hard to validate and in some aspects, as we have seen, contradicts existing conclusions from a similar simple model. A thorough reflection of our modelling approach is therefore needed. What are the strength and weaknesses of such an approach? To do this, a more broad reflection on conceptual modelling is necessary to see the role these kinds of models can play. Therefore, in this section we will try to use this generic insight to put our modelling results in perspective. We then see whether this reasoning is applicable to our modelling approach.

To formulate an answer to that question, let's for a brief moment look at the discussion around one of the first and maybe the most criticised global energy system modelling study: The Limits to Growth (LtG) [302]. The (compared to its scope) relatively simple model was used to support a narrative on the limitations of a finite planet and its consequence for population and economic growth and in this way illustrated an argumentation that the authors of LtG had about the world and its future development. The LtG study is a part of a broad tradition of energy system models. As we argued earlier (Section 5.1.2), the scenario development process of Shell and many other scenario studies can also be seen in this context.

Since the publication of the LtG study four decades ago, it has been the subject of wide range of criticism and even recently has been used as an example of over-hyping model success [251]. Although various categorisations of critique exist [303], we will focus on two main types, technical and epistemological, in order to later reflect on the results we deduced from ACT.

The technical criticism that dominated the first years after publications disputed the model assumptions. Mainly the assumption regarding the role of technology in the energy system has been subject of debate ranging from technology-optimist to technology-pessimists. We would argue that this is a legitimate debate that can been used to come to grips with the problem that modelling studies such as LtG try to address. This does however require transparency of the model and its assumption from the researchers involved in the modelling study which cannot be taken for granted.

The epistemological criticism has focused on whether anything can be learned from highly aggregated and abstract models. Edmonds [251] has characterised LtG as an analogical way of modelling that is not scientific as it made the impression of being predictive while unsupported by evidence. Although the authors of LtG themselves were aware of these limitations[2], the model has been perceived by the general public as a prediction.

This epistemological criticism shows the danger of this type of modelling which

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[2] Quoting LtG [302]: " Can anything be learned from a highly aggregated model? Can its output be considered meaningful . . . The data we have to work with are certainly not sufficient for such forecasts, even if it were our purpose to make them" And stating that the outputs "are not predictions of the values of the variables at any particular year in the future. They are indications of the systems behavioral tendencies only."

can be brought down to its duality of means: i) convince with a particular line of argumentation formulated in a narrative and ii) illustrate with a quantification by the use of a model and its outputs. Although LtG was published with unpretentiousness with regards to its quantification, its purpose with regards to its narrative was to convince the general public about the limits to growth. Critics however, focused on the weakest link, namely the quantification, and interpreted it as a detailed forecast. This is an often-seen reaction to scenarios; quoting Michael Liebreich: "[I]f it looks like a forecast, swims like a forecast and quacks like a forecast, it is a forecast... And if that is not the intention, why publish it at all?" [304]

Similar to Edmonds [251], Ehrenfeld [305] distinguishes *analogical modelling* and the use of *metaphors*. Ehrenfeld argues that whereas metaphors are figures of *speech* and suggestive, an analogy is a *practical notion* that compares two cases and suggests an alternative way of addressing the situation based on the presumption that they share similar properties and dynamics. However, completely different mechanisms may be at play. Therefore, while a metaphor can never be wrong (although it usefulness can be questioned), an analogy can be objectively be false.

Ehrenfeld observes that often a metaphor is used as a useful starting point of analysis. When the system understanding comes from the source of the metaphor 'learning by analogy' has occurred. Learning by analogy is different from the normal scientific method (as shown in Figure 5.5) and has been disputed as Ehrenfeld argues that learning by analogy is not necessary as the rules can be invented by independent observation and deduction of the system at hand. The application of the concept of critical transitions to a societal system is an example of learning by analogy; originally applied to analyse ecological systems a metaphor has been deduced which was applied to construct a model of society.

The usefulness of these conceptual models based on analogies is in doubt. Some researchers claim that although they "are extremely useful things ... this is not scientific knowledge ... reliable conclusions have to be based on evidence so they can be relied upon" [251]. This reflects the thought that science is supposed to be about exact reasoning, leading to certainty. This scientific method requires falsification [306]; and thus, the process of validation. The process of learning by analogy can therefore be classified as non-scientific as the argument that a certain analogy is appropriate is a subjective qualification.

However, in cases where facts are uncertain, values in dispute, stakes are high and decisions urgent, scientists have argued that traditional science as puzzle-solving is "at best irrelevant and at worst a diversion" [307]. Falsification in these cases can only be done on subjective grounds, as there are no objectives grounds to falsify on. (Figure 5.5 shows the relationship between a normal scientific

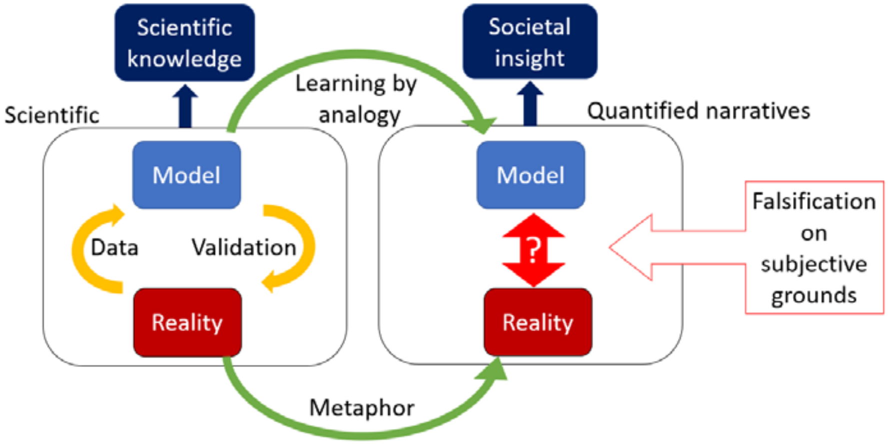


Figure 5.5 – Learning by analogy. Left-hand figure shows a methodology that can be qualified as scientific where data informs a model which can be validated and falsified. Right-hand figure shows learning by analogy where insights can be generated but where the falsification is done on subjective grounds.

modelling study and what the role is of metaphors, analogies and falsification on subjective grounds.) In fact, Ehrenfeld [305] recognises that this "unknowability" demands a whole different kind of science and decision-making process.

Researchers therefore have advocated the use of post-normal science [308, 309]. They argue that, as the future is fundamentally unknowable especially on longer time scales, scientific models can be used as having a metaphorical function [310, 311], designed to teach us about ourselves and our perspectives under the guise of describing and predicting the future state of the planet. Although this approach is different from the traditional understanding of scientific knowledge, it can help science to adapt and being useful for sustainability challenges in a complex world.

We would agree with both Ehrenfeld and Edmonds that any model used against the background of analogical thinking (or equivalently learning by analogy) could be disputed. However, when we enter the space of unknowability, such as the future of the energy system, models based on metaphors can give insights. However, explicit unpretentiousness and humility in model design and use is essential. Even then when modellers take that stance, they have to be aware that stakeholders (politicians, media, general population, etc.) will interpret their results as exact forecasts. Therefore, we would argue that an conceptual approach that explicitly does not make quantitative prediction about the future (like this study) but focus on qualitative insights, could function as model to illustrate and communicate certain narratives.

Based on this argumentation and reflecting on this modelling study we therefore, would argue that the application of the concept of critical transitions, our newly developed model ACT and conceptual modelling in general has a role to play in understanding, discussing and communicating about the energy transition. We must realise that in reality equilibria and tipping points (bifurcations) do not exist in strict sense. They are mathematical constructs which help us make sense of the world. The concept of critical transitions in that sense can reveal some fundamental features of reality that would otherwise be hard to comprehend [62].

5.7 Conclusion

In this study we have used the concept of critical transitions to explore how human behaviour with regards to energy transition influences this transition. We integrated relevant actor behaviour derived from the conceptualisation of the energy transition as common pool resource dilemma into our model. By doing so we could depart from the conventional mean-field approach and could integrate actor interaction and heterogeneity in a newly developed agent-based model of the concept of critical transitions (ACT).

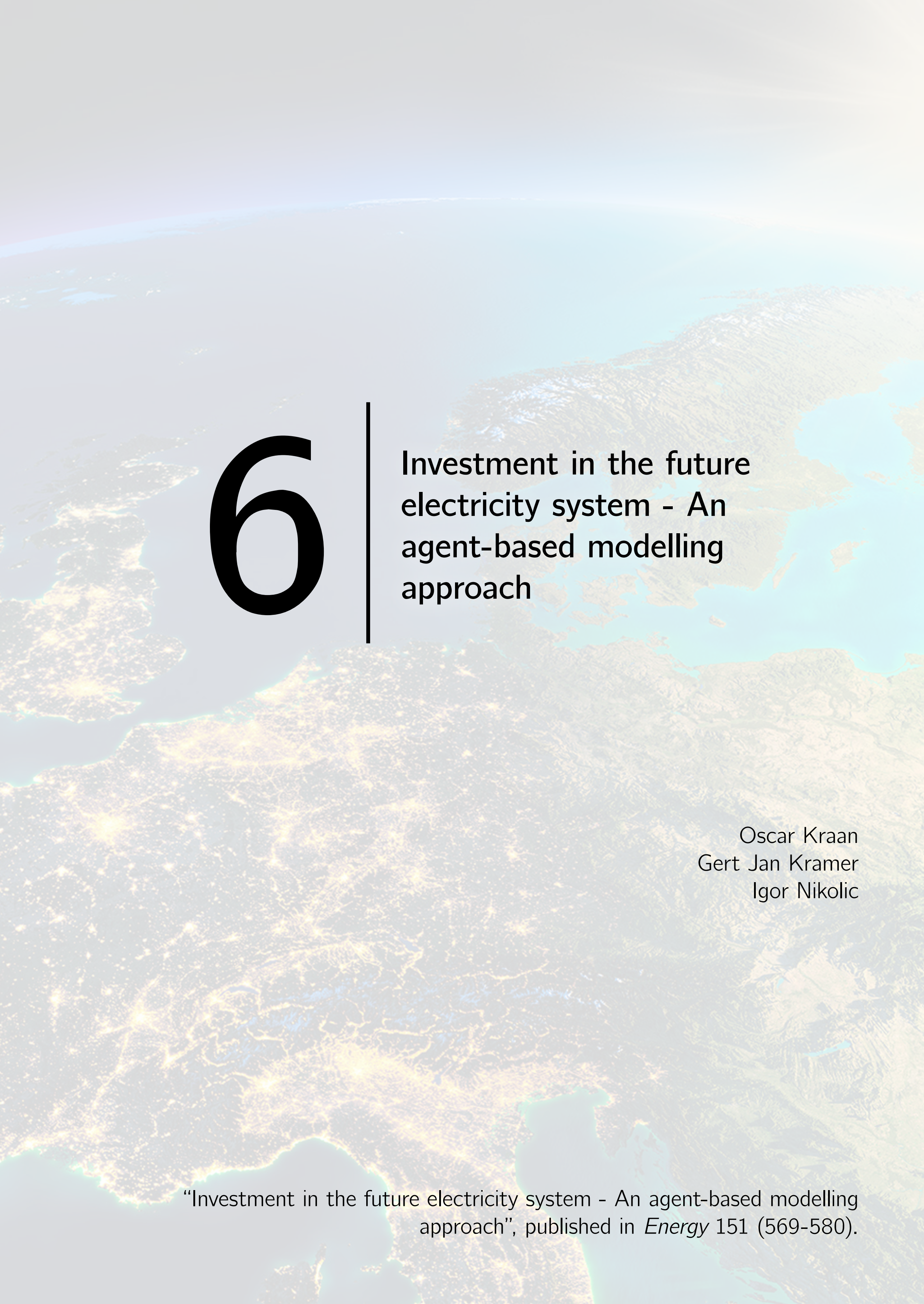
Results show the effect of five elements we explored: i) network interaction, ii) heterogeneity with regards to the perceived severity of the problem, iii) the influence of leaders, iv) influence of departing from a binary action level. We showed that the effect of leaders is more nuanced that what is assumed in existing literature on critical transitions; leaders can encourage a transition but can also try to stall any development till a critical transition is inevitable. Furthermore, model results suggest that the polarization of society decreases the pace of societal action while energy communities have an important role to play as they can increase this pace.

Reflecting on our modelling approach we recognised that conceptual models such as ACT are part of a long transition of models that are relatively simple regarding their scope. We have argued, based on an analysis of the criticism on The Limits to Growth report, that the correct valuation of these models needs a different perspective than the traditional science perspective. This perspective is offered by post-normal science that shows that when facts are uncertain, values are in dispute, stakes are high and decisions urgent, we should recognise that falsification of models can only be done on subjective grounds. Looking at ACT from this perspective shows us that these models and ACT specifically are meant to facilitate discussion on the possible evolution of the energy system between different stakeholders, and can be used to develop building blocks of narratives of the energy transition.

Valuing the models such as ACT however does put two requirements onto researchers. First and most important is that researchers are clear about the purpose of their model. Researchers should emphasize (even more) that these models cannot be used as forecasts and thus should resist to answer wrong or de facto political questions. Secondly, researchers need to be transparent about their models to be able to facilitate a legitimate and useful debate about their model assumptions. We have argued that with ACT we have met these requirements.

Acknowledgements

This research has been part of a Shell-sponsored project on the use of agent-based modelling in the energy scenario domain. The authors want to thank dr. Wander Jager and dr. Gary Polhill for their helpful suggestions and constructive comments on the draft of this paper.



6

Investment in the future electricity system - An agent-based modelling approach

Oscar Kraan
Gert Jan Kramer
Igor Nikolic

"Investment in the future electricity system - An agent-based modelling approach", published in *Energy* 151 (569-580).

Abstract

Now that renewable technologies are both technically and commercially mature, the imperfect rational behaviour of investors becomes a critical factor in the future success of the energy transition. Here, we take an agent-based approach to model investor decision making in the electricity sector by modelling investors as actors with different (heterogeneous) anticipations of the future. With only a limited set of assumptions, this generic model replicates the dynamics of the liberalised electricity market of the last decades and points out dynamics that are to be expected as the energy transition progresses. Importantly, these dynamics are emergent properties of the evolving electricity system resulting from actor (investor) behaviour. We have experimented with varying carbon price scenarios and find that incorporating heterogeneous investor behaviour results in a large bandwidth of possible transition pathways, and that the depth of renewables penetration is correlated with the variability of their power generation pattern. Furthermore, a counter-intuitive trend was observed, namely that average profits of investors are seen to increase with carbon prices. These results are a vivid and generic illustration that outcome-based policy cannot be solely based on market instruments that rely on perfectly rational and perfectly informed agents.

Keywords

Investor behaviour; Electricity markets; Agent-based modelling; Decarbonisation; Electricity; Scenarios

6.1 Introduction

The energy transition is gaining momentum in the last several years, due to rapidly falling prices of renewable energy technology and substantial institutional consensus on climate change created at the Conference of Parties in Paris in December 2015 [5]. The electricity sector is expected to take a leading role in the decarbonisation of the energy sector as it is crucial for a low-carbon energy system. The energy transition will therefore, have a large influence on the electricity system, as it entails a transition from the centralised and homogeneous fossil fuel-based system to a much more distributed and heterogeneous system based on intermittent renewable sources [312, 16, 233, 313].

Furthermore, the need for instantaneous balancing and limited storability of electricity, in combination with the intermittent nature of renewables will further increase the complexity of the electricity system. The liberalisation of the electricity system in many countries [314] has led to entry of investors, further increasing the complexity of the system as these new actors are now expected to play a key role in the transition.

Liberalised electricity markets are designed on the assumption that dispatchable electricity generation with a range of positive marginal costs can be ranked, which is the case for thermal generators such as coal or gas fuelled power generation assets [315]. This merit order in which the electricity price is set ensures economic efficient allocation of resources. With massive deployment of renewable energy sources, the market assumptions are undermined as renewable power generators cannot be dispatched and have zero marginal costs [316].

In electricity markets designed as ‘energy-only market’, electricity generators receive revenues for selling electricity but not for providing capacities [317, 318]. In theory these energy-only markets in which electricity prices should be covering capital investment, guarantee security of supply [319]. In practice, market imperfections and inadequate regulation can lead to ‘the missing money problem’, the problem that insufficient investments can lead to concerns around the security of supply [316, 317].

6.1.1 Modelling electricity markets

Modelling the development of the electricity mix within energy-only markets can give insight in the mechanisms taking place during the energy transition [56, 46, 247]. Many techno-economic studies on the energy transition have been carried out that can be classified in optimisation, equilibrium and simulation models [320, 321, 322, 323, 324, 325].

Large scale bottom-up optimisation models in general show cost-optimal pathways of the energy transition (e.g. [324, 326, 327]) and answer the question of ‘what should be’ [328]. Results from these studies are useful to depict an ‘ideal’ world in which a central actor with control power must be active that implements these multi-decade systems to achieve cost-optimal pathways. Western democracies however have deliberately moved away from centralised planning with the liberalisation of (electricity) markets. If we want to increase our understanding of these systems, we therefore, should focus more on the incorporation of heterogeneous actors with bounded rationality and imperfect information.

Whereas optimisation models rely on detailed bottom-up technologies, equilibrium models (e.g. [329, 330, 331]) try to model the overall market behaviour top-down with algebraic and/or differential equations (e.g. Worldscan [332]). However, when the problem under consideration is too complex to be addressed within a formal equilibrium framework, simulation models are an alternative to equilibrium models [320].

These and other neoclassical models that depend on economic rational behaviour have provided key insights for business decisions and policy makers [12]. Literature and simple observation of the real world suggest however, that these assumptions do not hold and that decision makers in the system are heterogeneous and exhibit bounded rationality in their decision-making behaviour [333, 334, 97]. Including bounded rationality relaxes the assumptions of perfect foresight and maximising utility [126]. Modelling these aspects requires different tools [328, 97, 34].

6.1.2 An agent-based approach to electricity sector investment

Agent-based modelling (ABM) can be used to simulate complex adaptive systems (CAS) such as the electricity system and is well suited to model adaptive heterogeneous actors (agents) such as investors that can be part of emergent system behaviour. Modelling the energy transition this way is therefore expected to give important new insights that complements the insights obtained from more traditional energy systems modelling.

Several large-scale ABM studies have been looking at the transition of the electricity system, focusing on the role of consumers (e.g. [335, 86]) and investors [336]. In these studies, the added value of modelling the role of investors in the energy transition and more specifically in the electricity system has been recognised (e.g. [337, 338, 339], for an overview: [56, 340]). Because previous ABM studies on the role of investors mainly focus on detailed behaviour (see e.g. [341] on detailed improvements to the EU Emission Trading System), there is a gap in the understanding of the impacts of investor behaviour on the fundamental dynamics of the electricity system in transition.

The goal of this study is thus to elucidate the fundamental processes that underline the transition of the electricity system. We have taken a conceptual approach aimed at identifying the minimum set of agent-types, behaviour rules and assumptions that could replicate the fundamental dynamics of the first phase of the transition and show possible concerns for the future. This approach has strengthened the transparency, tractability and reproducibility of model results as these are three fundamental challenges in ABM studies [342, 67].

We will focus on exploring the emergence of the deep decarbonisation of the electricity sector based on the interactions and individual investment decisions of heterogeneous bounded rational investors in the electricity market. The model represents a typical liberalised Western European electricity market designed as energy-only market [233] such as The Netherlands [343]. As this is a common feature of modern electricity markets, conclusions are potentially generalisable.

The organisation of this paper is as follows: in Section 6.2 the starting set of assumptions are discussed. The conceptualisation of our model is described in Section 6.3. In Section 6.4 we describe our results and in Section 6.5 we reflect on recent developments and present our main observations. We conclude in Section 6.6 with a reflection on our modelling approach.

6.2 Investment decisions in an evolving electricity system

Our model focuses on the role of investors and assesses the influence of their behaviour on the dynamics that drive the development of the electricity system. To avoid the trap of an over-parameterised model we aimed to keep our model as simple as possible. We argue that a reasonable starting set of assumptions for an investor-focused agent-based model, is the following:

1. Future electricity market prices, fuel prices and technology learning rates are unknowable.

2. Investors make investment decisions based on heterogeneous expectations about the future.

3. Past performance of investors affects their investment capacity (and may colour their outlook) but there is the possibility of new investors entering the market.

4. Investment opportunities in power generation assets are diverse with regards

to the energy resource, capital lay-out, running cost (including fuel) and CO_2 intensity.

Since our interest lies in the evolving electricity sector as ever more intermittent renewables enter the generation mix, an additional assumption is:

5. Renewable power generation assets have seasonal variable supply and there is no seasonal storage solution.

Finally, we make one additional assumption which is only true in specific liberalised markets, namely that:

6. The electricity market is as an energy-only market.

We will discuss these assumptions in more detail in the next sections.

Investors' heterogeneous view on the future and their investment decisions

To elaborate on the first assumption; because, (i) the future is fundamentally unknowable and inherently and irreducibly uncertain, (ii) the pace of the transition is unknown, (iii) the preferred technology options are unknown (because future costs and performance are unknown), and (iv) the future price-setting mechanisms in the market are unknown, one naturally expects different investors to have different expectations about the future (assumption 2). This can be understood as investors with different corporate strategies and different risk appetites. This leads to a heterogeneity of views on the development of the electricity market and the business environment which influences investment decisions.

Investors' expectations are related to capital providers that assess these expectations companies have. Besides this external component, investors also have an internal component that expresses their required return on capital invested. This internal component is also heterogeneous among investors; while incumbent investors may require a high return on capital invested for new projects, other investors may require a lower rate.

All investors evaluate opportunities by assessing the discounted cash flows in relationship with the size of the investment. The combination of the heterogeneous external expectations and internal requirements investors have, determines the discount rate with which they evaluate these cash flows.

Influence of past performance on new investment decisions

Because investors assess future investments heterogeneously, they will make different investment decisions. Their performance, based on the development of the electricity market and the choices investors have made, is reflected in the average profitability of the assets an investor owns and influences future decisions (assumption 3).

Although the electricity market is composed by a limited number of existing power producers, there is a possibility of new investors that can enter the market (e.g. Qurrent in The Netherlands [344]). We assume they are able to raise capital not based on past performance (which is non-existent), but on the basis of a business vision that is sufficiently new and appealing [345]. For the case at hand that means that renewable power companies can enter the market which are unburdened by a fossil legacy portfolio.

6.2.1 Power generation assets

The electricity system in most European countries is predominantly based on thermal power generation fueled by fossil resources. However, new, scalable renewable technologies have become available which produce electricity from intermittent resources (assumption 4). These renewable assets, (offshore) wind parks or solar PV-farms, have near-zero operating costs and near-zero CO_2-emissions but are variable on different scales; seasonal, day to day and second to second. The variability of electricity output from these renewable assets depends on the regional location, weather conditions and the mix of PV and wind turbine capacity. Especially the variability of these resources on a seasonal scale is of importance as there is limited possibility for large scale seasonal storage [346] (assumption 5).

Learning rate of renewable technology

The capital lay-out mentioned in assumption 5 with regards to renewable energy technology is especially relevant as renewable energy technology have shown large cost reductions in the last decades [16]. This reduction in turnkey costs can be explained by learning by doing which is a common process; unit costs follow learning curves and go down over cumulative investment. Internationally onshore wind power generators have shown a learning rate of 9% [16] while solar PV-panels have shown learning rate of around 20% percent per year [312, 16]. In Section 6.4 details can be found of the learning curves for our experiments.

6.2.2 Electricity markets and the incentive to invest

Assumption 6 treats the electricity market design. We will first discuss the electricity market and then take a closer look at energy-only markets.

Pro-market reforms in the electricity sector that took place in the 1980's and 1990's resulted in liberalised electricity markets, both in OECD and non-OECD countries and regions [318]. In these liberalised electricity markets, power generators offer different quantities of electricity at various prices that are ranked from the lowest to the highest Short Run Marginal Costs (SRMC). The market-clearing price is set by the SRMC of the marginal producer. The SRMC of an asset consists of the fuel and other variable operation and maintenance costs (OPEX) but excludes the costs of capital. The margin for electricity producers is defined by the inframarginal rent, the difference between the SRMC of the marginal producer and their own SRMC. Via this infra-marginal rent, investors need to regain their investment costs.

Energy-only markets and the scarcity rent

In energy-only markets, marginal producers at peak demand can use their market power to increase prices. This is caused by the fact that in electricity markets power buyers accept price premiums (scarcity rents) to prevent black-outs. The marginal producer at peak demand recovers its capital costs via this premium. This pricing mechanism therefore, creates an incentive to invest in the marginal producer at peak demand.

The scarcity rent is the quantification of the market power of the marginal producer when capacity is scarce and is crucial to maintain security of supply in an energy-only market. This market power has been observed in reality and its effect has been studied in several studies e.g. [316]. Because of this scarcity rent in electricity markets, electricity wholesale prices spike at moments of scarce capacity. In most western countries, consumers are protected against these price spikes but as smart meters are rolled out, there is discussion between policy makers if these prices spike should be fed back to consumers. For example, the Netherlands has chosen for an energy-only market [343, 347], while in Germany and the United Kingdom elements of a capacity market are being introduced.

6.3 Conceptualisation

The agent-based model in this study is developed by applying the 10-step framework as proposed by Van Dam et al. [96] and is written in the software environment of Netlogo [90]. Literature research combined with semi-structured interviews with experts at Shell and The Copernicus Institute of Sustainable Development have led to the conceptualisation of the model. The model has been extensively verified and has been validated with recording and tracking behaviour, single-agent testing and multi-agent testing [96]. The model, as well as the description, is open source and is published on openabm.org. [1] The software package R has been used for analysis [348]. During the model development best practices for scientific computing have been pursued [349]. For the mentioned detailed description of the model, the ODD protocol is followed [71, 72].

Based on our understanding of the electricity market and investor behaviour we developed the conceptualization of our model. Figure 6.1 shows our conceptualisation which will be discussed in more detail in the following sections.

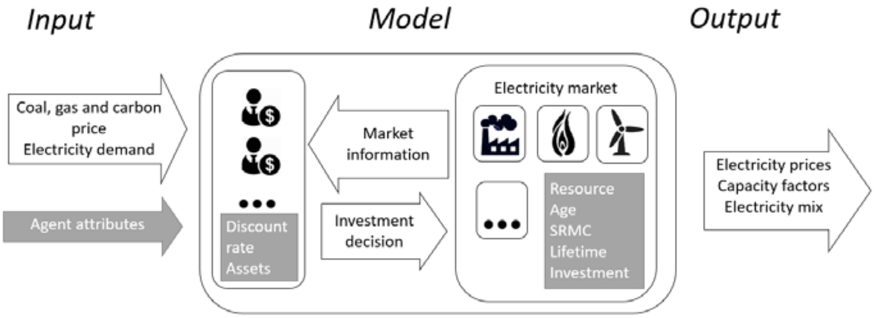


Figure 6.1 – Model description. Investors invest in power generation units based on market information and their heterogeneous discount rate. These assets are part of the electricity market. Investors and assets are initialised with agent attributes (grey). Other inputs and outputs of the model are depicted (white).

6.3.1 Investors

In the model investors use Net Present Value (NPV) as the key metric in the evaluation of investment opportunities in power generation assets of different types. An NPV in excess of zero triggers 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. These different discount rates are given to investors at initialisation. Additionally, at initialisation, investors are given an existing portfolio of gas and coal assets.

There also is the possibility for new ‘green’ investors not burdened by a legacy portfolio of fossil assets to enter the market; these are initialised with a random discount rate, and have no existing portfolio of assets. It is a priori not clear if this is an attractive business model, or that it adds anything to the dynamics of the transformation. But it is obviously of importance to at least be open to it, not the least because in the real world there are such players.

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[1] https://www.comses.net/codebases/5361/releases/1.2.0/

The adaptivity of investors is expressed in the model by making the discount rate of each individual investor dynamic. That is: each investor will see its discount rate increase or decrease over time, based on the profitability of its asset portfolio. During the model run, the discount rate an investor applies reflects therefore its expectations about the future, expressed by the discount rate at initialisation and its performance during the model run. This adjustment is made once a year after investments decisions have been made.

A visual representation of the decision-making process of investors is given in Figure 6.2.

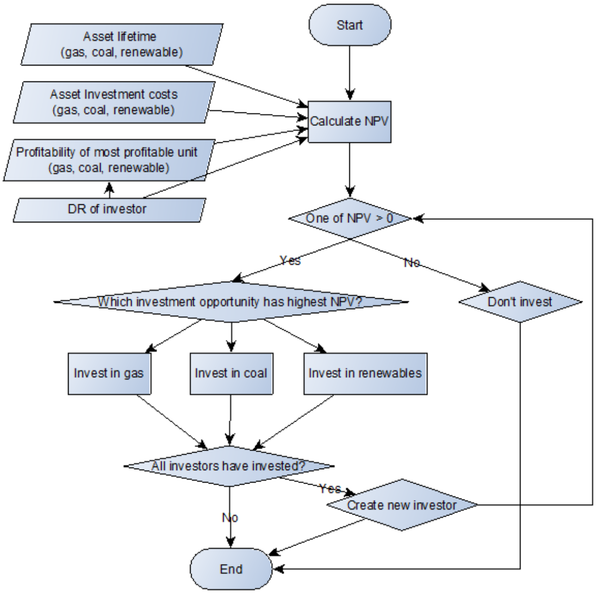

Figure 6.2 – Decision-making process of investors.

6.3.2 Assets

At initialisation assets have a heterogeneous age and efficiency within threshold values. Gas and coal assets have a constant dispatchable production, renewable assets have a variable supply on a seasonal scale.

For simplicity, but without loss of generality, we assume that investors can invest in assets of one GW-name-plate capacity. In our model, we have three types of assets: gas-fired power stations, coal-fired power stations, and renewable assets. These three asset-types have different properties with regards to their investment costs, their SRMC (based on the fuel costs), and the CO_2-intensity of the resource they are using. These properties (such as cost and efficiency) may drift over time, reflecting technology learning. The attributes of renewable assets can vary so as to reflect a particular mix of solar and wind assets. At initialisation, assets have a heterogeneous age and efficiency.

In the specific runs discussed in this paper, gas and coal assets have constant dispatchable production. Renewable assets have a variable supply on a seasonal scale modelled as a variation of a cosine function, based on empirical data [350, 351, 352, 353]. In the present case, we look at seasonal variation of renewables and accordingly use time slicing with 10 slices in the year, thus representing 'months'.[2] Also, in this paper we keep the unit cost of gas and coal assets constant; the unit costs of renewable assets decrease over time as a function of the cumulative investment in the technology. These costs follow a standard learning curve of the form given in Equation 6.1, where $C(t)$ is the cost of a renewable asset at time t, C_0 is the cost of renewable asset at initialisation, n is the number of renewable power generation assets of 1 $\mathrm{GW_p}$ and l is the learning rate.

$$C(t) = C_0 * n^{\frac{log l}{log 2}} \tag{6.1}$$

6.3.3 Electricity market

In the electricity market, during a year, assets produce electricity that satisfies the electricity demand. As said, the electricity market is modelled as energy-only market. In this paper, we are interested in the supply side and have assumed demand to be constant over time.

In our model, the electricity price is set by the merit-order, the actual market price is the SRMC of the marginal producer, plus a mark-up for generation scarcity, the "scarcity rent". This scarcity rent, $S(t)$, is taken to be a function of the excess capacity-factor as defined in Equation 6.2, where $S(t)$ is the scarcity rent at time t, S_{min} is the minimum scarcity rent, S_{max} is the maximum scarcity rent and α is the scarcity rent variable that determines curvature (see Figure 6.3).

$$S(t) = \frac{S_{max} - S_{min}}{\alpha - 1} * \alpha^{1/e(t)} + S_{min} - \frac{S_{max} - S_{min}}{\alpha - 1} \tag{6.2}$$

The time-dependent excess capacity, $e(t)$, is defined in Equation 6.3 as the potential power generation of all the assets in the system, i.e. the summation of the nameplate capacity of the coal and gas assets (1 GW) and the momentary power from renewable assets, relative to the (momentary, but here constant) demand. In Equation 6.3, D represents the (constant) demand D and $G(t)_i$ the

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[2] Note that there is no loss of generality. By going from 12 time slices in the year to 365 one would model days, by going to 8670 hours etc.

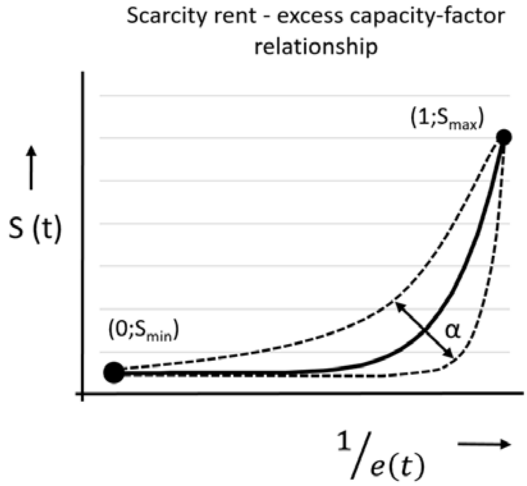


Figure 6.3 – Relationship between scarcity rent and excess capacity factor, where $S(t)$ is the scarcity rent at time t, S_{min} is the minimum scarcity rent, S_{max} is the maximum scarcity rent and α is the scarcity rent variable that determines curvature. The time-dependent excess capacity, $e(t)$, is defined as the potential power generation of all the assets in the system divided by demand D.

potential production at time t of all assets with resource i, including the variability of renewable assets $G(t)_{ren}$. Note that the excess capacity as we define it here is related to what in the power sector is called the “adequacy margin”. The adequacy margin is simply 1 - $e(t)$.

$$e(t) = \frac{\sum G(t)_{ren} + \sum G(t)_{gas} + \sum G(t)_{coal}}{D} \tag{6.3}$$

The scarcity rent approaches zero when enough capacity is available and no market player can use their market power to raise the price about the SRMC. On the other hand, the scarcity rent will be high at moments capacity is scare (low $e(t)$) to incentivise investment. The maximum electricity price, including the maximum scarcity rent, reflects the value of lost load (VOLL). We have chosen the functional form and parameterisation of the relation between the scarcity rent and the excess capacity factor such that outages do not occur.

6.3.4 Model narrative

Our model describes the time-evolution of the power system over years and decades. Within each year, the ‘clock tick’ of the model (the shortest time step in an ABM) is a month. Every month electricity prices are calculated based on existing assets. After a year has passed, the following steps are followed:

Investors calculate their profitability Based on production and the monthly electricity price, investors calculate their income from each of the assets in their portfolio. The profitability of investors' assets determines whether their discount rate will increase (low profitability) or decrease (high profitability). If the discount rate rises above a threshold, the investor goes bankrupt.

Investors evaluate new investment opportunities Investors make NPV calculations based on their individual expectations about the profits an investor can anticipate to make from a new asset. This profit will depend on the place of that investment in the (future) merit order. Although coal- and gas-based electricity production is mature technology, new units will have a slightly higher efficiency than older units. Thus, a new unit, with a slightly higher efficiency, will be ahead of the currently most profitable unit (of the same type, gas or coal) in the merit order. After evaluating all the options, investors decide to invest in an asset with the highest positive NPV (provided there is one). These assets are then placed in the system instantaneously and will generate power (and income) from that same year on. (That is, for the sake of simplicity we ignore investment lead times.)

New investors New investors can enter the market when an investment opportunity has a positive NPV. New investors are initialised with a random discount rate within threshold values. Because only a limited number of investors in the world can raise the capital needed to invest in these large-scale electricity production units, only one new investor can enter the market each year. Finally, assets may be taken out of operation and removed from the system:

Asset elimination Finally, assets may be taken out of operation and removed from the system when their lifetime is reached.

6.4 Experimental setup and results

In this section, we describe the setup of the various experiments we conducted with the model and we give a brief overview of the results these experiments have produced.

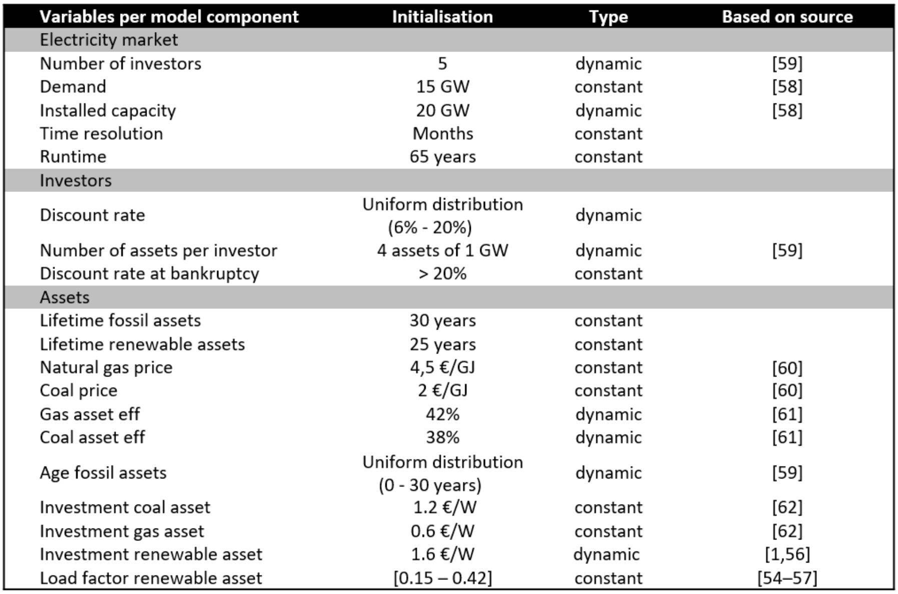
6.4.1 Experimental setup

Four experiments have been carried out around the key exogenous parameters of the model to explore their effect on the dynamics of the electricity market.

- Carbon price development.
- Heterogeneity of investors.
- Variable production patterns of renewable power generation.
- Cost decline of renewable power technology.

We have setup the model to represents the Dutch electricity system, with approximate Dutch generation capacity (20 GW) and demand (15 GW), with 5 investors (the utility companies), and a representative age distribution of assets and resource mix. Power plant efficiencies, resource prices and investment prices of a 1 GW asset are based on order of magnitude numbers from literature and experts (see Table 6.1). The model runs for 780 months representing the years 2000-2065, a realistic time frame for the transition of the electricity system. Carbon prices are modelled to historic prices of the EU-ETS between 2000 and 2015. Power generation by renewables is modelled to realistic power generation by a mix of wind and solar assets (see Section 6.4.2). The learning rate for renewable assets is assumed to be 20% (see Section 6.4.2). In all our experiments we have initialised the model to represent the Dutch electricity system in 2000 [354]. An overview of the most important values at initialisation are given in Table 6.1.

Table 6.1 – Variables of parameters at initialisation



Variables per model component	Initialisation	Type	Based on source
Electricity market			
Number of investors	5	dynamic	[59]
Demand	15 GW	constant	[58]
Installed capacity	20 GW	dynamic	[58]
Time resolution	Months	constant	
Runtime	65 years	constant	
Investors			
Discount rate	Uniform distribution (6% - 20%)	dynamic	
Number of assets per investor	4 assets of 1 GW	dynamic	[59]
Discount rate at bankruptcy	> 20%	constant	
Assets			
Lifetime fossil assets	30 years	constant	
Lifetime renewable assets	25 years	constant	
Natural gas price	4,5 €/GJ	constant	[60]
Coal price	2 €/GJ	constant	[60]
Gas asset eff	42%	dynamic	[61]
Coal asset eff	38%	dynamic	[61]
Age fossil assets	Uniform distribution (0 - 30 years)	dynamic	[59]
Investment coal asset	1.2 €/W	constant	[62]
Investment gas asset	0.6 €/W	constant	[62]
Investment renewable asset	1.6 €/W	dynamic	[1,56]
Load factor renewable asset	[0.15 – 0.42]	constant	[54–57]

6.4.2 Results

Results of four experiments are discussed in the following sections. Graphs in these sections show results from 30 model runs in each of the scenarios; shaded areas show the first quartile on both sides of the median while the thick lines show the median.

Carbon price

Figure 6.4 shows the development of the electricity mix under two carbon price scenarios. In the left graph the carbon price has been kept constant at 6 €/tonneCO_2, the approximate carbon price in the EU ETS program between 2010 and 2015 [63]. In the right graph, we linearly increased the carbon price from 6 €/tonneCO_2 after 15 years with 2 €/tonneCO_2 to 34 €/tonneCO_2 in 2030. After thirty years, the carbon price remains constant till the end of the model run. This carbon price scenario will be our "base case (BC)".

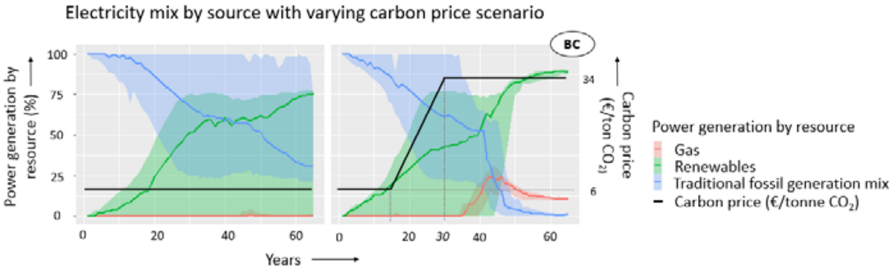


Figure 6.4 – Electricity production in percentage by resource with two carbon price scenarios. Carbon price starts at 6 €/tonneCO_2 at initialisation and is after 15 years, either constant (left) or 15 years linearly increased till 34 €/tonneCO_2, our base case (BC) (right). Graphs show that with an increased carbon price, the variation of outcomes percentages in 2060 is substantially reduced. Model runs represent the years between 2000 and 2065.

Because we are interested in the decarbonisation of the electricity system from the current mix towards a renewable-based energy system and prevent a near-technicality with regards to run-up effects of initialisation, three outcomes parameters are depicted. The blue colour depicts the traditional fossil generation mix as installed at initialisation and shows whether the current mix is sustained during the model run. The red colour depicts the percentage of production delivered by the extra only-gas assets that are added, which contribute to the decarbonisation because of their lower emission intensity. The green colour indicates the mix of renewables in the electricity mix.

Firstly, comparing the two graphs we see that with an increased carbon price, the variation of renewable generation percentages in 2060 is substantially reduced compared to the scenario with no further increase of the carbon price. However, although an increased carbon price reduces the bandwidth of possible pathways from 2050 onwards, there is a very large range of possible pathways in the intermediate period. This is mainly due to the distribution and development of discount rates that the (relatively few) investors use in their financial evaluation and that heavily impacts on the start of the learning curves of renewables.

Secondly, we see in the right graph (with the increased CO_2 price), that the penetration of renewable power generation stalls before full conversion to renewables (the stalling point is at ca. 87%). This emerging 'penetration limit' is higher with an increased carbon price.

Thirdly, the choice between gas and coal assets is based on their relative investment and fuel costs and their subsequent performance in the last year. In all carbon price scenarios, these costs are related to their relative carbon intensity. This is shown by Equation 6.4, where p_{gas} is the profitability of a gas asset, p_{coal} is the profitability of a coal asset, P_{gas} is the price of gas (€/MWh), P_coal is the price of coal (€/MWh), η_{gas} is the carbon intensity of gas (kgCO_2/m^3) and η_{coal} is the carbon intensity coal (kgCO_2/kg).

$$p_{gas} = p_{coal} \longleftrightarrow P_{gas} - P_{coal} = P_{CO_2}(\eta_{coal} - \eta_{gas}) \tag{6.4}$$

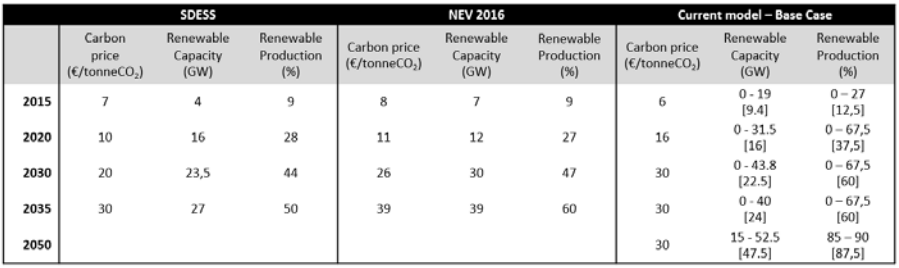
Fourthly, if we increase the yearly carbon price, renewables enter the market earlier. Gas can come back into the system if carbon prices are further increased and electricity from gas assets becomes cheaper than electricity from coal assets.

In Table 6.2 and Figure 6.5 results of our model are compared with two influential scenario studies about The Netherlands: Scenarios for the Dutch Electricity Supply System (SDESS) by Frontier Economics commissioned by the minister of Economic Affairs [355], and "Nationale Energieverkenning 2016" (NEV) by major governmental related organisations (Energie Centrum Nederland (ECN), Centraal Bureau voor de Statistiek (CBS) and Plan Bureau voor de Leefomgeving (PBL) [356]).

The comparison of our model results with mentioned conventional scenario studies shows that results from these studies are in the range of our results. Although these conventional modelling studies show sensitivity analyses in their reports, a notable difference is the large bandwidth of possible pathways in our results.

The average electricity price in Figure 6.5 shows the effect of the penetration of renewable power generation on the average electricity prices over the year. Because renewable assets have near-zero SRMC they decrease the electricity price on average. The increased carbon price however increases the price of electricity

Table 6.2 – Comparison of scenarios of the Dutch Electricity system: Scenarios for the Dutch electricity supply system (SDESS) [355], “Nationale Energieverkenning 2016” (NEV) [356] and Current model, Increased carbon price



	SDESS			**NEV 2016**			**Current model – Base Case**		
	Carbon price (€/tonneCO_2)	Renewable Capacity (GW)	Renewable Production (%)	Carbon price (€/tonneCO_2)	Renewable Capacity (GW)	Renewable Production (%)	Carbon price (€/tonneCO_2)	Renewable Capacity (GW)	Renewable Production (%)
2015	7	4	9	8	7	9	6	0 - 19 [9.4]	0 – 27 [12,5]
2020	10	16	28	11	12	27	16	0 - 31.5 [16]	0 – 67,5 [37,5]
2030	20	23,5	44	26	30	47	30	0 - 43.8 [22.5]	0 – 67,5 [60]
2035	30	27	50	39	39	60	30	0 - 40 [24]	0 – 67,5 [60]
2050							30	15 - 52.5 [47.5]	85 – 90 [87,5]

from fossil assets. Therefore, with variable supply by renewables, electricity prices decrease when renewables produce and increase when they don’t produce. The combined effect makes electricity prices more volatile during the year. With further penetration of renewables between 2040 and 2060, the decreasing effect becomes stronger than the effect of the carbon price and therefore electricity prices on average go down.

If we define the price volatility as the difference between the minimum and maximum electricity price over the period and compare the price volatility in this study with the SSDES study, the bottom graph in Figure 6.5 shows that this price volatility increases with the penetration of renewable power. (The price volatility in the NEV- scenario study is not publicly available.) These results are in line with conventional scenario studies, although with our ABM-approach we can show the bandwidth of possible pathways.

Heterogeneity of investors

To explore the effect of heterogeneity of investors on our model results in Fig. 6 the effect of this heterogeneity on the development of the electricity mix is depicted. While in model runs that are depicted in the right graph all investors have a discount rate of 10%, in the left graph, investors have a heterogeneous discount rate with a uniform distribution between 4% and 20%. In both scenarios, the low carbon price scenario is used as depicted.

The left graph shows that the electricity mix stays constant over time if we assume homogeneous investors: with the given discount rate (at initialisation) and carbon price, investors will not invest in renewable or gas assets. The main difference in the outcome of the model runs is caused by the initialisation of the learning process. Because the learning process is initialised at different moments

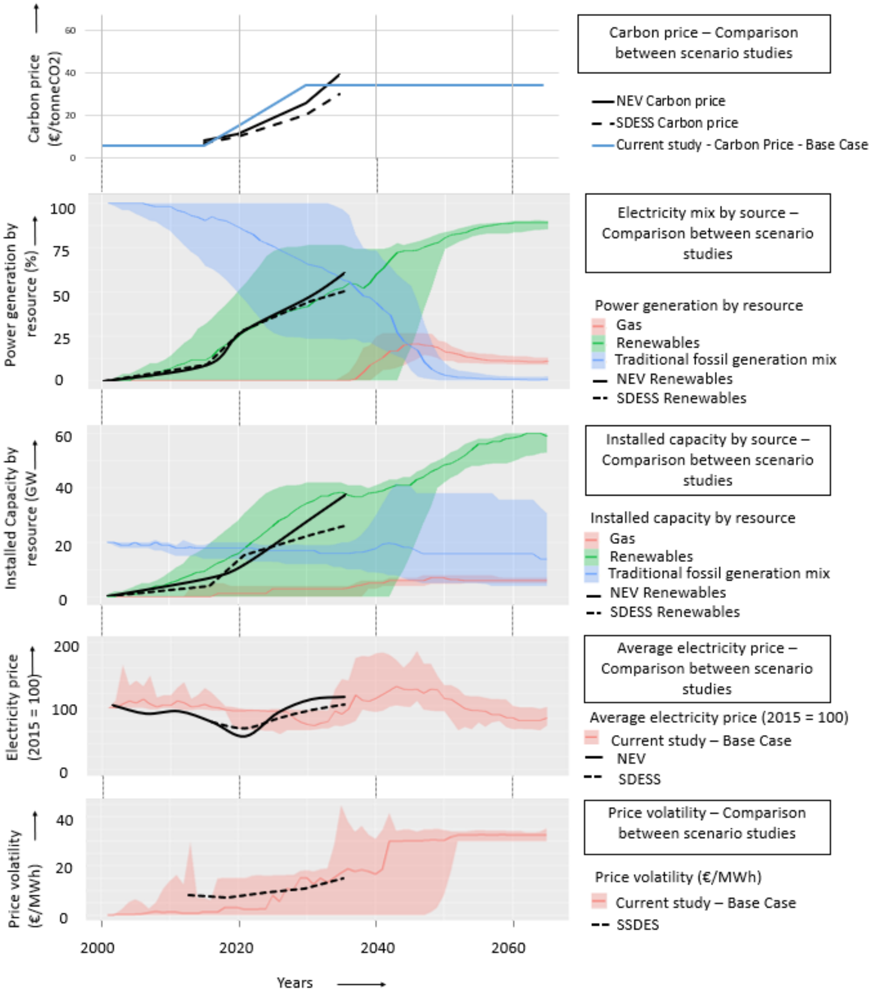


Figure 6.5 – Comparison between current study and two other scenario studies, SDESS and NEV. Graphs depict Renewable power production percentage, Installed capacity, Average electricity prices, and Price volatility in the period 2000-2065. Price volatility is defined as the difference between maximum and minimum electricity prices in a year. Graphs show conventional scenario studies are in range of outcomes of our agent-based model but the current study shows large bandwidth of possible pathway.

due to the heterogeneity of investors, different pathways are taken. If we exclude this heterogeneity, investors will make the same decisions and will basically behave as one.

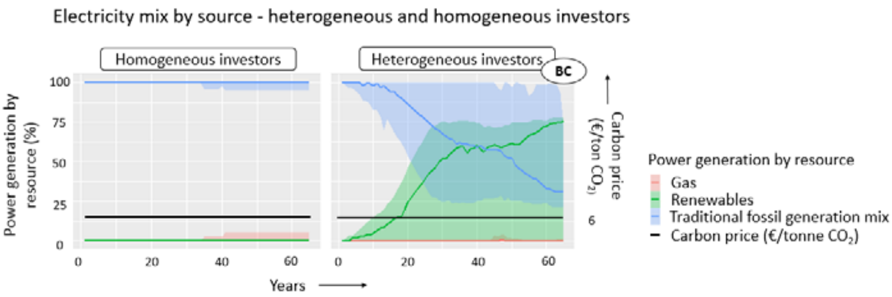


Figure 6.6 – The effect of heterogeneity of investors on the electricity mix. Right graph shows possible pathways with heterogeneous investors, while in the right graph all investors are initiated with the same discount rate.

Variability of renewable energy sources

To explore the effect of the variability of renewable energy sources in our model, we experimented with three electricity generation (load factor) patterns (based on empirical data [350, 351, 352, 353]).

Three power generation patterns are tested: a scenario (i) with no variability and constant production, (ii) with solar variability patterns associated with only renewable solar assets and (iii) with a realistic combination of wind and solar assets (i.e. 70% wind and 30% solar).

Figure 6.7 shows the development of the electricity mix with three different renewable power generation patterns. The left graph shows that renewable electricity is favourable over other sources if it would be able to produce constant over time since they are in front of the merit-order. The middle graphs show the development of the electricity mix if renewable assets would have a full intermittent load factor pattern. This would be the case if all renewable capacity would be supplied by solar assets, as their minimum power output goes to zero in winter. In this case fossil back-up power generation capacity is necessary to be able to fulfil demand. Therefore, a technical decarbonisation limit emerges. Whether this back-up power will be supplied by the traditional mix or by gas depends on the carbon price.

If, on the other hand, a mix between wind and solar assets is used, renewables (a mix between wind and solar assets) would show reduced variability which results in a higher emerging penetration limit as the right graph shows (our base case). This however is not a “technical” limit as production does not go to zero over the year.

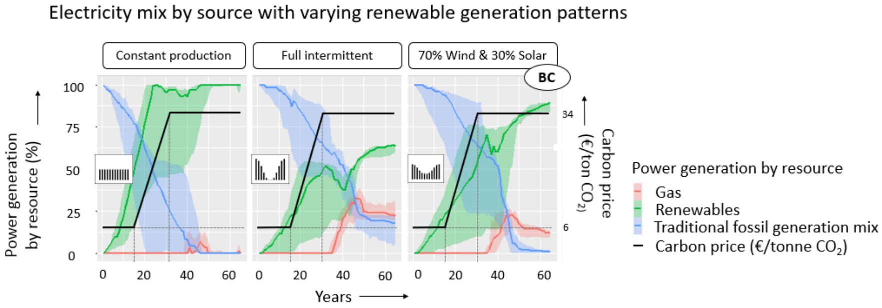


Figure 6.7 – Electricity mix with varying power generation from renewable generation. Left graph shows mix when renewables have no seasonal variability, middle graph shows mix when only renewable generation is only provided by solar (i.e. when electricity production is full intermittent) and right graphs shows mix with realistic production pattern, our base case (BC). Small graphs indicate load-factor pattern.

Substantial cost decline of renewable power generation assets

Steep learning curves of renewable assets in the last decades, has had a large influence on the development of the electricity system. In Section 6.4 we saw that the fact that production does not go to zero over the year suggests that renewable power generation could supply full demand when enough renewable capacity is build. Therefore, we tested if a full renewable system can emerge if we assume that renewable power generation technology will continue to decrease in price.

Figure 6.8 shows three renewable power generation costs curves with three different stabilisation levels, 1 €/W (our base case); 0.75 €/W and 0.25 €/W, which are based on empirical data and scenario studies [312, 352].

Figure 6.9 shows that with substantial further cost reduction of renewable assets, the penetration of renewable electricity mix can be increased. The left-hand graph shows that even a full renewable electricity mix can emerge when costs are reduced sufficiently. This would however require a substantial renewable capacity instalment of ca. 6.5 times the peak load incorporating the load factor pattern of our base case

Profitability of investors

The effect of this penetration of renewable power generation on the profitability of investors is shown in Figure 6.10. The figure shows the average discount rate of investors in the model in 30 model runs with different linear increasing carbon price scenarios. What we see is that increasing the carbon price gradient beyond

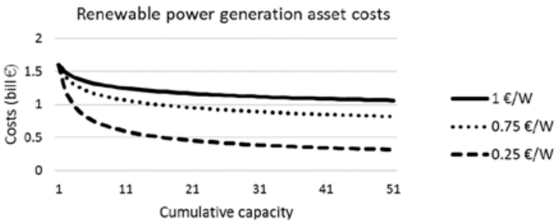


Figure 6.8 – Three scenarios for the cost development of a renewable power generation asset with a one GW name-plate capacity.

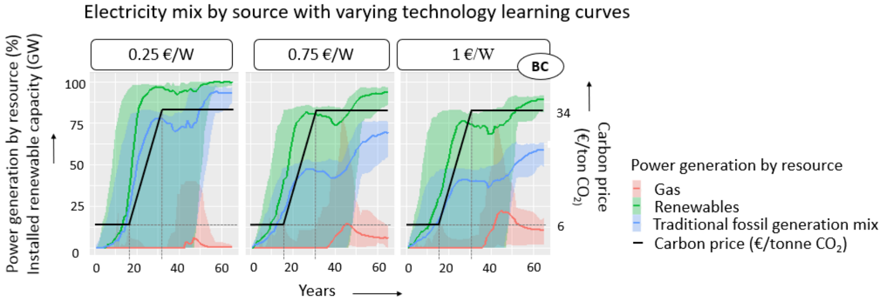


Figure 6.9 – Electricity mix by source with varying technology learning curves. The right graphs show our base case (BC). If, due to technological learning, the investment size of renewable power generation assets decreases substantially, they would be able to supply 100% of power demand. This would require substantial investment in renewable power generation capacity as depicted (in blue).

the technical limit, increases the profitability of investors on average.

6.5 Validation and discussion on model results

6.5.1 Qualitative validation

With our conceptual, simple model we have simulated the development of the electricity mix in the period 2000 till 2065. Because of the high-level, abstract nature of our approach, validation of the model is qualitative and semi-quantitative.We validated our model against the developments in the Netherlands electricity sector between 2000 and 2015.

This period saw an increase in electricity generation by wind and solar from less than 1% in 2000 to 8% 2015 [357], similar to the transition in other Northern

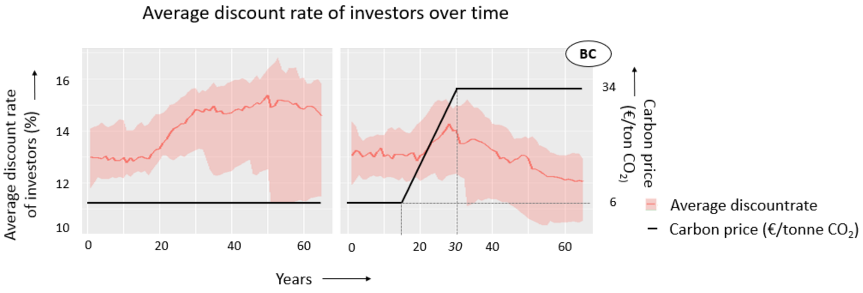


Figure 6.10 – Figure shows the average discount rate of investors over time in the model in 30 model runs with different linear increasing carbon price scenarios. What we see is that increasing the carbon price gradient beyond the technical limit, increases the profitability of investors on average.

Europe countries. Although we are aware that governmental incentives have influenced these developments we argue that we can relate model results to the following historical dynamics: (i) the increase of the share of coal in the electricity mix and gas fuelled power stations being dismantled [321, 358], (ii) on average decreasing electricity prices [359], (iii) increased electricity price volatility [317, 347], and (iv) decrease of the profitability expressed by the Moody rating of large incumbent utilities [360]. Our investor-based model of the electricity sector was able to reproduce these trends as reported in the literature (e.g. [361, 362]).

6.5.2 Discussion on first phase dynamics

A well-known development that we observed in the first phase, which we define here as the phase till approximately 10% of renewables in the energy mix, is the merit-order effect [340, 363, 364]. When coal is cheaper than gas, it will go in front of gas in the merit order which leads to coal assets being profitable and gas assets ultimately being dismantled. The introduction of renewables reinforces this development in two ways; more capacity is added leading to overcapacity, and renewables capacity has a low SRMC and therefore, pushes gas assets further up the merit order [341, 364, 365]. This development causes electricity prices to fall, and volatility to increase. Furthermore, we saw that in the first phase of the transition where renewables enter the market, profitability of existing assets decrease. This caused profitability of incumbent investors to decreases and their discount rate to increase which relates to their Moody ranking.

6.5.3 Discussion on later phase dynamics

Developments that emerge in our model in later phases (in systems with more than 10% renewables in the electricity mix) of the transition lead us to the following observations:

The end-point of the transition is fully determined by the renewable resource. In the absence of storage, the transition is necessarily incomplete as fossil back-up remains needed; a renewable penetration limit of ca. 87% emerges under the assumption that renewable assets consist of a mix between wind and solar power generation (Section 6.4.2). This penetration depth of renewables is correlated with the variability of their generation pattern and by the ‘ultimate’ cost level of renewables. Only with low or moderate seasonal intermittency (typical of wind) and very low cost (more typical of future PV) do renewables without fossil back-up or storage reach 100% penetration, but then only at the expense of significant curtailment.

Market incentives are inept tools for outcome-based policy. While conventional modelling methods show a limited number of possible pathways, our results show that incorporating more realistic investor behaviour results in a large bandwidth of possible outcomes. Therefore, caution should be taken in interpreting conventional techno-economic analyses as we have shown that incorporating heterogeneity and bounded rational behaviour of investors has a large influence on the probability distribution of outcomes (Section 6.4.2). In the current market design, the mere setting of a carbon price will not always result in delivering on decarbonisation goals, to which governments have signed up. Therefore, we conclude that outcome-based policy cannot be solely based on market instruments that rely on perfect rational and perfectly informed agents.

Only with a very large cost decrease of renewable power generation can the electricity system be fully decarbonised and this is only possible with very high overcapacity. Full decarbonisation is possible if a mix between wind and solar assets is used but that would require substantial investment in (over)capacity of renewable power generation assets which is only attractive for investors if the investment size for renewable assets is substantially decreased (Section 6.4.2).

The profitability for investors increases with the carbon price. This is a new and non-intuitive result which we attribute to the effect of the carbon price on the electricity price and inframarginal rents investors receive. It follows logically from the reasoning that if we increase the carbon price, electricity prices increase in periods were fossil generations set the price. Therefore, infra-marginal rents increase and profitability of non-marginal producers increase (Section 6.4.2).

Energy-only markets become increasingly volatile. The implementation of energy-only markets requires political courage to allow price spike to occur to ensure enough investments are made. Such volatility increases with renewables penetration, making the market system, while theoretically "efficient", increasingly unappealing to electricity consumers, both corporate and private; a further reason why liberalized, energy-only markets are unattractive to policy makers and politicians.

Scarcity rent is not a technology neutral mechanism. Because only fossil assets are dispatchable they can use market power to supply demand when supply is scarce. As renewables power generation is non-dispatchable, it cannot use this market power and therefore, the scarcity rent is not a technology neutral mechanism.

6.5.4 Discussion on conceptualisation of decision making process

The conceptualisation of the decision-making process in an agent-based model is key. For this conceptualisation we have deliberately followed a keep-it-simple approach. For now (i.e. the present paper) that meant taking the long-term view (expressed by their heterogeneous discount rate) as sole differentiator between investors; the discount rate is the numeric pars pro toto of the investor's long-term outlook.

We realise fully well that investor behaviour is more complex and that a vast variety of factors contribute to the investor's appetite for new investment [334, 365]. We could think of factors such as preference for types of assets, previous experiences (i.e. company history), outlook for governmental intervention, risk appetite amongst others.

However, we argue that our simplification is justified, given the purpose of our model, since these factors would be impossible to quantify and extremely uncertain, even more so if we look at investment decisions decades from now. Therefore, we have decided not to do so, and solely refer to their long-term view with which we incorporate the mentioned factors.

6.5.5 Comparison to literature

The field of electricity market modelling is an active and fast-growing field of research. In Section 4 we showed how our results compare with influential conventional scenario studies. In general, there is lively discussion on the role of government and markets in the design of electricity markets [315, 317, 319, 324, 336, 338, 341, 362, 366]. What we argue here is that increasing reality in electricity market models (with agent behaviour), has implications for scenario studies and market design.

Some of these issues have been raised in earlier agent-based model studies. Increased volatility is a well-known phenomenon which has been reported earlier (e.g. [365, 367, 319]). Our result that profitability of investors increases with carbon prices has been reported once before but in a different context, i.e. carbon-trading [366].

Moreover, to our knowledge and based on a review of previous literature, there has been no other modelling effort that incorporated the endogenous investment in renewable generation and learning curve dynamics. Secondly, although market power has been analysed previously [316], this study goes further in analysing the effect of market power in energy-only markets.

To summarise, we would argue that within this complex field of research this modelling study has shown a novel conceptualisation which resulted in conclusions that could be supported with a comparatively simple and transparent approach.

6.6 Conclusion

We have shown that an agent-based model of investor behaviour is able to simulate the transition of the electricity system with only a very limited set of assumptions. The simulations bring out key challenges of the transition and link them back to the fundamental parameters of the technologies and investor behaviours.

With this approach - which is transparent, tractable and reproducible - we have been able to simulate the influence of heterogeneous investors in the electricity market. This approach has shown great additional value to conventional techno-economic energy scenarios as it has given us a natural way to think about investors, their decision-making process and its effect on the system behaviour. In future research, we will extend this approach to include storage to resolve the intermittency problem.

Finally, we want to stress the importance of ABM in giving modellers a natural way to think about actors and actor behaviour. The great advantage of the 'keep-it-simple'-approach to agent-based model that we practiced in this paper is that it allows a wide range of stakeholders (not just scientist-modellers) to be actively engaged in the conceptualization of the model and in the discussion of its results. It thereby does full justice to the power of ABM, which is that modellers have a natural way to structure their thoughts about assumed agent behaviour, by allowing meaningful discussion of the agent assumptions with the agents or their representatives. This, we have found, is never a fully straightforward, one-way process but encourages stakeholder engagement throughout the process. In this way, ABM can give insights on problems related to complex adaptive systems such as the energy system as it gives us a tool to encompass essential features of these systems.

Acknowledgements

This research has been part of a Shell-sponsored project on the use of agent-based modelling in the energy scenario domain. The authors want to thank Anne-Sjoerd Brouwer, Burkard Schlange and Lisette de Heiden from Royal Dutch Shell, Emile Chappin from Delft University of Technology, Bert de Vries from Utrecht University and Jeroen Huisman for their insights, helpful suggestions and constructive comments on the draft of this paper.

7

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

Oscar Kraan
Gert Jan Kramer
Igor Nikolic
Emile Chappin
Vinzenz Koning

“Why fully liberalised electricity markets will fail to meet deep decarbonisation targets even with strong carbon pricing”, under review at *Energy Policy.*

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 bounded rational investor behaviour within different electricity market design.

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 the century.

Keywords

Investor behaviour, Electricity market design, agent-based modelling, Storage, Flexibility, Sustainability

7.1 Introduction

The electricity system will play a key role in the energy transition now that zero-carbon energy technologies are becoming attractive to market players [16]. Although often policy makers that try to encourage this transition focus on reaching intermediate goals [368], major scenario studies [210, 15, 7] expect that in the long run a fully renewable electricity system will be key to limit climate warming to less than two degree. This transition has to take place while maintaining the affordability and reliability of the electricity system – the energy trilemma [369].

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 [370]. It will also bring opportunities for businesses and investors. Technological progress, learning by doing and deployment subsidies have made renewable power generation an increasingly interesting investment opportunity for investors [16].

Investors look increasingly into developing wind and solar assets as other options face various constraints: In many regions the potential for hydro-power has largely been exploited [210], 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 [371]. Moreover, the limited resource base for biomass [181] combined with its potential to fulfil other more difficult to decarbonise energy service demands, makes biomass for the electricity system a non-favourable option.

To integrate ever larger shares of intermittent renewable assets in the supply mix, the electricity system will need to become more flexible [372, 373, 374]. Next to increased transmission and demand response, this flexibility can be provided by storing excess supply, profiting from price differences (arbitrage). As battery costs have been steadily decreasing, utility scale storage becomes a realistic investment opportunity [375] and various studies have shown circumstances under which storage investments would be profitable [376, 377, 378, 379, 380, 381, 382, 383].

7.1.1 Three challenges for liberalised electricity markets

Since the 1990's many electricity markets have been liberalised around the world [384]. These liberalised electricity markets are set up to ensure that supply meets demand continuously at least costs [385]. 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 assumes that power generators can be ranked based on their marginal costs in the merit order. Second, current market designs assume that 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, constructed to accommodate the liberalisation are compatible with set targets.

7.1.2 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 (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 [386]: 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" [371], where marginal producers do not earn back their initial investment.

While scarcity pricing in theory should ensure system adequacy [387, 388, 389, 369, 385, 390], 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 [391]. 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 [385] 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 [369, 392], in practice we have seen other market designs being proposed and implemented around the world (especially in Western Europe

[393]). These alternative designs aim to ensure system adequacy while integrating larger shares of intermittent capacity [394, 395, 396, 397, 398], and incorporate various types of Capacity Remuneration Mechanisms (CRMs) in which operators also receive compensation for their capacity and not only for produced electricity [399, 400, 401, 402, 403].

To evaluate whether a) energy-only markets or b) markets with an 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 CRM 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 mentioned 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?

This paper is organised as follows; in Section 7.2 we shortly discuss the literature on electricity market modelling and give more background into agent-based modelling and the way this tool has been used to study electricity markets. In Section 7.3 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 7.4 discusses the experimental setup, the KPIs (reliability, affordability and renewable) and the hypotheses for the different experiments. Results from experiments are presented in Section 7.5 and discussed in Section 7.6. Conclusions and policy recommendations are given in Section 7.7.

7.2 Background

7.2.1 Modelling electricity markets

There are various modelling techniques to analyse electricity markets [56, 320, 404, 405, 323]. Most dominant are optimisation models that have proven to be successful by showing policy makers cost-optimal pathways of the energy transition based on assumptions of rational actors and neoclassical economics [406, 407, 408], often focused on a 100% renewable target [409, 410] and/or utility scale storage [411, 412, 413, 414, 415, 416].

While in general for the design of a fair market the assumption of rational agents is broadly sufficient, in designing electricity markets for the achievement of a specific purpose, analysing of specific market designs needs simulation of more realistic behaviour of investors subject to these rules. 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. [338, 66, 340])

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

Agent-based modelling is to mode 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 interrelated and heterogeneous actors. [417, 418, 419].

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 in 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. [420, 397, 421], some focusing on evaluating CRMs, e.g. [422] (for reviews of these agent-based modelling approaches to electricity markets we refer to [338, 66, 340]). Some studies also have focused on the role of storage, mainly at household level [423, 424, 425, 426] and found its effect on the system to be largely depending on the operating dynamics [426] but that storage at household level can be profitable under certain sets of conditions [423].

To our knowledge, only three agent-based modelling studies integrated the possibility of utility scale electricity storage. Geneouse et al. [427] 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. [428] 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 (renewable, affordable and reliable).

7.3 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, focusing 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 [66, 417], 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 [429], augmenting it with the possibility to invest in utility-scale storage. For a detailed description of the previously model we refer the reader to [429].

7.3.1 System conceptualisation

Investors in the electricity market & flexibility as investment option

Our system conceptualisation starts with the assumption that investors are profit maximising and they evaluate investment opportunities on that basis. How much revenue they expect to gain from an asset is determined by the future electricity price that 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 consist 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 [430] 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 an possible scarcity rent when electricity is scarce.

These scarcity rents tend to follow a curve [385] as depicted in Figure 7.1 and given in Equation 7.1

$$S(t) = \frac{S_{max} - S_{min}}{\alpha - 1} * \alpha^{1/e_s(t)} + S_{min} - \frac{S_{max} - S_{min}}{\alpha - 1} \tag{7.1}$$

In Figure 7.1 the horizontal axes indicates the inverse ratio of potential power generation over demand, given by $e_s(t)$ the excess capacity factor, following Equation 7.2. $G_p(t)$ 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 7.3. $e_s(t)$ is related to the adequacy margin which is simply $1 - e_s(t)$.

$$e_s(t) = \frac{G_p(t)}{D(t)} \tag{7.2}$$

$$G_p(t) = \sum G_c + \sum G_g + \sum G_r(t) \tag{7.3}$$

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 incentivises investments which decreases possible market power 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.

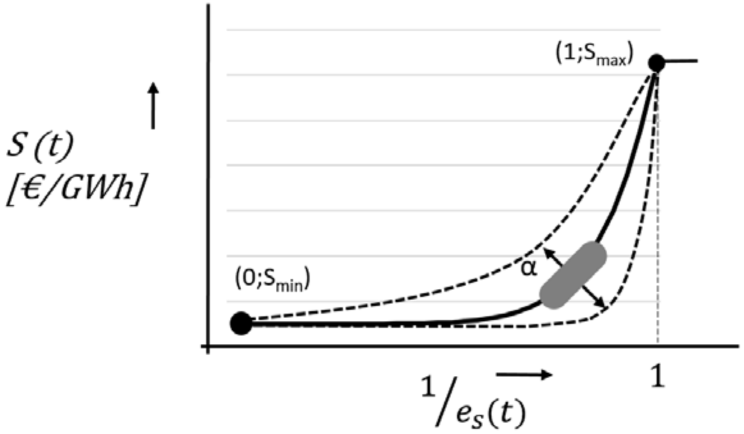


Figure 7.1 – Scarcity rent. Figure shows the development of the scarcity rent ($S(t)$) with regards to the excess capacity factor (e_s), i.e. the supply/demand ratio given in Equation 7.2. α determines the curvature of the curve, S_{min} and S_{max} determine the minimum and maximum value of the scarcity rent subsequently.

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 then could be used at other moments in time. This would add a term $G_s(t)$ to G_p, setting G_p equal to Equation 7.4:

$$G_p(t) = \sum G_c + \sum G_g + \sum G_r(t) + \sum G_s(t) \tag{7.4}$$

Storing excess power and selling it in 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. Further, 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 renewable 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 Figure 7.2 and given in functional from in Equation 7.5. The horizontal axes in this figure depicts the fraction of excess renewable power E_r supply over storage capacity C_s given by e_f in Equation 7.6.

$$F(t) = \frac{F_{max} - F_{min}}{\alpha - 1} * \alpha^{1/e_f(t)} + F_{min} - \frac{F_{max} - F_{min}}{\alpha - 1} \tag{7.5}$$

$$e_f(t) = \frac{\sum E_r(t)}{\sum C_s(t))} \tag{7.6}$$

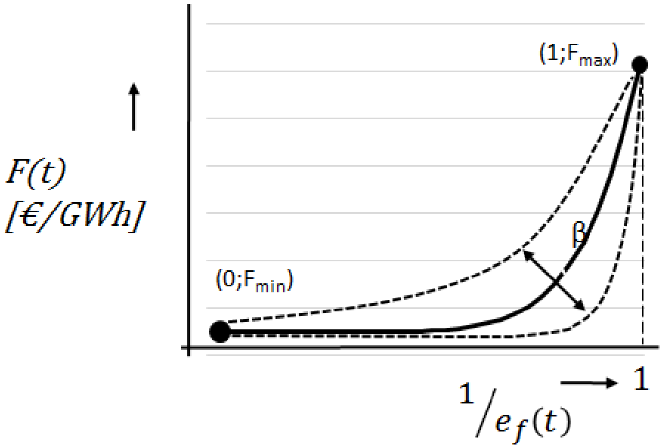


Figure 7.2 – Floor price. Development of the floor price ($F(t)$) with regards to the ratio of available storage capacity and excess renewable production (e_f). β determines the curvature, F_{min} and F_{max} determine the minimum and maximum floor price subsequently.

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 Figure 7.1. 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 incentive to create excess capacity is lacking while it is necessary to fulfil demand in a fully renewable electricity system.

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 7.2). 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 Figure 7.1. In the other extreme case, when no conventional power generation in the system, the ratio $e_f(t)$ is equal to 1 which makes F_{max} equal to S_{max}. However, what is the value of the scarcity rent and floor price when the ratios are just below 1? That's 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 Figure 7.3.

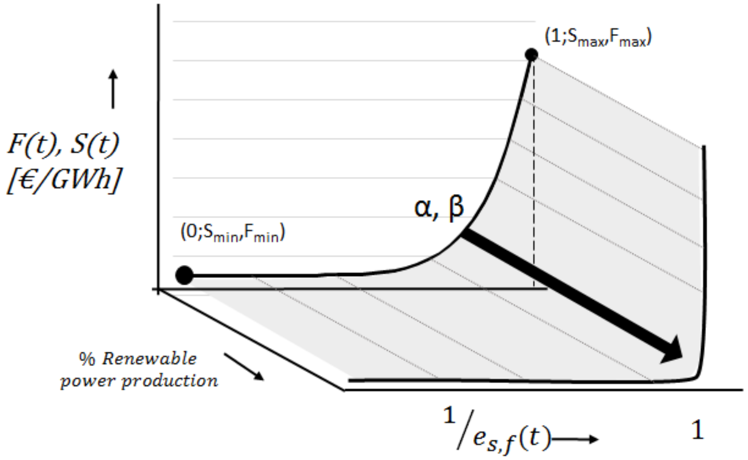


Figure 7.3 – Scarcity rent and floor price development with increasing shares of renewable power production. Figure shows that the curvature of the scarcity rent and floor price increases with larger shares of renewable power production.

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.

A business innovation: storage-backed-renewables

To circumvent this flexibility market, investors could consider to invest in a 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.

7.3.2 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 [349]. For the model description, the ODD protocol [72, 71] has been followed. The model is open source and can be found on-line together with the ODD protocol[1]. The model is extensively verified through single-agent testing, recording and tracking behaviour and multi-agent testing [96]. Here we first briefly discuss the existing model and then describe its extension.

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 investment 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 dynamic: Investors will see their discount rate 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

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[1] https://www.comses.net/codebase-release/d0793525-3d2c-4032-a389-30d8928c3c0d/

in this paper, renewable assets have a variable supply on daily scale, modelled as a cosines function.

In the electricity market, assets produce electricity that satisfies the in-elastic and constant electricity demand. The electricity price is set by the SRMC of the marginal producer plus the scarcity rent discussed in Section 7.3.1.

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 [429] has been modified to be able to integrate storage as asset type. As described in Section 7.3.1, 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 setup 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 7.3.1.

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 7.3.1.

7.4 Experimental setup and hypotheses

To answer the question whether in specific market designs a 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 Figure 7.4. 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 the defined as,

$$\overline{Rel} = \frac{\sum_{y=2071}^{2100} O(y)}{365 * 24 * 30} \tag{7.7}$$

with $O(y)$ the number of hours without outage in year y divided over 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, $\overline{A}$ is the defined as,

$$\overline{A} = \frac{\frac{1}{30} * \sum_{y=2071}^{2100} C(y)}{C_r} \tag{7.8}$$

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 in as,

$$\overline{Ren} = \frac{\frac{1}{30} * \sum_{y=2071}^{2100} R(y)}{D} \tag{7.9}$$

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 [429]. Here we analysed that an insufficient CO_2 price would not lead to success as to 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 7.2) and lack of investment possibilities for flexibility, i.e. storage to be able to integrate intermittent renewables while meeting demand. These finding have been replicated in this study (see Fig 7.10) and further our subsequent analysis has focused on the subsequent four layers.

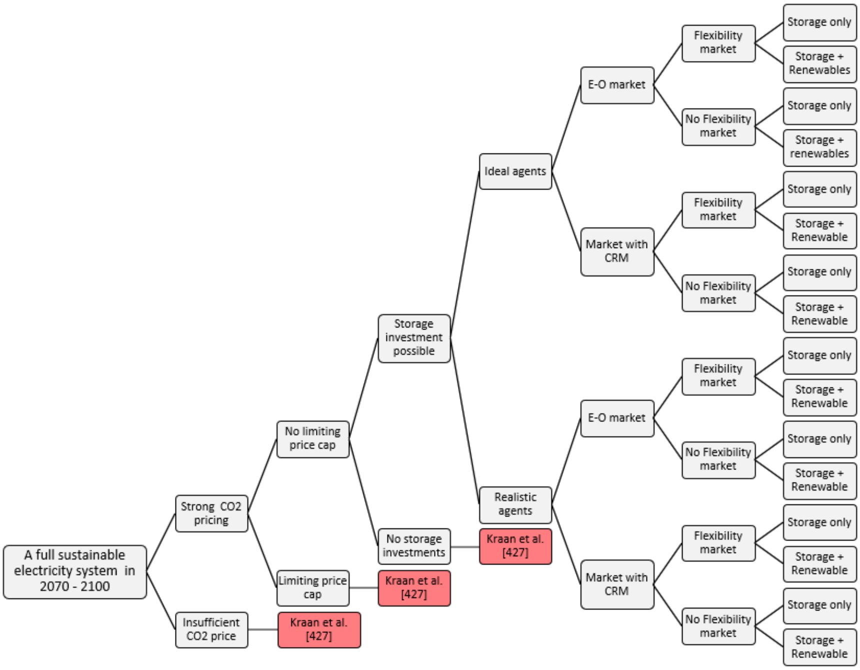


Figure 7.4 – Experiment-tree. Figure shows how the experiments are differentiated starting from our criterion of success given in the far left-hand box.

7.4.1 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 options is positive for a longer period of time parametrised to three years. Furthermore, assets have a specific build-time before they become active, parametrized 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.

7.4.2 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 Figure 7.1 and Figure 7.2 are dynamic, and linearly depended on the percentage renewables in the system as depicted in Figure 7.3. 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 7.3.1.

We expect the investment signal to become discontinuously 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 renewable 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.

7.4.3 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 operates 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.

7.4.4 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 7.3.1.

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.

7.4.5 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 active in The Netherlands. 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 Figure 7.5. The default carbon price level is set at 200 €/tCO_2, a carbon price level that would be sufficient to reach climate goals [7]. Renewable power generation is modelled to represent a utility-scale solar farm and modelled as cosine with a 24 hour 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. The Table 7.1 gives an overview of the important values at initialisation.

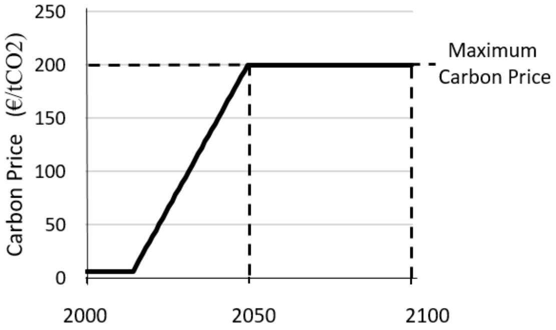


Figure 7.5 – Carbon price scenario. Figure shows the reference CO_2 scenario. In subsequent experiments the Maximum Carbon Price has been varied but the reference year of 2050 is kept the same (see Section 7.5.1).

7.5 Results

The results from the sixteen experiments as discussed in Section 7.4 are outlined in Figure 7.6. 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 7.4 is denoted with green for yes and red for no. The column on the far right shows the experiment result measured against the overall success criterion.

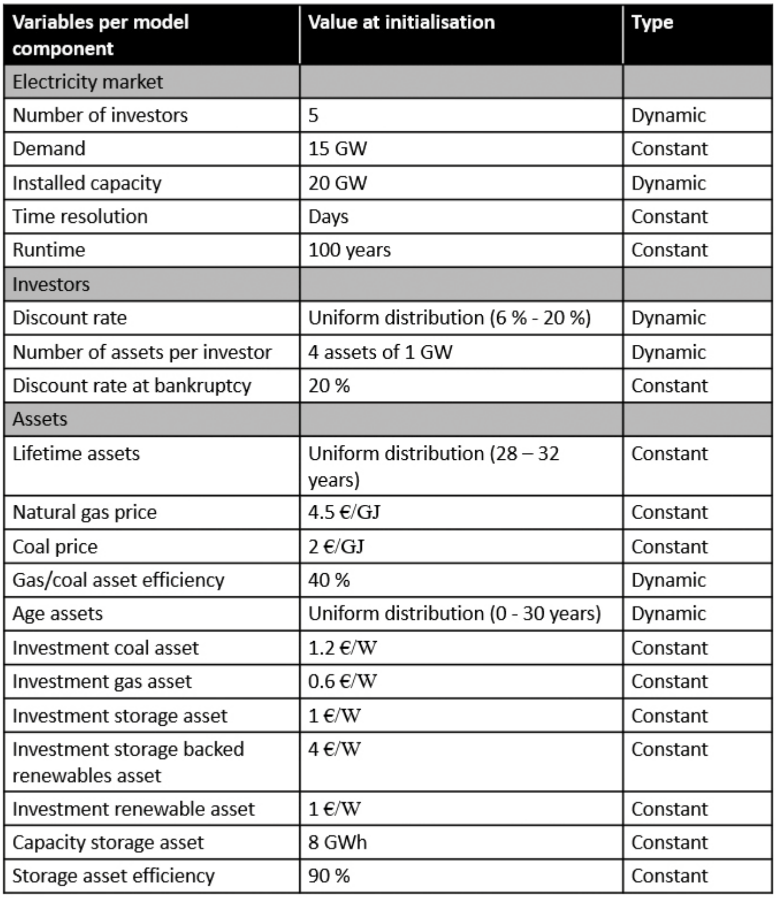
The table in Figure 7.6 shows that most experiments fail on one or several criteria. Only one experiment meets the overall success criterion, experiment 4.1 which will be discussed in more detail in Section 7.5.1

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 scenario does not meet our success criterion, a third scenario was explored. This third scenarios "Realistic market with CRM" shows how the success criterion can be met with an CRM.

7.5.1 Three scenarios

To further explore the three scenarios, these scenarios will be discussed subsequently. Figure 7.7, 7.8 and 7.9 show the time development of the KPIs for

Table 7.1 – Values of variables of parameters at initialisation

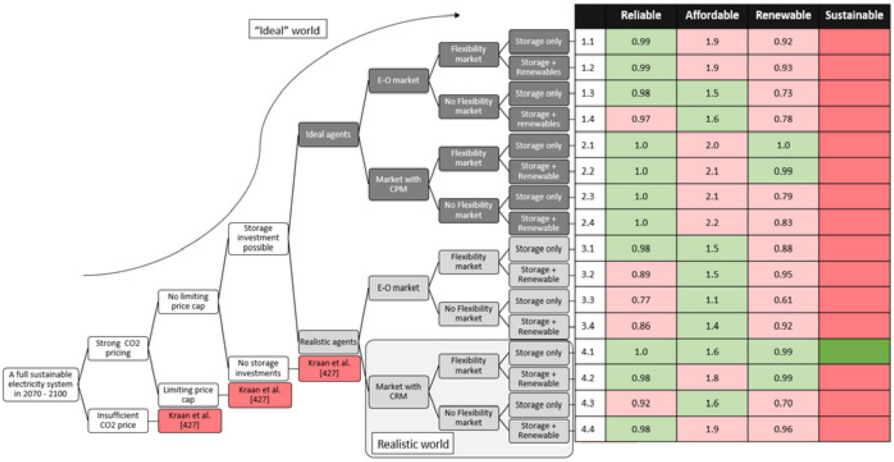


Variables per model component	Value at initialisation	Type
Electricity market		
Number of investors	5	Dynamic
Demand	15 GW	Constant
Installed capacity	20 GW	Dynamic
Time resolution	Days	Constant
Runtime	100 years	Constant
Investors		
Discount rate	Uniform distribution (6 % - 20 %)	Dynamic
Number of assets per investor	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 backed renewables asset	4 €/W	Constant
Investment renewable asset	1 €/W	Constant
Capacity storage asset	8 GWh	Constant
Storage asset efficiency	90 %	Constant

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.

Energy-only market with ideal agents

This scenario 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 Figure 7.7. The erratic behaviour corresponds with our hypothesis given in Section 7.4.2. Since agents, investors as well as assets, behave ideally, i.e. respond immediately to investment signals that create assets



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

Figure 7.6 – 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 "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 7.5.1 and subsequently in Figure 7.7, 7.8 and 7.9.

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 emerges; when there is an incentive to invest, agents immediately invest and remove the investment incentive vice versa. These market fluctuations represent a major element of uncertainty and results in inefficiencies.

Energy-only market with realistic agents

This scenario explores the emerging electricity system in an energy-only market in which (more) realistic investor make investment decisions. Figure 7.8 shows a fully renewable electricity system does not emerge in this scenario. Reliability is of (minor) concern in line with our hypothesis expressed in Section 7.4.1 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.

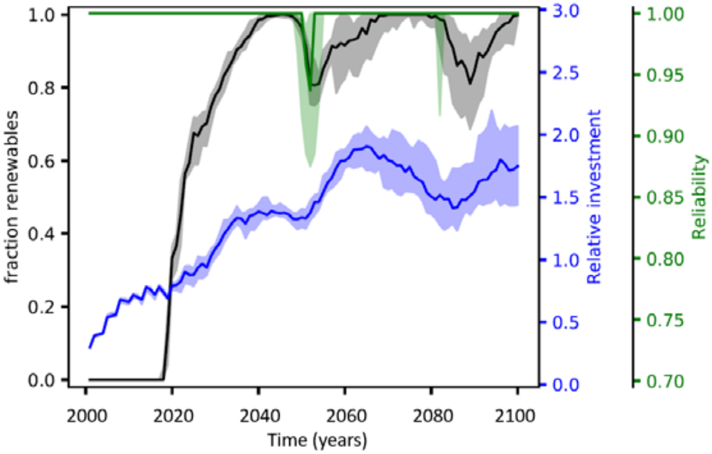


Figure 7.7 – Ideal energy - only market. Figure shows under ideal circumstances and unrealistic assumptions on investors behaviour, targets can be met but investment cycles emerge. The shaded areas show the first quartile on both sides of the median while the thick lines show the median. Figure is based on experiment 1.1.

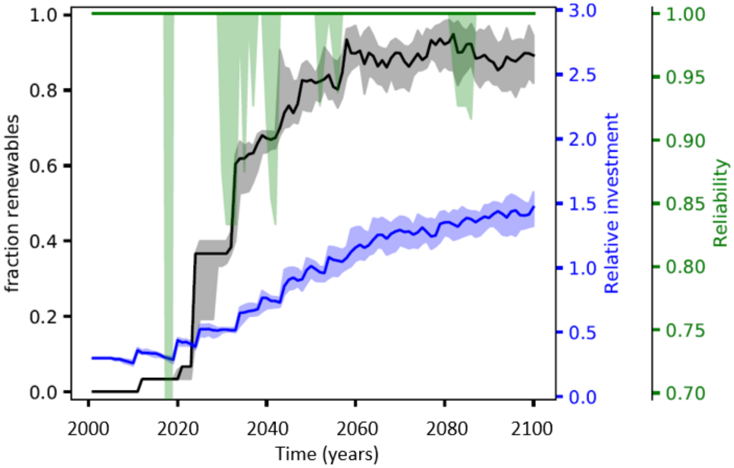


Figure 7.8 – Realistic energy-only market. Figure shows that renewable target cannot be reached in this scenario. The shaded areas show the first quartile on both sides of the median while the thick lines show the median. Figure is based on experiment 3.1.

Market with realistic agents and CRM

Figure 7.9 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 Figure 7.3, 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 7.5.1) 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.

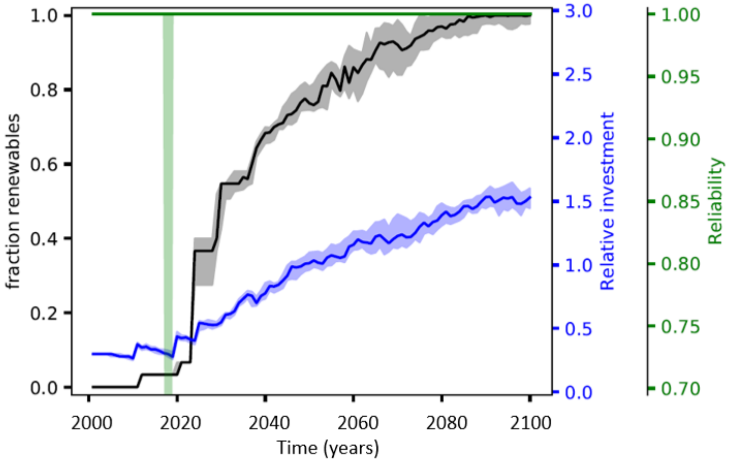


Figure 7.9 – Realistic market with CRM. Figure shows that this scenario can reach the set target on all three KPI, showing it can attain a fully sustainable electricity system in the period 2070-2100. The shaded areas show the first quartile on both sides of the median while the thick lines show the median. Figure is based on experiment 4.1.

Sensitivity to carbon price scenarios

To further test these three scenarios, we explored them under different carbon price developments, see figure 7.10. The maximum carbon price (see Figure 7.5) 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.

Figure 7.10.a shows that in a realistic energy-only market, even with a doubling of carbon prices compared to the experiments depicted in figure 7.6, a fully renewable energy system does not emerge. This suggest that an energy-only market *cannot* deliver a sustainable electricity system.

A fully renewable electricity system *can* emerge from a market with a successful implemented CRM. It would however require a 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%.

Figure 7.10.b shows that reliability requirements can be met in markets with a CRM, while especially in realistic energy-only markets, reliability is of concern. Figure 7.10.c 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 (Figure 7.10.a).

7.5.2 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 is 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 fully 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 cost of the system are increasingly internalised; while the current system heavily depends on fossil resources with low capital/fuel cost ratios, a renewable-based

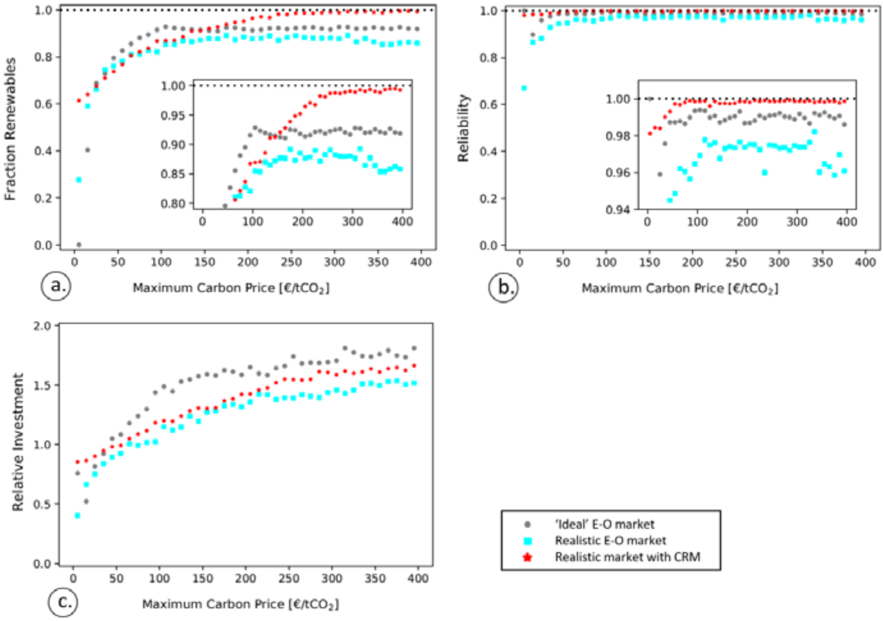


Figure 7.10 – Sensitivity to carbon price scenarios: a. Renewable fraction; b. Reliability; c. Relative Investment. Graphs show that a CO_2 price in the excess of 200 €/tCO_2 is necessary to reach a fully renewable energy system in scenario “Realistic market with CRM”. Graphs also shows that results 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.

electricity system fully rely on invested capital. A sustainable electricity system will, therefore, have substantial higher capital requirement relative to today.

7.6 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.

7.6.1 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 includes, 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.

7.6.2 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, based in 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 7.1). Investing in these technologies, we would argue, would need strong governmental support apart from higher CO_2 prices, supporting our conclusions.

7.6.3 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 [334]. 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.

7.6.4 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 [66].

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.

7.7 Conclusions and policy implications

7.7.1 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 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) an 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, the good news is that technological development in the last decades 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 working of electricity markets in the future. It is our experiences 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.

7.7.2 Policy implications

The policy implications from this study are three-fold. Firstly, this study shows 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, 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, policy makers will need to make use of models that explicitly incorporate investor behaviour, and limit over reliance 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

This research has been part of a Shell-sponsored project on the use of agent-based modelling in the energy scenario domain. The authors want to thank Jeroen Huisman, Anne-Sjoerd Brouwer, Burkard Schlange and Chris Laurens for their helpful suggestions and constructive comments.

8

Conclusions, Recommendations & Reflection

8.1 Research context, focus and approach

This dissertation contains a number of different approaches aimed to further our understanding of the unfolding energy transition. In this chapter the conclusions of more than four years of my research endeavours on the emergence of the energy transition are brought together. We will present the main conclusions in Section 8.2 and give recommendations for policy makers in Section 8.3 and for business decision makers in Section 8.4. We also will reflect on our findings in Section 8.5. Before we describe our conclusion we will shortly recap the research context, focus and our research approach in Section 8.1.

8.1.1 Research context and focus

Climate change is one of the largest challenges facing humanity. As the energy system is the single largest contributor to the emissions of greenhouse gases, predominantly the result of burning fossil fuels, the world's society will have to engage in a transformative change of the energy system; an energy transition. This transition will need to emerge from the interaction between social actors, the economy, technologies and the ecosystem. This makes the transition of the energy system a complex problem and an intellectual challenge. Against this background this thesis has explored the question:

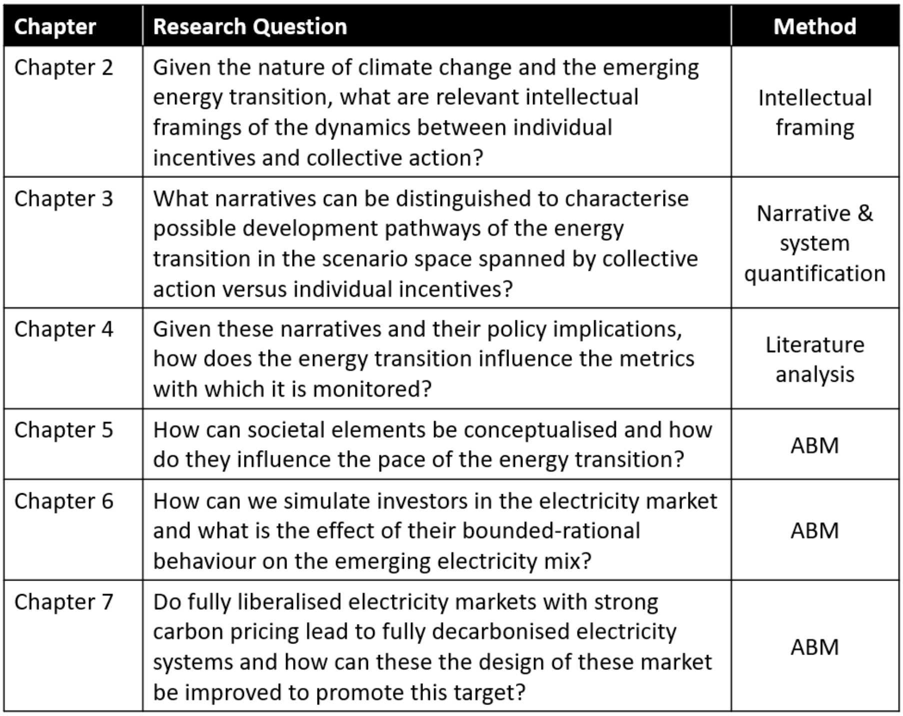
How do individual incentives and their interaction influence the path and the pace of emergence of the energy transition?

We can never hope to answer this question in its full form but this question did guide our research endeavours and results have provided insight into various aspects of this question. Our analysis of the the nature of the problem of climate change and the identified relevant frameworks in this context (see Chapter 2) has led to a sequence of more specific questions which have been addressed in Chapter 3 to 7, see Table 8.1.

Simulating interacting actors as computer entities, "agents", has given us the means to explore the dynamics of actor interactions. The application of a relative new modelling method "agent-based modelling" with which these agents can be simulated, has given additional tooling for the quantification of narratives of the energy transition; agent-based modelling facilitates the interplay between two key aspects of scenario making: story telling and quantitative modelling.

Insights obtained by simulating realistic actor behaviour have provided insight in the dynamics between individual incentives and collective action. Model results have provided new insights that can be used to put current, and possible future developments of the unfolding energy transition into perspective. Ultimately the

Table 8.1 – Research questions by chapter. Right-hand column indicates the used research method.



Chapter	Research Question	Method
Chapter 2	Given the nature of climate change and the emerging energy transition, what are relevant intellectual framings of the dynamics between individual incentives and collective action?	Intellectual framing
Chapter 3	What narratives can be distinguished to characterise possible development pathways of the energy transition in the scenario space spanned by collective action versus individual incentives?	Narrative & system quantification
Chapter 4	Given these narratives and their policy implications, how does the energy transition influence the metrics with which it is monitored?	Literature analysis
Chapter 5	How can societal elements be conceptualised and how do they influence the pace of the energy transition?	ABM
Chapter 6	How can we simulate investors in the electricity market and what is the effect of their bounded-rational behaviour on the emerging electricity mix?	ABM
Chapter 7	Do fully liberalised electricity markets with strong carbon pricing lead to fully decarbonised electricity systems and how can these the design of these market be improved to promote this target?	ABM

insights from these studies can be used to support strategic decisions making by public as well as private actors and to anticipate the consequences of their (future) decisions.

8.1.2 Research approach

Given the complex nature of the problem of climate change, our research approach was required to accommodate several aspects: i) the scale and nature of the problem of climate change (with regards to time and space), ii) facilitate stakeholder engagement, iii) tackle the challenges of agent-based modelling and iv) bridge the gap between story tellers and modellers, between scientist and politicians and between scientists and decision makers in business.

This has lead us to our general research approach that has focused on finding a minimal representation of the relevant system elements with a minimum set of assumptions that still did right to the complexities of the problem. Trying to understand how the energy transition will emerge brings us to the border of science as uncertainties are large, decisions stakes are high, choices have to be made and values are in dispute. Therefore, this research approach can be seen as example of post-normal science. It has given us a perspective with which we could explore the added value of agent-based modelling.

8.2 Conclusions

Conclusions from our research endeavours were generated in research projects that covered various aspects of our research question. Presented models and analysis were based on the theoretical background and intellectual framings which were presented in Chapter 2. In this chapter we presented specifically selected frameworks relevant to our research question. These frameworks guided the conceptualisation of actor behaviour in agent-based models. Perspectives from economics, psychology and ecology gave background to the dynamics between individual incentives and collective action.

Especially the common pool resource dilemma has been shown to effectively highlight the conflict between individual incentives and collective action in the context of climate change. The dilemma is in the case of climate change however especially challenging because of three aspects; the intergenerational time scale, international scale and the unpredictability's of the consequences of climate change. Insights from psychology and sociology have shown several elements that separate human behaviour from the assumptions of neo-classical economics; education, world views and bounded rational behaviours led to insights into the decision-making structures of realistic actors that were used in several simulation models.

Insights generated in the various research projects, ordered by chapter, will be discussed subsequently:

Chapter 3: Optimistic assumptions on technology development of solar fuels open a new narrative of how the demand for fuels with net zero emissions can be met. But at the same time that is a risky bet. Two narratives of the energy transition gave us a new perspective on the possible pathways of the energy transition across the century. *All Renewable* and *Balancing Act* show which possibilities society has to tackle climate change while supplying an increasing energy demand. Both narratives start from the notion that today the energy transition progresses with increased energy efficiency, the build-out of electric renewables and sector electrification. However, these developments will run into limits as there are sectors that are hard to electrify (aviation, shipping, heavy road transport, and high temperature process industries). Therefore, a demand for hydro-carbon based fuels will persist. That demand could either be met by balancing remaining emissions with negative emissions or by producing a new type of renewables-based fuel, a Solar Fuel.

This chapter showed what would be necessary for these options to become reality. In *Balancing Act*, the world's society would need to overcome the collective action problems currently keeping (bio-energy) carbon capture and storage from large scale deployment and large new distribution and transmissions infrastructures from roll-out. However, a bet on technology alone will ultimately lead to a bet on the development and production of solar fuels. These hydrocarbon fuels require air-abstracted CO_2, renewable electricity, water electrolysis (producing hydrogen), CO_2 activation, and finally synthesis of the hydrogen and activated CO_2. If optimistic assumptions on technology development become reality, these net-zero CO_2 emitting fuels, could become affordable (at a price of 200$/bbl) which could lead to large-scale market-led deployment. The fact that individual (commercial) incentives would stimulate the development of these solar fuels, sets *All Renewables* aside from *Balancing Act* which would require more government involvement to overcome the collective action problems associated with *Balancing Act*.

Chapter 4: As energy generated from renewable and non-combustible resources gains a significant share of the energy mix, Total Primary Energy and Electricity Generation Capacity, key metrics for energy policy, have become ambiguous and potentially misleading. Designing policy and building models of the energy transition requires thorough understanding of energy metrics, the building blocks of policy targets and energy scenarios. The ongoing decarbonisation has caused energy derived from renewable and non-combustible resources to become more prominent. This has caused shares of resources with abundant availability but limited instantaneous availability to increase. This chapter showed that the ongoing electrification of the energy system combined with the decarbonisation of the electricity system has caused the current set of energy scenario metrics to become unrepresentative. Two key primary energy metrics are affected: Total Primary Energy and related indicators Energy Efficiency and Energy Intensity, and Electricity Generation Capacity.

The primary energy equivalent for non-combustible energy sources such as wind and solar are not widely measured and not consistently defined. The resulting various statistical representations of their primary energy equivalent with the use of accounting methods results in ambiguity. Similarly, intermittent renewable power generation has various capacity factors which makes interpretation and steering on Electricity Generation Capacity ambiguous.

Taken together we conclude that these metrics have become unrepresentative, difficult to interpret and ultimately misleading. This is problematic as we showed that these metrics can steer climate policy and investment decisions based on statistical artefacts, rather than valid representation of the energy system.

To overcome these problems modellers are recommended to be explicit and transparent on their accounting method to calculate the primary energy equivalent for non-combustible energy sources and to highlight possible consequences of the used approach such that conclusions based on statistical artefacts are prevented. Further recommendations include the suggestion to focus on Total Final Consumption as this metric is free of the mentioned definitional ambiguity. With regards to Electricity Generation Capacity the recommendation is given to put them in perspective by accompanying them with the expected capacity factor or involved size of the investment. This would help putting this figures in context and facilitate a more profound understanding.

Chapter 5: The societal dynamics of climate change and the energy transition suggests that the energy transition can be seen as a critical transition. With the application of agent-based modelling the influence of the societal dynamics on the pace of the energy transition can be usefully explored. Critical transitions are transition in which fast and rapid system changes are triggered by relatively small changes in external conditions. In this chapter the concept of critical transitions is applied to the energy transition to explore how social dynamics around the energy system influence the pace of its transition. We integrated the concept in an agent-based model and explored various social aspects of complex problems such as the effect of leaders, the heterogeneity of actors, and networks that form local communities.

The two key findings; i) the importance of local communities and ii) leaders can both encourage and discourage the energy transition; a finding that nuances existing literature on critical transitions. A reflection of the chosen approach, revealed general notions about conceptual models: these models provide useful tools to discuss the dynamics between individual incentives and collective behaviour.

Chapter 6: Effective policy design to decarbonise the electricity system requires the design and evaluation of these policies based on the realistic behaviour of agents. This is enabled by agent-based modelling. The transition of the electricity system will be key to the transition of the energy system as a whole. In this chapter the influence of the design of the liberalised electricity market on the emerging electricity mix is shown by simulating realistic behaviour of investors in this market.

The chapter showed that simulating the "realistic behaviour" of agents helps designing and evaluating policy for a specific (non-economic) target, in this case decarbonisation of the electricity system. Agent-based modelling gives an additional tool for this policy development process. It gives policy makers the chance to design and evaluate the effect of their policies based on simulations of the realistic behaviour of agents subject to these policies. Chapter 7 has shown examples of the insights that can be obtained by using this method.

Chapter 7: Fully liberalised electricity markets will fail to meet deep decarbonisation targets even with strong carbon pricing. The full decarbonisation of the electricity system will require increased flexibility to incorporate increasing shares of intermittent, non-dispatchable electricity generation such as electricity derived from wind and solar radiation. By simulating investor behaviour and building on findings presented in Chapter 6, this chapter explored whether current electricity markets designed as liberalised markets in combination with strong carbon pricing will incentivise investors to invest in the required mix of storage and renewable electricity generation assets to attain a full renewable, reliable and affordable energy system in the second half of the century.

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 (and even further to 400 €/tCO_2), these markets give insufficient stable investment signals for realistic investors to invest in a sustainable electricity system. Possible alternatives for these fully liberalised markets, in which the capacity requirement of the system is institutionalised via capacity remuneration mechanisms, have been explored and we conclude that they provide a credible solution direction.

8.3 Recommendations for policy makers

Research presented in this dissertation has had several implications for policy design.

Firstly, policy makers should be aware of the nature of the problem of climate change. The problem of climate change is a common pool resource dilemma that is especially challenging because the consequences of climate change are unpredictable over time (intergenerational) and space (global). This makes studying the emergence of the energy transition an example of post-normal science. In this perspective on science it is an illusion that scientists can speak truth to power. The fact that scientists can't give a definitive answer to policy makers, makes that these decisions are de facto political decisions (for which politicians should not shy away). To make these decisions as well informed as they can, various perspectives should be incorporated in policy design discussions. In this dissertation agent-based modelling is presented as an additional tool for scenario development as it complements insights from other methodologies.

Policy makers need to balance providing the most efficient, cost optimal market design structure based on a fair set of rules for all actors in liberalised markets with achieving a specific outcome. In the case of climate change this is not solely e.g. cost minimisation based on rational agents, but should be related to total carbon emissions and realistic actor behaviour. Therefore, policy makers should increasingly rely on the simulation of realistic actor behaviours to evaluate the outcome of specific policy measures. This means that policy makers should increasingly focus on models that explicitly incorporate realistic behaviour of agents, and limit over-reliance on models that focus on lowest (system) costs, assume perfect information, perfect rationality and homogeneous actors. This dissertation shows that embracing these complexities of the energy transitions gives a different and richer perspective on the possible development trajectories of the energy system.

Our perspective highlighted the following specific policy design recommendations:

Carbon-neutral fuels need to be considered Although the share of electricity in the energy mix will rise substantially (from the current 20 % to approximately 60%), demand for carbon-based fuels will persist. How can that demand be met while eliminating the associated emissions? The traditional narrative of the major outlooks (such as the IPCC) relies on the policy enforced deployment of large scale carbon capture and sequestration, often in combination biomass. But recent technology developments have opened a new narrative. This narrative relies on the integration and further development of new technologies, one of which is Direct Air Capture of CO_2. This could lead to market-led production of a zero-carbon fuel, a solar fuel. Given these two pathways of the energy transition it would be prudent policy to stimulate the traditional narrative of trying to overcome the collective action problems as well as stimulate market development of solar fuel production. (Chapter 3).

Effective climate change policy design requires focusing on the right (energy) metrics As the overall objective of climate policy is to decrease greenhouse gas emissions, policy targets should be expressed in metrics that support this target. Moreover, policy makers should be aware of the different accounting issues surrounding the key energy metrics Total Primary Energy, Energy Efficiency, Energy Intensity and Electricity Generation Capacity. Policies goals which are based on statistical artefact should be prevented and therefore we recommend to shift focus from primary energy (Total Primary Energy) to energy consumption (Total Final Consumption). (Chapter 4).

Social dynamics influence the pace of the energy transition Policy makers should be aware that actors in the real world are bounded rational and may react differently to policy measures than rational, idealised actors would do. Their social dynamics influence policy outcomes and therefore policies should be developed around these insights. Moreover, these insights can be used in policy design, often referred to as *nudging*. (Chapter 5).

Electricity markets need a re-design Electricity markets need to fully decarbonise to meet internationally agreed goals to global warming. To facilitate this full decarbonisation while maintaining affordability and reliability, policy makers will have two tasks. Firstly, they need to shift their focus from the improvement of energy-only markets to developing appropriate capacity remuneration mechanisms. Effectively designed capacity remuneration mechanisms can give investors the right incentives to invest in the combination of renewable electricity generation and flexibilisation of the electricity system to be able to absorb these intermittent sources. Secondly, 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. (Chapter 6 and 7).

8.4 Recommendations for business decision makers

Research presented in this dissertation has had several implications for business decision makers:

Support strategic decision making with model development. Model development should be an essential part of the business decision making process. Although it is easy to criticise models and their outcomes as they will always only reflect a part of reality, model development as part of strategic decision making, forces stakeholders to engage in a structures approach and critically evaluate assumptions and outcomes.

Be involved in the model development process. Similar to policy makers, business decision makers from time to time find themselves in situations where the stakes are high, values in dispute and decisions urgent. In those cases, it is easy to outsource the process of decision making to a modelling team that has to come up with an answer. However, our experience has shown that the insights from modelling studies often are generated in the model development process. Therefore, to create the most value from modelling studies in general, is to engage in this modelling process.

Create an environment that enables transdisciplinary knowledge sharing. For stakeholders to be able to engage in this modelling process requires a transdisciplinary environment. Our experience is that agent-based modelling in general, and our modelling approach especially, is well suited to enable this transdisciplinary environment and bridge the gap between modellers and stakeholders. Agent-based modelling gives a natural way to think about actors, their interactions and the system emerging dynamics and an approach focused on a minimal representation of these agents enables stakeholder engagement, transparency, reproducibility and tractability.

Apply agent-based modelling to support strategic decision making. Many corporate models used in day-to-day business are optimisation models, think of supply-chain optimisation, logistics optimisation, operation optimisation etc. Also in scenario planning, scenario developers tend to focus on technological and economic developments and base their analysis on learning curves and empirical validated relationships between key drivers. Strategic decision making however, involves developing a plan to achieve a certain goal in the face of uncertainty, often caused by human reflexivity. Agent-based modelling is perfectly suited to simulate these actors interaction in a business environment and evaluate strategic choices. It gives scenario developers a tool to explore the emergent collective behaviour and quantify narratives of actor behaviours and their interaction.

8.5 Reflection

8.5.1 On modelling of the energy transition

As human decision making is complex, models that try to simulate this decision making process in the energy domain are subject to large uncertainties. Simulating the emergence of a transition inherently requires conceptualising agent behaviours which are different from the empirical validated historical decision making processes of the past. Simulation methods such as agent-based modelling face modellers therefore with a continuous quest for plausible, believable agents behaviours.

The model conceptualisation of the (uncertain) actor behaviours can lead to outcomes which are straightforward reflecting input assumptions. However, conventional models eliminate this uncertainty by relying on rational agents.

Relying on rational agents which in reality are *bounded* rational can create a sense of certainty that is illusive.

This aspect I encountered in a project where I modelled consumers deciding between mitigation and adaptation to climate change based on dynamic costs expectation of mitigation and adaptation efforts [431]. This modelling exercise illuminated this problem; straightforward quantifying of a narrative faces the danger of getting results that are straightforward and directly reflecting the assumptions put in the model. However, this still can have value as illustration of a particular narrative facilitates discussions between stakeholders on assumptions and dynamics.

In the projects described in Chapter 6 and 7 of this dissertation, actors were chosen with a plausible behavioural drive but who are heterogeneous and bounded rational; investors in the energy system. We found ourselves more comfortable with their decision making process as their decision making process is relatively straightforward; in its most rudimentary form investors have a commercial drive. Results from these models have highlighted interesting aspects of the electricity market and its transition (which are described in Chapter 6 and 7).

The research project described in Chapter 5 led us to more fundamental epistemological questions on the value of the application of agent-based modelling to the energy transition. It resulted in the characterisation of our approach as post-normal sciences as described in Chapter 2 and Chapter 5. It also highlighted the importance of modelling for insight instead of for numbers reflecting the perspective on the value of modelling as a means to find clear and explicit reasoning.

Valuing the application of agent-based modelling requires modesty on the requirement to be truth-finding. This challenge is equally challenging for conventional modelling methods and are related to modelling studies in general; “All models are wrong, some are useful” [432]. This highlights that the value of modelling in general is most often in the insights its creates, often generated in the modelling development process.

We have shown that agent-based modelling has an essential role to play in providing new perspectives on the way societal actors will, can and must tackle the problem of climate change. That role can be summarised in the following three aspects:

1. **Quantifying story lines of actor behaviour provides tools to improve communication between researchers and stakeholders.** With the application of agent-based modelling a story line can be illustrated and structured giving the means to discuss assumptions and outcomes with a variety of stake holders, even without generating directly *new* insights from the modelling exercise itself.

2. **Quantification via conceptualisation and simulations brings the means to analyse this actor behaviour in a structured way.** Agent-based modelling forces researchers to think about actor interactions and structure them in model conceptualisations. This in itself can generate insights. Dynamics emerging from these agent behaviours can be further explored and analysed to generate additional insights. Vice versa agent interaction can be further analysed in relationship to the emergent dynamics of interest.
3. **Quantification enables the use of computer power to simulate and analyse actor dynamics and thereby shed light on emergent behaviour in complex systems.** Simulating actor behaviour in computer models expands the possibilities to calculate the outcomes of their complex interactions.

8.5.2 On the emergence of the energy transition

Apart from these insights on the value of modelling, and agent-based modelling specifically, more than four years of dedicated research on the emergence of the energy transition has highlighted several aspects.

An inclusive energy transition Given the nature of climate change, its complex and common pool resource character, this transition will need to be inclusive. Inclusive here means that all actors and all sectors need to be on board of this transition. Not one energy consuming sector can be disregarded in tackling climate change, all sectors will need to transition and decarbonise. Although some sectors may be easier to decarbonise than others, to get to net-zero emissions within the coming decades, all sectors will need to contribute. This means that for example, international air-travel, so far often disregarded given its international character and the few technological options it has to decarbonise, will need extra attention. It also means we cannot disregard any energy carrier. Although there is often a lot of attention given to the electricity sector, it currently only provides one-fifth of our energy demand. The fuels-part of energy sector therefore should not be forgotten.

Inclusive also means all countries, especially the large contributors, need to be on board. So far, the international negotiation architecture of the United Nations, the UNFCC is our best hope to achieve further international agreement to limit climate change. Although such negotiations, unilateral or at national level between various stakeholders (such as the Dutch *Energie Akkoord*), sometimes only achieve seemingly slow progress, the energy transition is such a wide ranging, all-encompassing system change, they are needed for a successful energy transition. Inclusive however does not mean that individual actors, being countries, businesses or individuals should wait on others. There are plenty economic, strategic, moral and ethical reasons to individually transition the energy system. Therefore, we need brave politicians that do not shy away for de facto political decisions on the future of the energy system.

Balancing efforts Actors in this energy transition will need to balance their efforts on current and future problems. The United Nations now have articulated 17 Sustainable Development Goals [433], which means this is not an obvious task. To achieve such a balance, it is easy to get distracted by trendy, fashionable issues such as the circular economy. The other extreme is focusing on climate change and forgetting the growing energy demand of a growing world population. Decision makers should keep their eye on the ball and be aware of the overarching stresses climate change is treating our human society with while balancing the current needs of the world population. Sometimes efforts on subjects such as to decrease noise levels near airports, or limit air pollution can be a double edged sword that also limits climate change. But decision makers should always be aware their decision take effect on the right problems.

Take your own responsibility Actors (individuals, politicians, businesses) are easily caught to be pointing fingers at others for being responsible to take further steps to transition the energy system. Consumers pointing at cooperations, businesses pointing at their shareholders (often pension funds) which point at their obligation to their pension receivers bringing us back to square one. The same holds for by citizens elected politicians. The point is that all these actors have their responsibility. An important and guiding principle articulated by Mahatma Gandhi is still true: “you must be the change you want to see in the world”.

9

Samenvatting

9.1 Onderzoekscontext, focus en aanpak

Dit proefschrift bevat een aantal verschillende benaderingen om inzicht te geven in de zich ontwikkelende energietransitie; intellectuele kaders zijn beschreven, mogelijke paden zijn gesuggereerd en bevindingen uit simulatiemodellen zijn gepresenteerd. In dit hoofdstuk wordt een korte samenvatting gegeven van meer dan vier jaar van mijn onderzoek naar de zich ontwikkelende energietransitie. Bovendien bevat dit hoofdstuk een reflectie op dit onderzoek en worden aanbevelingen voor beleidsmakers en bedrijfsvertegenwoordigers gegeven.

9.1.1 Onderzoekscontext en focus

Klimaatverandering is een van de grootste uitdagingen voor de mensheid in haar huidige vorm. Aangezien het energiesysteem de grootste bijdrage levert aan de uitstoot van broeikasgassen door het gebruik van fossiele brandstoffen, zal de samenleving moeten werken aan een transformatie van het energiesysteem; een energietransitie. Deze transitie zal moeten voortkomen uit de interactie tussen sociale actoren en hun drijfveren, de economie, technologieën en het ecosysteem. Dit maakt de transitie een complex probleem en niet alleen een technische, maar ook een intellectuele uitdaging. Tegen deze achtergrond heeft dit proefschrift de vraag onderzocht:

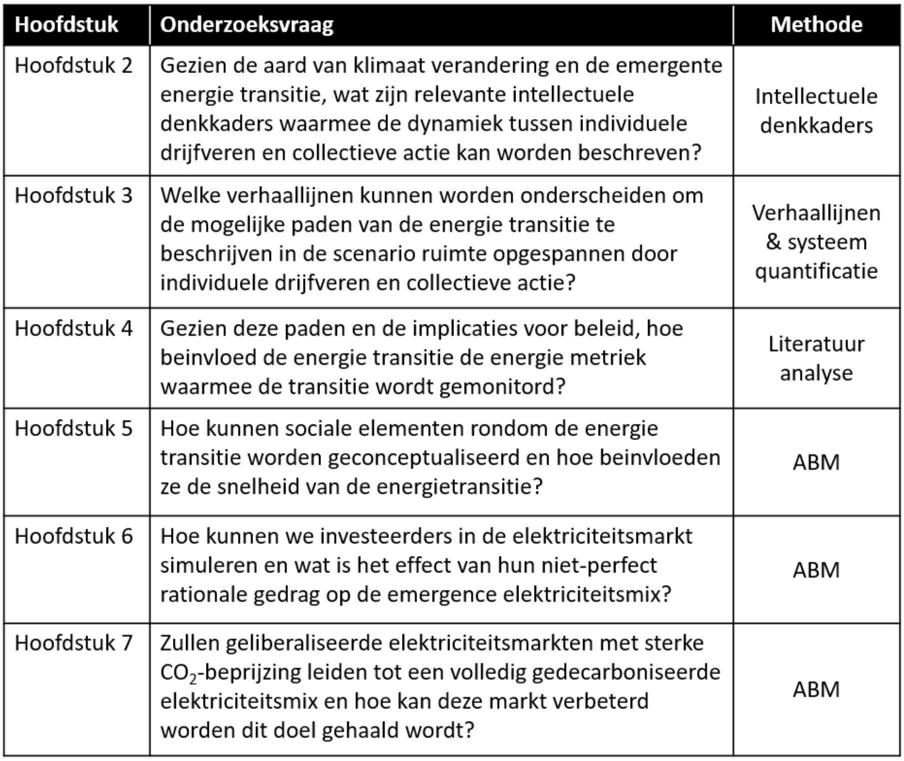
Hoe beïnvloeden individuele drijfveren en de interacties tussen actoren het pad en het tempo van de zich ontwikkelende energietransitie?

We kunnen niet verwachten deze vraag in zijn volledige vorm te kunnen beantwoorden in deze dissertatie. Deze vraag heeft wel de richting van ons onderzoek bepaald en de resultaten hebben inzicht gegeven in verschillende aspecten van deze vraag.

Het simuleren van interacterende actoren als computer-entiteiten, “agenten”, geeft ons de middelen om de dynamiek van interacties tussen actoren te verkennen. De toepassing van een relatief nieuwe modelleringsmethode, “agent-based modelling” (of agent-gebaseerde modellering), waarmee deze agenten kunnen worden gesimuleerd, biedt scenario ontwikkelaars een additionele methode voor het quantificeren van scenarios van de energietransitie. Agent-gebaseerde modellering geeft de mogelijkheid om *verhalenvertellers* te verbinden met *modelleerders*.

Inzichten verkregen door het simuleren van realistisch actor-gedrag hebben inzicht gegeven in de dynamiek tussen individuele motieven, prikkels en collectieve actie. Modelresultaten hebben nieuwe inzichten opgeleverd die kunnen worden gebruikt om actuele en mogelijke toekomstige ontwikkelingen rondom de energietransitie in perspectief te plaatsen. De gegenereerde inzichten kunnen worden

Tabel 9.1 – Onderzoeksvragen per hoofdstuk. Rechter kolom geeft de gebruikte onderzoeksmethode aan.



Hoofdstuk	Onderzoeksvraag	Methode
Hoofdstuk 2	Gezien de aard van klimaat verandering en de emergente energie transitie, wat zijn relevante intellectuele denkkaders waarmee de dynamiek tussen individuele drijfveren en collectieve actie kan worden beschreven?	Intellectuele denkkaders
Hoofdstuk 3	Welke verhaallijnen kunnen worden onderscheiden om de mogelijke paden van de energie transitie te beschrijven in de scenario ruimte opgespannen door individuele drijfveren en collectieve actie?	Verhaallijnen & systeem quantificatie
Hoofdstuk 4	Gezien deze paden en de implicaties voor beleid, hoe beinvloed de energie transitie de energie metriek waarmee de transitie wordt gemonitord?	Literatuur analyse
Hoofdstuk 5	Hoe kunnen sociale elementen rondom de energie transitie worden geconceptualiseerd en hoe beinvloeden ze de snelheid van de energietransitie?	ABM
Hoofdstuk 6	Hoe kunnen we investeerders in de elektriciteitsmarkt simuleren en wat is het effect van hun niet-perfect rationale gedrag op de emergence elektriciteitsmix?	ABM
Hoofdstuk 7	Zullen geliberaliseerde elektriciteitsmarkten met sterke CO_2-beprijzing leiden tot een volledig gedecarboniseerde elektriciteitsmix en hoe kan deze markt verbeterd worden dit doel gehaald wordt?	ABM

gebruikt ter ondersteuning van strategische beslissingen door publieke en private actoren en om te anticiperen op de gevolgen van hun (toekomstige) beslissingen.

9.1.2 Onderzoeksaanpak

Gezien de complexe aard van het probleem van klimaatverandering moest onze onderzoeksbenadering verschillende aspecten bestrijken: i) de omvang en aard van het probleem van de klimaatverandering (met betrekking tot tijd en ruimte), ii) het faciliteren van dialoog met belanghebbenden, iii) het aanpakken van de uitdagingen van agent-gebaseerde modellering en iv) de kloof overbruggen tussen verhalenvertellers en modelleerders, tussen wetenschappers en politici en tussen wetenschappers en bedrijfsvertegenwoordigers. Dit heeft geleid tot onze algemene onderzoeksaanpak die zich richtte op het vinden van een minimale weergave van de relevante systeemelementen met een minimum aan veronderstellingen die recht deed aan de complexiteit van het probleem.

Proberen te begrijpen hoe de energietransitie zich zal ontwikkelen, brengt ons naar de grens van de wetenschap omdat de onzekerheden en belangen groot zijn, keuzes gemaakt moeten worden en culturele waarden in het geding zijn. In dat licht kan onze onderzoeksbenadering worden gezien als een voorbeeld van postnormale wetenschap. Dit heeft ons een perspectief gegeven waarmee we de meerwaarde van agent-gebaseerde modellering konden verkennen.

Ons onderzoek heeft geleid tot verschillende conclusies en aanbevelingen die hieronder zullen worden besproken. Deze samenvatting eindigt met een reflectie op het onderzoeksproces en de bevindingen.

9.2 Conclusies

Conclusies van ons onderzoeks werden gegenereerd in onderzoeksprojecten die verschillende aspecten van onze onderzoeksvraag exploreerde. Gepresenteerde modellen en analyses zijn gebaseerd op de in Hoofdstuk 2 gepresenteerde intellectuele kaders. Deze verschillende intellectuele kaders hebben de basis gevormd voor de conceptualisering van het actorgedrag in de agent-gebaseerde modellen. Perspectieven vanuit de economie, de psychologie en de ecologie gaven achtergrondinformatie over de dynamiek tussen individuele drijfveren en collectieve actie.

Omdat de atmosfeer wordt gedeeld door ons allen is gebleken dat het “common pool resource dilemma” een relevante beschrijving geeft van het dilemma van actoren in de energie transitie; het dilemma tussen individuele drijfveren en collectieve actie. Dit dilemma is in het geval van klimaatverandering vooral uitdagend vanwege de volgende drie aspecten; de intergenerationele tijdschaal, de wereldwijde geografische schaal en de onvoorspelbaarheid van de gevolgen van klimaatverandering en de zich ontwikkelende energie transitie. Inzichten uit de psychologie en sociologie hebben verschillende elementen laten zien die het menselijk gedrag onderscheiden van de veronderstellingen van de neoklassieke economie; persoonlijke vorming, wereldbeelden en begrensd rationeel gedrag leidden tot beslissingsstructuren die in verschillende simulatiemodellen zijn gebruikt.

De in de verschillende onderzoeksprojecten gegenereerde inzichten, gerangschikt per hoofdstuk, zullen respectievelijk worden besproken.

Hoofdstuk 3: Optimistische veronderstellingen over de technologische ontwikkeling van Solar Fuels maken een nieuw scenario mogelijk over hoe de vraag naar brandstoffen kan worden voorzien zonder additionele broeikasgas emissies. Tegelijkerheid blijft dit een risicovolle gok. Twee energietransitie scenarios geven ons een nieuw perspectief op de mogelijke paden van de energietransitie: *All Renewable* en *Balancing Act* laten zien welke mogelijkheden de samenleving heeft om klimaatverandering aan te pakken en om aan de stijgende energievraag te blijven voldoen. Beide verhaallijnen gaan uit van het idee dat de energietransitie vandaag de dag wordt gedreven door verbeterde energie-efficiëntie, de verdere uitbouw van elektrische, hernieuwbare energiebronnen en sectorgewijze electrificering. Deze ontwikkelingen zullen echter tegen grenzen aanlopen omdat er sectoren zijn die moeilijk te elektrificeren zijn (denk aan de luchtvaart, scheepvaart, zwaar wegvervoer en hoge temperatuur processtechnologie). Dit zal leiden tot een residuele vraag naar op koolstofgebasseerde brandstoffen. De vraag naar deze brandstoffen kan emissie-loos worden voldaan door de resulterende emissies af te vangen of de resterende emissies in evenwicht te brengen met negatieve emissies. Een andere manier zou zijn een nieuw type, op hernieuwbare energie gebaseerde brandstoffen, zogenaamde "Solar Fuels", te produceren.

In dit hoofdstuk wordt besproken wat er nodig zou zijn om deze scenarios bewaarheid te laten worden. In *Balancing Act* beschrijft een scenario waarin de wereld de collectieve actieproblemen overwint. Dit zou leiden tot grootschalige toepassing van (bio-energie) koolstofafvang en -opslag en de uitrol van grote nieuwe distributie- en transmissiesinfrastructuren. *All Renewable* beschrijft daarentegen een scenario waarin wordt gegokt op technologie ontwikkeling dat uiteindelijk zou moeten leiden tot de ontwikkeling en productie van zonnebrandstoffen. Deze emissieneutrale koolwaterstofbrandstoffen zouden moeten worden geproduceerd door uit de lucht geabstraheerde CO_2 te synthesiseren met waterstof. Dit kan mogelijk gemaakt door gebruik te maken van hernieuwbare elektriciteit, waterelektrolyse (productie van waterstof), CO_2 activering van de uit de luch geabstraheerde CO_2. Als optimistische veronderstellingen over technologieontwikkeling werkelijkheid worden, kunnen deze emissieneutrale brandstoffen betaalbaar worden (tegen een prijs van 200 $ /bbl) wat zou kunnen leiden tot grootschalige marktgestuurde inzet.

Het feit dat individuele (commerciële) drijfveren de ontwikkeling van solar fuels zouden kunnen stimuleren, differentieert *All Renewables* van *Balancing Act* waarvoor meer betrokkenheid van de overheid vereist is om de collectieve actieproblemen te overwinnen.

Hoofdstuk 4: Nu energie afkomstig van hernieuwbare en niet-brandbare bronnen een steeds belangrijker deel van de energiemix wordt, wordt de precieze betekenis van belangrijke energie metriek, Totale Primaire Energie en Elektriciteitsproductiecapaciteit, steeds onduidelijker en mogelijk misleidend. De ontwikkeling van modellen voor de energietransitie vereist diepgaand inzicht in energie-metriek, de bouwstenen van beleidsdoelen en energiescenario's. De afgelopen decennia zijn fossiele, brandbare energie bronnen met een eenvoudig te bepalen primaire energie equivalent, de dominante energiebron in de energiemix geweest. De voortgaande decarbonisatie heeft er echter toe geleid dat energie afkomstig van hernieuwbare en niet-brandbare bronnen een groter deel van de energie mix beslaat. Hierdoor wordt er meer energie geproduceerd uit bronnen met een ruime totale beschikbaarheid, maar een beperkte instantane beschikbaarheid (wind en zon).

Dit hoofdstuk heeft laten zien dat de aanhoudende elektrificatie van het energiesysteem in combinatie met de decarbonisatie van het elektriciteitssysteem ertoe heeft geleid dat de huidige energie-metriek niet meer representatief is. Dit heeft invloed op belangrijke energie-metriek: Totale primaire energie en bijbehorende indicatoren Energie-efficiëntie en Energie-intensiteit, en Elektriciteitsproductiecapaciteit.

De primaire-energie-equivalent voor niet-brandbare energiebronnen zoals wind en zon wordt niet consequent gedefinieerd in energie modellen en scenario's. De resulterende verschillende statistische representaties van hun primaire energie-equivalent resulteert in onduidelijkheid. Evenzo heeft intermitterende hernieuwbare energieopwekking verschillende capaciteitsfactoren die interpretatie en sturing op elektriciteitsproductiecapaciteit ambivalent maken. Dit maakt dat deze metrieken niet-representatief, moeilijk te interpreteren en uiteindelijk misleidend worden. Dit is problematisch omdat deze energie-metriek klimaatbeleid en investeringsbeslissingen stuurt op basis van statistische artefacten, in plaats van een feitelijke weergave van het energiesysteem.

Om deze problemen te verhelpen, wordt modelleerders en energie scenario ontwikkelaars aangeraden om expliciet en transparant te zijn over de toegepaste statistische methodes om het primaire energie-equivalent voor niet-brandbare energiebronnen te berekenen en mogelijke consequenties van de gebruikte aanpak te benadrukken. Hierdoor kunnen conclusies op basis van statistische artefacten worden voorkomen. Een verdere aanbeveling beslaat de suggestie om te focussen op energie-*verbruik* en dus op de energie-metriek Totale Energie Verbruik omdat deze energie-metriek vrij is van de besproken ambiguïteit. Met betrekking tot de productiecapaciteit voor elektriciteit wordt de aanbeveling gedaan om deze cijfers in perspectief te plaatsen door ze te begeleiden met de verwachte capaciteitsfactor (waarmee de verwachte electriciteits opwekking kan worden berekend) of de grote van de gemoeide investering.

Hoofdstuk 5: De maatschappelijke dynamiek rond klimaatverandering en de energietransitie geeft aanleiding tot het simuleren van de energietransitie als een potentiële kritische transitie. Met de toepassing van

op agenten gebaseerde modellering kan hun invloed op het tempo van de energietransitie worden onderzocht. Kritische transities zijn snelle en sterke systeemveranderingen veroorzaakt door relatief kleine veranderingen in externe omstandigheden. In dit hoofdstuk wordt dit concept toegepast op de energietransitie om te onderzoeken hoe de sociale dynamiek rond het energiesysteem het tempo van de transitie beïnvloedt. We hebben het concept geïntegreerd in een agent-gebaseerd model en verschillende sociale aspecten van de emergente energie transitie onderzocht. De invloed van leiders, de heterogeniteit van actoren en het effect van netwerken die lokale gemeenschappen vormen zijn onderzocht.

De twee belangrijkste bevindingen zijn; i) het belang van lokale gemeenschappen en ii) leiders kunnen zowel de energietransitie stimuleren als ontmoedigen; een bevinding die bestaande literatuur over kritische overgangen nuanceert. Een analyse van de sterke en zwakke aspecten van de gekozen aanpak heeft geleid tot een reflectie op het gebruik van conceptuele modellen. Deze modellen bieden een nuttig hulpmiddel om de dynamiek tussen individuele prikkels en collectief gedrag te analyseren, deze dynamiek in de juiste context te plaatsen en een dieper begrip mogelijk te maken.

Hoofdstuk 6: Effectief beleid om het elektriciteitsnet te decarboniseren, vereist het ontwerpen en evalueren van dit beleid op basis van het realistische gedrag van actoren. De transitie van het elektriciteitssysteem zal cruciaal zijn voor de transitie van het energiesysteem als geheel. In dit hoofdstuk wordt de invloed van het ontwerp van de geliberaliseerde elektriciteitsmarkt op de uiteindelijke elektriciteitsmix geanalyseerd door het realistische gedrag van investeerders in deze markt te simuleren.

Dit hoofdstuk heeft laten zien dat het simuleren van het “realistisch gedrag” van agenten helpt bij het ontwerpen en evalueren van beleid met een specifiek (niet economisch) doel, in dit geval decarbonisatie van het elektriciteitssysteem. Het simuleren van investeerders in het elektriciteitssysteem met agent-gebaseerde modelen biedt een extra hulpmiddel voor dit beleidsontwikkelingsproces. Het geeft beleidsmakers de kans om het mogelijk effect van hun beleid te analyseren op basis van simulaties van het realistische gedrag van agenten.

Hoofdstuk 7: Volledig geliberaliseerde elektriciteitsmarkten zullen niet voldoen aan volledige decarbonisatie doelstellingen, zelfs niet met sterke CO_2-beprijzing De volledige decarbonisatie van het elektriciteitssysteem vereist een grotere flexibiliteit om het toenemend aandeel van variabele elektriciteitsopwekking zoals als elektriciteit afgeleid van wind en zonnestraling te kunnen accomoderen. Door het gedrag van investeerders te simuleren en voort te bouwen op de bevindingen uit Hoofdstuk 6, laat dit hoofdstuk zien dat de geliberaliseerde elektriciteitsmarkt, zelfs met sterkte CO_2-beprijzing, niet zal leiden tot een volledige hernieuwbaar, betrouwbaar en betaalbaar energiesysteem in de tweede helft van de eeuw.

Met behulp van simulatie modellen hebben we laten zien dat het ontwerp van de elektriciteitsmarkt als als zogenaamde ënergy-only"markt (i.e. een markt waarin enkel daadwerkelijk geleverde energie wordt vergoed) investeerders niet zal stimuleren om te investeren in de vereiste mix van flexibiliteit en hernieuwbare elektriciteitsproductie. We hebben aangetoond dat onder een CO_2-scenario van 200 €/tCO_2 (en zelfs oplopend tot 400 €/tCO_2), deze markten onvoldoende stabiele investeringssignalen geven aan investeerders om te investeren in een duurzaam elektriciteitssysteem. Mogelijke alternatieven voor deze volledig geliberaliseerde markten, waarin de capaciteitsvereiste van het systeem is geïnstitutionaliseerd via capaciteitsbeloningsmechanismen, zijn onderzocht. We concluderen dat een system waarin de beschikbare elektrikiteitsproductie-capaciteit beloond wordt (in plaats van geproduceerde elektriciteit) een geloofwaardige oplossingsrichting biedt.

9.3 Aanbevelingen voor beleidsmakers

Onderzoek gepresenteerd in dit proefschrift heeft verschillende implicaties voor beleidsontwikkeling. Verschillende beleidsaanbevelingen worden gedaan:

Ten eerste moeten beleidsmakers zich bewust zijn van de aard van het probleem van de klimaatverandering. Het probleem van de klimaatverandering is een “common pool resource” dilemma dat vooral uitdagend is omdat de gevolgen van klimaatverandering onvoorspelbaar zijn over tijd- (intergenerationeel) en ruimte- (wereldwijd) dimensies. Omdat de belangen en onzekerheden groot zijn maakt dat het bestuderen van de ontwikkeling van de energietransitie een voorbeeld van postnormale wetenschap. In dit perspectief op de wetenschap is het een illusie te denken dat wetenschappers de waarheid in pacht hebben om beleidsbepalers mee te kunnen inlichten. Het feit dat wetenschappers geen definitief antwoord kunnen geven aan beleidsmakers, maakt dat deze beslissingen de facto politieke beslissingen zijn (waarvoor politici niet mogen schrikken). Om deze beslissingen zo goed mogelijk te maken, kunnen verschillende perspectieven worden ingebouwd in beleidsdiscussies. In dit proefschrift wordt agent-gebaseerde modellering gepresenteerd als een extra hulpmiddel voor scenario- en beleidsontwikkeling als aanvulling op inzichten uit andere methodieken.

Beleidsmakers moeten een evenwicht vinden tussen de meest efficiënte, kostenoptimale marktontwerpstructuur en een marktstructuur die gericht is op het bereiken van een specifiek resultaat. In het geval van klimaatverandering is dit niet alleen bijvoorbeeld kostenminimalisatie op basis van rationele agenten, maar moet gerelateerd zijn aan de totale CO_2-uitstoot en het realistische gedrag van de actor. Daarom moeten beleidsmakers gebruik maken van simulaties van realistisch actorgedrag om de uitkomst van specifieke beleidsmaatregelen te evalueren. Dit betekent dat beleidsmakers zich, in plaats van te veel te vertrouwen op modellen die uitgaan van perfecte informatie, perfecte rationaliteit, homogene actoren en focussen op de laagste (systeem) kosten, zich meer moeten richten op modellen die realistisch gedrag van agenten expliciet incorporeren. Dit proefschrift laat zien dat het omarmen van deze complexiteiten van de energietransities een ander en rijker perspectief biedt op de mogelijke ontwikkelingstrajecten van het energiesysteem.

Ons onderzoeksperspectief heeft de volgende specifieke aanbevelingen voor beleidsontwikkeling:

CO_2-neutrale brandstoffen Hoewel het aandeel van elektriciteit in de energiemix aanzienlijk zal stijgen (van de huidige 20% tot ongeveer 60%), zal de vraag naar op koolstof gebasseerde brandstoffen blijven bestaan. Het gebruikelijke verhaal van de belangrijkste scenario ontwikkelaars (zoals het IPCC) is afhankelijk van door de overheid opgelegde grootschalige koolstofafvang en -opslag, vaak in combinatie van biomassa. Door de integratie van verschillende opkomende technologieen zou echter een CO_2 neutrale brandstof kunnen worden geproduceerd waarvan de productie commercieel aantrekkelijk zou kunnen worden. Die zou kunnen leiden tot marktgedreven productie van CO_2 neutrale brandstoffen.

Gezien deze twee mogelijke scenarios voor de energietransitie, overheid of markt-gedreven, zou het voor beleidsontwikkelaars verstandig zijn ook de marktontwikkeling van de productie van solar fuels te stimuleren. (Hoofdstuk 3).

Energie-metriek Aangezien de algemene doelstelling van klimaatbeleid is om de uitstoot van broeikasgassen te verminderen, moeten beleidsdoelen worden uitgedrukt in energie-metriek die deze doelstelling ondersteunen. Bovendien moeten beleidsmakers zich bewust zijn van de verschillende boekhoudkundige kwesties rond belangrijke energiestatistiek en beleidsdoelstellingen voorkomen die zijn gebaseerd op statistische artefacten. (Hoofdstuk 4).

Sociale dynamiek en het tempo van de energietransitie Beleidsmakers moeten zich ervan bewust zijn dat actoren in de echte wereld niet perfect rationeel zijn en mogelijk anders reageren op beleidsmaatregelen dan rationele, geïdealiseerde actoren zouden doen. De sociale dynamiek van actoren beïnvloedt beleidsresultaten en daarom zou moet beleid kunnen worden ontwikkeld dat rekening houdt met deze inzichten. Bovendien kunnen deze inzichten worden gebruikt in beleid, bekend onder de term *nudging*. (Hoofdstuk 5).

Elekticiteitsmarktontwerp Elektriciteitsmarkten moeten volledig gedecarboniseerd om internationaal overeengekomen doelen om klimaatverandering tegen te gaan te halen. Om deze volledige decarbonisatie te faciliteren met behoud van betaalbaarheid en betrouwbaarheid van het elektriciteitssysteem, zullen beleidsmakers twee taken hebben. Ten eerste moeten zij hun aandacht verleggen van de verbetering van markten ontworpen als *energy-only* markten naar de ontwikkeling van geschikte capaciteitsbeloningsmechanismen. Dit mechanisme zou investeerders de juiste prikkels kunnen geven om te investeren in de combinatie van hernieuwbare elektriciteitsopwekking en flexibilisering van het elektriciteitssysteem om elektriciteits van variabele productie technologien zoals uit zon en wind, te kunnen absorberen. Ten tweede moeten flexibiliteitsmarkten, waarin opslagbedrijven kunnen betalen voor een overschot aan hernieuwbare elektriciteitsopwekking, worden gefaciliteerd. Dit zou investeerders de motivatie kunnen geven om overtollige hernieuwbare energie te genereren die op andere momenten kan worden opgeslagen. (Hoofdstuk 6 en 7).

9.4 Aanbevelingen voor zakelijk besluitvorming

Onderzoek gepresenteerd in dit proefschrift heeft geresulteerd in verschillende aanbevelingen ter verbetering van zakelijke besluitvorming:

Ondersteun van strategische besluitvorming met modelontwikkeling Modelontwikkeling zou een essentiële rol moeten spelen binnen het besluitvormingproces van bedrijven. Hoewel het gemakkelijk is om modellen en hun uitkomsten te bekritiseren omdat ze altijd slechts een deel van de werkelijkheid weerspiegelen, dwingt modelontwikkeling als onderdeel van strategische besluitvorming de belanghebbenden ertoe zich in te zetten voor een structurele aanpak en veronderstellingen en resultaten kritisch te evalueren.

Wees betrokken bij het modelontwikkelingsproces Net als beleidsmakers bevinden zakelijke besluitvormers zich bij tijd en wijle in situaties waarin de belangen groot zijn, culturele waardes verschillen, en beslissingen dringend zijn. In die gevallen is het al te eenvoudig om het besluitvormingsproces uit te besteden aan een modelleerteam. Onze ervaring heeft geleerd dat de inzichten uit modelstudies vaak worden gegenereerd in het modelontwikkelingsproces. Om de meeste waarde uit deze modelstudies te halen, is het daarom voor zakelijke besluitvormers belangrijk om niet enkel te wachten op de resultaten maar om actief deel te nemen aan dit modelleringsproces.

Creëer een omgeving die transdisciplinaire kennisuitwisseling mogelijk maakt Uit ervaringen uit deze disseratie blijkt dat agent-gebaseerde modellering in het algemeen, en onze modelleringsaanpak in het bijzonder, buitengewoon geschikt is om de kloof tussen modelmakers en belanghebbenden te overbruggen: agent-gebaseerde modellering biedt een natuurlijke manier om na te denken over actoren, hun interacties en de resulterende dynamiek van het systeem. Een aanpak die gericht is een minimale weergave van deze actoren en focust op de fundamentele dynamiek maakt betrokkenheid van belanghebbende, transparantie, reproduceerbaarheid en traceerbaarheid van model resultaten mogelijk.

Gebruik agent-gebaseerde modellering om strategische besluitvorming te ondersteunen Veel modellen die worden gebruikt in de dagelijkse bedrijfsvoering zijn optimalisatiemodellen; denk aan supply chain-optimalisatie, logistieke optimalisatie, operationele optimalisatie, enz. Bij strategische besluitvorming gaat het echter vaak om het ontwikkelen van een strategisch plan om een bepaald doel te bereiken in een zakelijke omgeving waarin de onzekerheden groot zijn. Deze onzekerheden worden vaak veroorzaakt door menselijke reflexiviteit; mijn handelen heeft invloed op anderen waarop ik mij weer kan/moet aanpassen. Agent-gebaseerde modellering is bijzonder geschikt om de interactie tussen actoren in een commerciele omgeving te simuleren en strategische keuzes te evalueren.

Gebruik agent-gebasseerde modelling als additionele methode voor scenario-ontwikkeling Veel bedrijven maken scenario's om strategische beslissingen te ondersteunen. Shell heeft bijvoorbeeld een lange geschiedenis in scenario-ontwikkeling. Binnen dit scenario-denken kunnen scenario-ontwikkelaars zich eenvoudig verliezen in technologische en economische ontwikkelingen; leercurves, empirisch gevalideerde relaties tussen belangrijke factoren, etc. Agent-gebaseerde modellering geeft deze scenario-ontwikkelaars een hulpmiddel om verhalen van het gedrag van actoren, hun interactie en hun emergente collectieve gedrag te onderzoeken en te quantificeren.

9.5 Reflectie

9.5.1 Het modelleren van de energie transitie

Omdat menselijke beslissingen complex zijn, zijn modellen die dit besluitvormingsproces (in het energiedomein) proberen te simuleren, onderhevig aan grote onzekerheden. Het simuleren van een transitie vereist inherent het simuleren van agent-gedrag dat anders is dan de empirisch gevalideerde historische besluitvormingsprocessen uit het verleden. Simulatiemethoden zoals agent-gebaseerde modellering zorgen er daardoor voor dat modelmakers voortdurende zoeken naar plausibel, geloofwaardig agent-gedrag.

De modelconceptualisering van het (onzekere) gedrag van actoren kan leiden tot uitkomsten die de begin-assumpties direct weerspiegelen. Conventionele modellen elimineren deze onzekerheid echter door te vertrouwen op rationele agenten. Vertrouwen op rationele agenten die in werkelijkheid rationeel begrensd zijn, kan een gevoel van zekerheid creëren dat illusoir is.

Dit aspect ben ik tegengekomen in een project waarbij ik consumenten modelleerde die konden kiezen tussen mitigatie en aanpassing aan klimaatverandering op basis van dynamische kostenverwachting van mitigatie- en aanpassingsinspanningen [431]. Deze modelleringsoefening bracht precies dit probleem aan het licht; eenvoudige quantificering van een verhaal leidt soms tot resultaten die direct de veronderstellingen weerspiegelen die in het model zijn opgenomen. Dit kan echter nog steeds waarde hebben als illustratie van een bepaald verhaal. Dit kan discussies tussen belanghebbenden over aannames en dynamieken mogelijk maken en daardoor toch nuttig zijn.

In de projecten beschreven in Hoofdstuk 6 en 7 van dit proefschrift werden actoren gekozen met een plausibele motivatie maar die heterogeen en niet perfect rationeel zijn; investeerders in het energiesysteem. De aannames die we moesten maken om hun besluitvormingsproces plausibel te simuleren konden relatief eenvoudig blijven, in de meest elementaire vorm zullen investeerders een commerciële motivatie hebben. Resultaten van deze modellen hebben interessante aspecten ontwikkelende elektriciteitsmarkt naar voren gebracht (die worden beschreven in Hoofdstuk 6 en 7).

Het onderzoeksproject dat beschreven is in Hoofdstuk 5 leidde ons tot meer fundamentele epistemologische vragen over de waarde van de toepassing van agent gebaseerde modellering op de energietransitie. Het resulteerde in de karakterisering van onze benadering als post-normale wetenschap zoals uitvoerig beschreven in Hoofdstuk 2 en Hoofdstuk 5. Het benadrukte ook het belang van de juiste motivatie voor modelleer-studies: Men zou moeten modelleren om inzicht te verkrijgen in plaats om preciese getallen te verkrijgen. Dit weerspiegeld het perspectief op modellering als een middel om een duidelijke en expliciete redenering te vinden.

Om agent-gebaseerde modellering te kunnen waarderen is het een vereiste om bescheiden te zijn over de eis om aan waarheidsvinding te doen. Deze uitdaging is even uitdagend voor conventionele modelleringsmethoden en heeft betrekking op modelstudies in het algemeen; “Alle modellen zijn fout, sommige zijn nuttig” [432]. Dit benadrukt dat de waarde van modelleren in het algemeen het vaakst ligt in de inzichten die het creëert die vaak ontstaan in het model-ontwikkelingsproces.

We hebben aangetoond dat agent-gebaseerde modellering een essentiële rol kan spelen om nieuwe perspectieven te bieden op de manier waarop maatschappelijke actoren het probleem van klimaatverandering kunnen en moeten aanpakken. Die rol kan worden samengevat in de volgende drie aspecten:

1. **Gequantificerende verhaallijnen van actorgedrag bieden hulpmiddelen om de communicatie tussen onderzoekers en belanghebbenden te verbeteren.** Met de toepassing van agent-gebaseerde modellering kan een verhaallijn worden geïllustreerd en gestructureerd. Op deze manier kunnen aannames en uitkomsten worden besproken met een verschillende belanghebbenden, zelfs zonder direct *nieuw* inzicht te krijgen uit de resultaten van het model zelf.

2. **Quantificering via conceptualisatie en simulaties biedt de mogelijkheid om het gedrag van actoren op een gestructureerde manier te analyseren.** Agent-gebasseerde modellering dwingt onderzoekers na te denken over actorinteracties en ze te structureren in model-conceptualisaties. Dit alleen kan inzichten genereren. Dynamiek die voortkomt uit deze agentgedragingen kan verder worden onderzocht en geanalyseerd om aanvullende inzichten te genereren. Vice versa kan agent-gedrag verder worden geanalyseerd in relatie tot de zich ontwikkelende dynamiek.

3. **Quantificering maakt het gebruik van rekenkracht van computers mogelijk waarmee emergent gedrag in complexe systemen kan worden bestudeerd.** Simulering van het gedrag van actoren in computermodellen vergroot de mogelijkheden om de uitkomsten van hun complexe interacties te berekenen.

9.5.2 De zich ontwikkelende energietransitie

Naast de inzichten over de waarde van modellering en specifiek de waarde van agent-gebaseerde modellering, heeft meer dan vier jaar onderzoek naar de zich ontwikkelende energietransitie een aantal additionele inzichten gebracht.

Een inclusieve energietransitie Gezien de aard van klimaatverandering, het complexe en common pool resource-karakter, zal deze transitie een inclusief karakter moeten hebben. Inclusief betekent hier dat alle actoren en alle sectoren betrokken moeten zijn bij deze transitie. Niet één energieverbruikende sector kan buiten beschouwing worden gelaten bij het aanpakken van de klimaatverandering, alle sectoren zullen moeten bijdragen om in de komende decennia tot nulnulemissies te komen. Dit betekent dat bijvoorbeeld luchtvaart, die tot nu toe vaak buiten beschouwing worden gelaten vanwege het internationale karakter en de beperkte technologische mogelijkheden, extra aandacht nodig zal hebben. Het betekent ook dat we geen enkele energiedrager mogen negeren. Hoewel er vaak veel aandacht is voor de elektriciteitssector, voorziet deze sector momenteel slechts een vijfde van onze energievraag. Het brandstof-gedeelte van de energiesector mag daarom niet worden vergeten.

Inclusief betekent ook dat alle landen, met name de grote contribuanten, aan boord moeten zijn. Tot dusverre is de internationale onderhandelingsarchitectuur van de Verenigde Naties, het UNFCC, onze beste hoop om verdere internationale overeenstemming te bereiken om de klimaatverandering te beperken. Hoewel dergelijke onderhandelingen, unilateraal of op nationaal niveau tussen verschillende belanghebbenden (zoals het Nederlandse *Energie Akkoord*) soms slechts ogenschijnlijk trage vooruitgang boeken, is de energietransitie zo'n brede, alomvattende systeemverandering, dat ze nodig is voor een geslaagde energietransitie. Inclusief betekent echter niet dat individuele actoren, zijnde landen, bedrijven of individuen op anderen moeten wachten. Er zijn tal van individuele, economische, strategische, morele en ethische redenen om het energiesysteem te transformeren. Daarom hebben we dappere politici nodig die niet wegschrikken voor de facto politieke beslissingen over de toekomst van het energiesysteem.

Het balanceren van inspanningen Actoren in deze energietransitie moeten hun inspanningen in evenwicht houden met de huidige en toekomstige problemen. De Verenigde Naties hebben nu 17 Duurzame Ontwikkelingsdoelen [433] geformuleerd, wat betekent dat dit geen voor de hand liggende taak is. Om zo'n balans te bereiken, is het gemakkelijk om afgeleid te worden door trendy, modieuze kwesties zoals de circulaire economie. In het andere uiterste richt men zich op klimaatverandering en vergeet men de groeiende energievraag van een groeiende wereldbevolking. Beslissers moeten hun oog op de bal houden en zich bewust zijn van de overkoepelende impact die klimaatverandering heeft op onze samenleving, terwijl ze rekening houdt met de huidige behoeften van de wereldbevolking. Soms kunnen inspanningen op onderwerpen zoals het verlagen van het geluidsniveau in de buurt van luchthavens of het beperken van luchtvervuiling een tweesnijdend zwaard zijn dat ook de klimaatverandering beperkt. Maar besluitvormers moeten zich er altijd van bewust zijn dat hun beslissing effect heeft op het juiste probleem.

Neem je eigen verantwoordelijkheid Actoren (individuen, politici, bedrijven) kunnen gemakkelijk betrapt worden op het wijzen van anderen op hun verantwoordelijkheid om verdere stappen te nemen om het energiesysteem te veranderen. Consumenten wijzen naar bedrijven, bedrijven wijzen naar hun aandeelhouders (vaak pensioenfondsen) die wijzen op hun verplichtingen jegens hun pensioengerechtigden wat ons weer terug brengt naar het begin. Hetzelfde geldt voor door burgers gekozen politici. Het punt is dat al deze actoren hun verantwoordelijkheid hebben. Een belangrijk en leidend beginsel dat is verwoord door Mahatma Gandhi is nog steeds waar: "je moet zelf de verandering zijn, die je in de wereld wilt zien".

Acknowledgements

This dissertation is the result of four years of inspiring discussions and dedicated research at several institutes in The Netherlands. I would like to thank Royal Dutch Shell for the financial support of this PhD.

Gert Jan Kramer It has been a great pleasure to work with you, Gert Jan. You were an excellent supervisor, generous with your time and always giving me the freedom to follow my own ideas. From the first discussions we had during my bachelor thesis project to one of our last in Wageningen I always felt privileged to be able to work you.

Igor Nikolic It was a pleasant surprise that from the second year of my PhD onward I was able to start working with you, Igor. Coming from a different perspective to modelling, we had very interesting discussions around agent-based modelling and the value of modelling in general. Thanks for all your time and effort.

Vinzenz Koning Vinzenz, your constructive feedback and advice in the last phases of my PhD were greatly appreciated. I am more than happy you will take the subject under your responsibility and wish you all the best to advance it.

Shell colleagues Within Shell I had the pleasure to work together with a wide variety of people and the many discussions we have will stay close to me. Martin, your precision, dedication and of course, your British sense of humour I truly valued and I was happy with the chance to work together. Chris, thanks you very much for all your support. I would also like to thank the energy futures team for the warm welcome: Burkard, Shoba, Angelika, Alexander and Maaike; the scenarios team, especially Jeremy and Wim for their guidance and the trust they had in me and the colleagues from Project & Technology and New Energies especially Anne-Sjoerd, Lisette, Arian, Quirine, Jeff, Arnoud, Ingmar, Joep, Mark, Tatiana, Jeff, Andreas, Katharina, Jonathan, Erik, and Edwin: Thank you!

Utrecht Halfway my PhD I joined Utrecht University and I am happy to have gotten this opportunity. I would like to thank the various (PhD)-colleagues who handed out ice creams when our brains overheat, with whom I shared a nice drink after a colloquium and the various colleagues I shared offices with.

Delft I am happy to have shared memorable moments with various colleagues at Delft University of Technology. Emile, our conversations about our modelling work, the energy transition or about life outside of academia, will always stay close to me. Telli, I was happy to share an eye-opening trip to Saudi Arabia with you, the dinner (with accompanying dress code) we had with our Saudi colleagues was very special. Gerben, your expertise in the use of various software tools was indispensable and I am very grateful for all your patience and help.

Leiden In the first years of my PhD I was lucky to share a room with three great personalities, Benjamin, Coen and Laura, thank you for a great time in the office. Gjalt, thanks for the inspiring conversations we had. A special thanks to Susanna with whom I shared various Kafkaesque situations battling bureaucracy. Arnold thanks for your guidance throughout my PhD and your time and effort to help me comply to all set rules and regulations.

Friends During my PhD I enjoyed the support of some great friends. With Edwin I could have long evening discussions about life or squash out any frustration. Jelle always has been a great friend, I am sure he will inspire many young scientists. Although far away Stephanie is always close to my heart, fantastic we still see each other regularly. In Li Lan I recognise the drive to make the world a better place. Let's keep on pushing Li Lan! With Florentien I share the passion for swing music & dance, she is simply the sweetest friend I have. Pieter, Renske, Jelle; I hope we will keep on eating pancakes once in a while. Dennis, Samantha, Paul, Cynthia, Etiënne, Anneke, Pauline, Patricia and Aleksandra, thanks for great moments we have shared on the dance floor.

Family Of course I could not have finished this PhD without the support of my family. My dear mother gave me the feeling any decision I would make she would support, thank you for love and care. My father stimulated me with the thousands of books that surrounded me since I was young and from whom I inherited that same love for books and the interest in a wide variety of topics.

Leanne Of all people, I most grateful for the support Leanne has given me throughout my PhD. Thank you, my lovely Leanne, for all your encouragement, patience, for sharing the passion for dancing, but most of all for your love.

Oscar Kraan – October 2018

About the author

Oscar Kraan was born on the 9th of December 1985 in The Hague, The Netherlands. After graduating in 2004 from the Gymnasium Haganum in The Hague, he went to Leiden to study physics. During his studies in physics Oscar got interested in the energy transition and was invited for two honours programs related to the energy transition. In this period, he also served in various committees of his study, student and sport association. He finished his Bachelor's studies in 2012 with a bachelor thesis in which he compared the potential of wind and wave energy. He then continued his studies with an M.Sc. in Energy Science at Utrecht University which he obtained in 2013. He graduated with a combined internship and master thesis on agent-based modelling of space heating in the built environment, conducted at and in collaboration with Shell.

After graduating Oscar continued to work on the energy transition and started his PhD which was Shell sponsored and conducted in collaboration with Leiden University, Utrecht University and Delft University of Technology. In the last five years he conducted research on energy scenarios and the simulation of the evolution of energy system focusing on the dynamics between individual incentives and collective behaviour. This work has resulted in five scientific articles, several opinion articles in Dutch media and strategic insights for various stakeholders. In addition, Oscar supervised Master student thesis projects at various Universities in The Netherlands. Next to his scientific work Oscar collaborated with Shell's scenario team on the *Net Zero Emission outlook* as well as Shell latest scenario *Sky*. From November first 2018 Oscar will be working at Deloitte as Senior Strategy Consultant for energy related industries.

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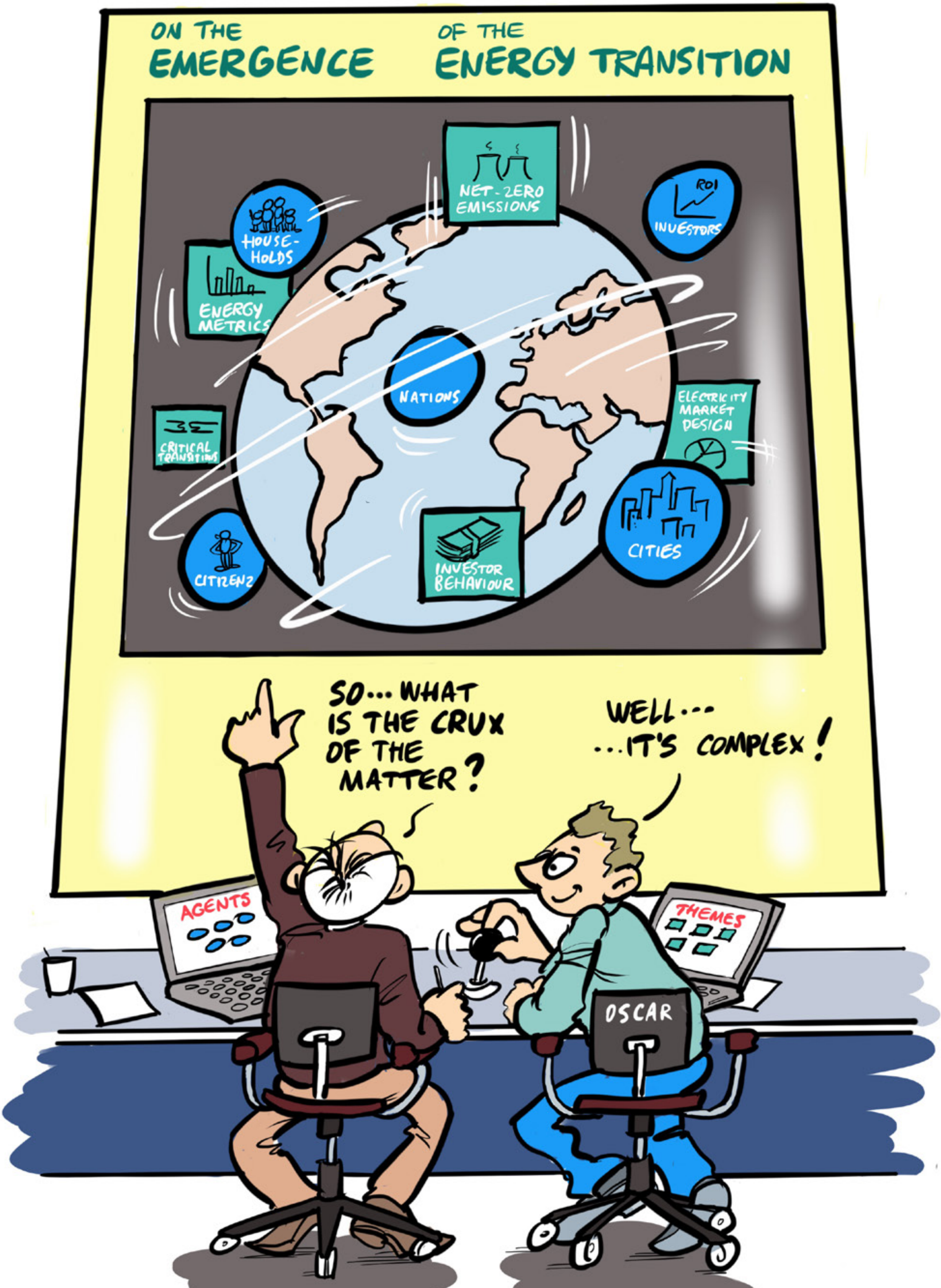
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