Universiteit Leiden
The Netherlands

On the emergence of the energy transition

Kraan, O.D.E.

Author: Kraan, O.D.E.
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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

[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].

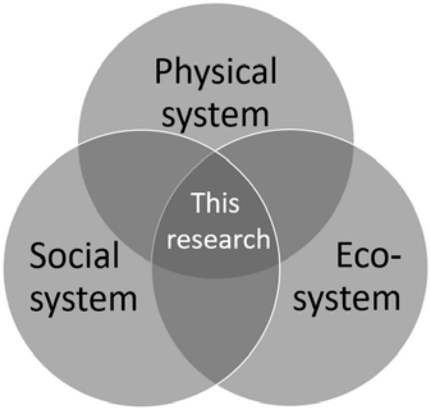

Figure 2.1 – Three systems. This research is located at the intersection of the physical, social and ecosystem.

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]

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

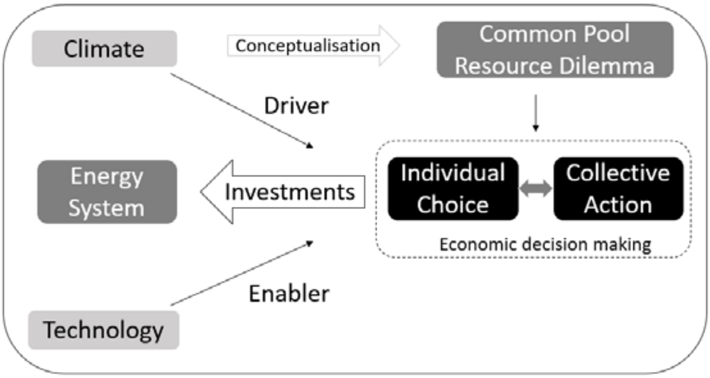

Figure 2.2 – A perspective on the energy transition. Figure shows climate change conceptualised as common pool resources dilemma. It is the ultimate driver for the decision-making process that may lead to the required investments to transition the energy system. Technology here creates decision possibilities 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	
		High	Low
Excludability	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".

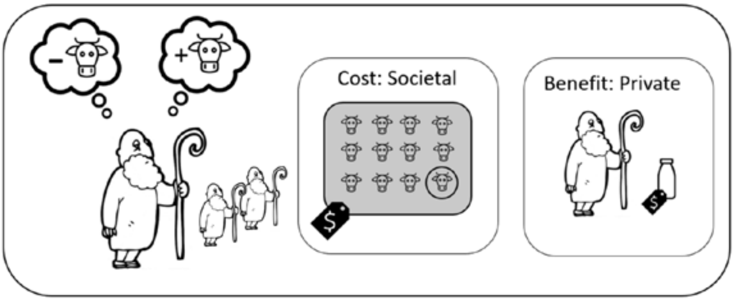

Figure 2.4 – The tragedy of the commons. Individual herdsmen have the incentive to increase the number of cattle on a commonly owned pasture because the costs are bore societal while there are individual benefits

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.

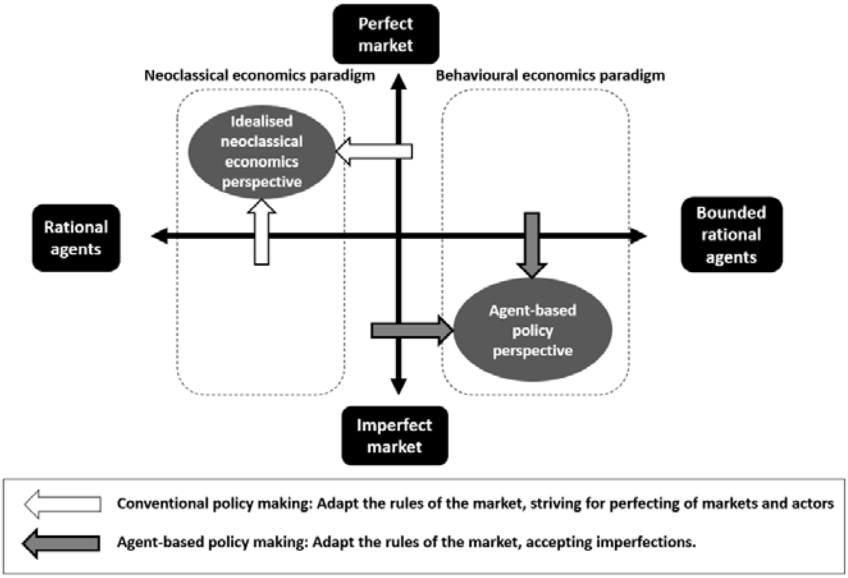

Figure 2.7 – Policy perspective matrix. The application of agent-based modelling enables modellers to depart from the conventional perspectives on economic decision making which is ground in the neoclassical economics paradigm. In this perspective policy makers are aware a particular market may be imperfect, 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].

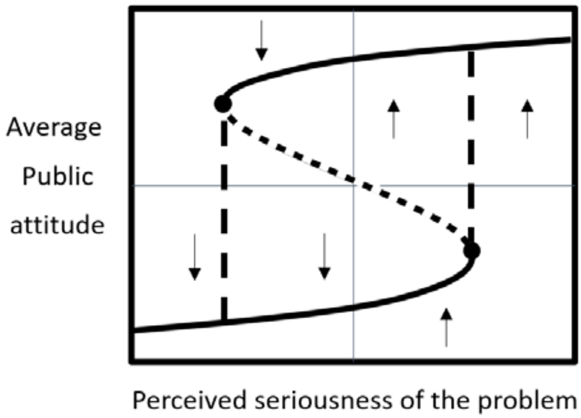

Figure 2.8 – The concept of critical transitions. Figures shows a situation in which the average public attitude to a problem increases slowly with the perceived seriousness of the problem. When a bifurcation point is reached, a critical transition can occur to a state with an higher average public attitude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

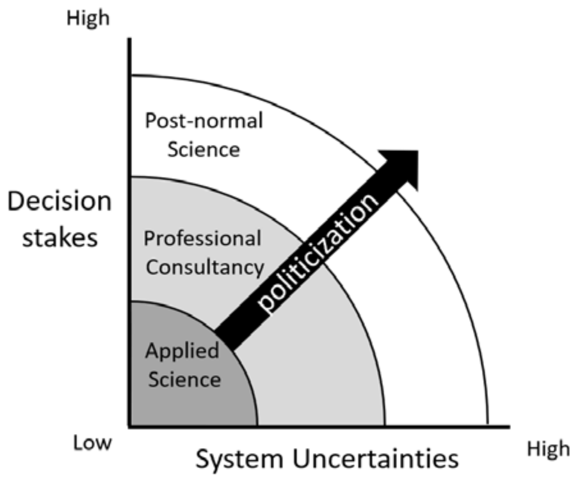

Figure 2.9 – A diagram differentiating Applied Science, Professional Consultancy and Post-normal Science. Figure shows that when decisions stakes are uncertainties large, we enter the space of Post-normal science. During this process decision are increasingly political in nature as scientific research 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).