On the emergence of the energy transition

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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).

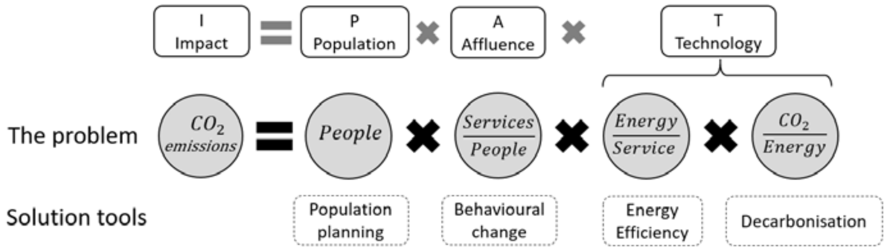

Figure 1.1 – A simple formula that summarises the challenge of mitigate climate change, adapted from [9]

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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].

[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.

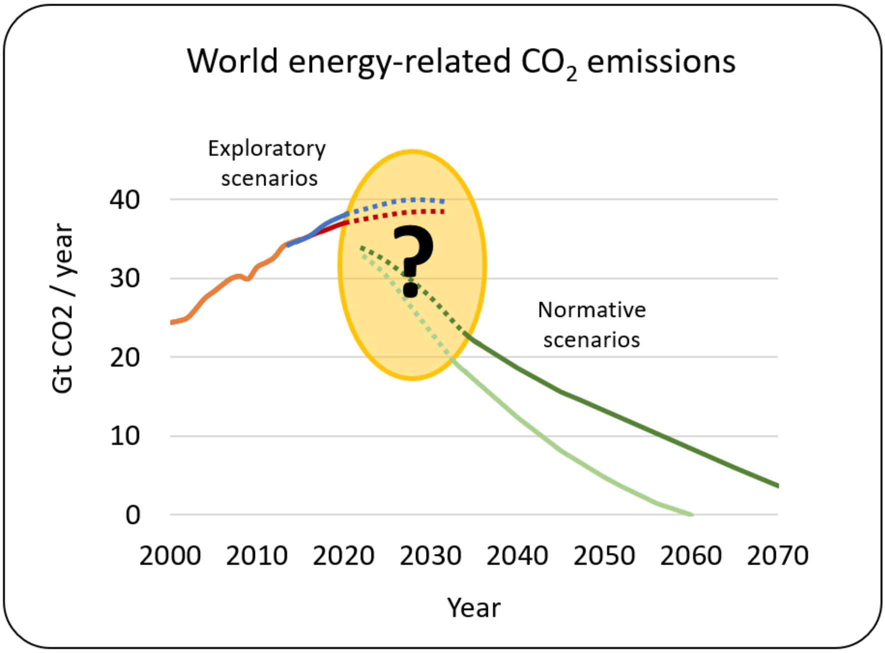

Figure 1.2 – World energy-related CO_2 emissions. Figure shows historical emissions [31], exploratory scenarios (indicatively shown in red and blue based on Shell New Lens Scenarios [32]) and normative scenarios (based on IEA 2°C scenario in light green and IEA Beyond 2°C scenario in dark green [33]). 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.