On the emergence of the energy transition
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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”.