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## Original research article

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



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## ABSTRACT

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

## 1. Introduction

Energy system models and their resulting scenarios are used to understand the transformation of the energy system. They offer us a possibility to meaningfully assess future developments, facilitate experimentation, promote rigorous analyses and provide a tool to communicate about findings [38,79,84,19]. We observe that most energy models designed to analyse the energy system are techno-economic in their nature [48] and that conceptual models that focus on societal elements [65] are heavily criticised [14].

### 1.1. Modelling the role of human behaviour in the energy transition

Internationally agreed goals to limit climate change by decarbonisation of the energy system require that the world will have to engage in transformative change of the system; an energy transition [1]. Although there is scientific consensus on the severity of climate change, it is uncertain whether society will act accordingly. A better understanding of the role of human behaviour in the transition of the energy system is therefore of vital importance to improve our understanding of this transition. [70,69,74,47,75,61]

Traditionally energy system models are dominated by techno-economic considerations and are generally based on neo-classical economics, equilibria, and the assumption of rationality of decision making agents (which are not explicitly modelled). These models are not able to

capture the change in energy system structure and dynamics of disruption, innovation and non-linear change in human behaviour [56]. This has led to the recognition of the importance of simulating the more realistic behaviour and interaction of different actors (companies, governments, consumers) [48,1,78].

At the same time, the field of sociology and psychology has produced a wealth of knowledge about the decision-making process of groups and individuals which led economists already in the 1950s to conclude that the core assumptions of neo-classical economics (perfectly informed and perfectly rational agents) has its limitations as basis of systems modelling and analysis. This resulted in efforts to increase the realism of economic theory by incorporating findings from psychology in what we now know as behaviour economics [35]. In sociology, the increase in computer power and tools to encompass social behaviour lead to the development of social simulation with agent-based models (ABMs). The development of the complex adaptive system perspective has bundled these findings in a general system perspective that focuses on actor behaviour which can be used in simulation models of the energy system [18].

### 1.2. The role of simulation models

In the broad spectrum of modelling approaches for the simulation of energy transitions, we can distinguish two types of simulation models, empirical models and conceptual models. Empirical models of the

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energy transition often focus on a specific case, e.g. a relatively small scale transition in specific industries (e.g. [8,55,54,17,51]). These empirical models have shown important insights and have highlighted the importance of simulation of realistic actor behaviour to explain historical transitions and future concerns [18,50].

Although global energy transitions have occurred in the past [68], the scale of dealing with global warming makes the world move into uncharted territory. The global energy transition under the influence of global warming therefore has little empirical evidence to relate to. Conceptual models, i.e. those not necessarily fitted to empirical data but based on general concepts and theories and frameworks [27] that capture relevant parts of the energy transition dynamics can help to give insight. These conceptual models are based on metaphors, narratives and images that provide insight and are important instruments that engage public and politicians and bridge different disciplines.

The combination of these qualitative story-lines (narratives) and quantified models is a way to come to grips with an understanding of how this energy transition will unfold [42]. This process is known as scenario development [81]. The scenarios developed by Royal Dutch Shell are a well known example of this scenario practice [59,60]. In these studies, scenarios (combinations of narratives and quantification of these narratives) are used to communicate results of energy models. The combination of qualitative narratives and quantifications of these narratives strengthens the communication about the transitions. The continuous interaction between the quantitative model and the qualitative narrative increases the fundamental understanding of the system at hand.

We recognise the tension between conceptual models that can be characterised as following a KISS (Keep It Simple) approach [2] versus more complicated models following a KIDS approach (Keep It Descriptive) [15,2]. However, large-scale complex simulation models, following a KIDS approach, that describe the system in more detail, suffer from the subsequent large parameter space for which values cannot be determined within a reasonable amount of time, if measurable at all. A common solution is to *fit* the model predictions to empirical data which often lead to impressively good results [62]. However, a good fit does not guarantee any realism of parameter values or model structure. True validation of these large simulation models, some argue, is therefore simply impossible [62,37,73]. Based on this argumentation, this paper will take a KISS approach but deliberately includes descriptive relevant actor behaviour.

### 1.3. Research objective and structure of the paper

The importance of the integration of human behaviour in simulation models (as discussed in Section 1.1), combined with the drive for conceptual models with a quantitative basis (as discussed in Section 1.2), brings the concept of critical transitions [65] into focus. This concept, which we will explore in more detail in Section 2, gives us the possibility to integrate relevant aspects of human behaviour in a conceptual model with quantitative basis. With an agent-based modelling approach we studied the question what the concept of critical transitions can tell us about the influence of relevant behavioural dynamics of actors in the energy transition.

Before we develop such a agent-based model, we must explore the key dynamics of the energy transition in the light of the concept of critical transitions focusing on the role of human behaviour. This we will do in the next section, Section 2. In the subsequent section, Section 3, we present the model design followed by a presentation of the model results in Section 4. We then discuss the model results in Section 5. To put our modelling approach and results in context, we reflected on our modelling approach in Section 6. Specifically we discuss whether this approach is suited not just to gain understanding, but also to *communicate* about the challenges of the energy transition. In Section 7 we lay out our main conclusions.

## 2. Critical transitions

### 2.1. The energy transition and critical transitions

Historically, the energy system has undergone several shifts of dominant energy sources (e.g. from wood to coal and from coal to oil) [68]. Understanding the timescales of these historical transition [71,72] as well as possible future transitions pathways have resulted in the study of *regime shifts* [76], *critical transitions* [65] and several other closely-related fields of research (e.g. [77,33,24,58]). Currently, the most pressing question is the pace of the transition from non-renewable CO<sub>2</sub> energy sources to renewable, decarbonised energy sources in the coming decades [71]. Why is society slow in its response to climate change, and will the required energy transition consist of a fast structural change or will it follow a more gradual and smooth trajectory? These questions on system transition types can be related to the concept of critical transitions and more general to bifurcation theory [34,65].

The concept of critical transitions [65] explores which system characteristics may lead to different types of transitions. It shows the development of a catastrophe fold; when external condition change a bifurcation point can be passed that makes a previously stable system show a critical transition to another system state (see Fig. 1).

Scheffer et al. [65] show several aspects of actor behaviour that are relevant to the analysis of critical transitions. Social aspects such as peer pressure, the absence of leaders, the complexity of the problem and homogeneity of the population can decrease the pace in which society acts to a certain problem (see Section 1). Because of its focus on actor behaviour in transitions this concept is relevant to address the point we made in Section 1.1: the importance of including actor behaviour in models of the energy transition.

An existing conceptualisation of critical transitions focuses on overall system behaviour by using a mean-field approach. Throughout this paper we will refer to this mean-field approach by Scheffer et al. as *existing* or *original* model. The acronym for mean-field-approach, MFA, has been added to these references to increase transparency on what model has been meant. A complementation of this conceptualisation that focuses on relevant *actor* behaviour would give a richer understanding on the role of human behaviour in the energy transition. But what is the relevant actor behaviour from which the different types of the energy transition emerges? This we will explore in the next section, Section 2.2.

### 2.2. Relevant actor behaviour in the energy transition

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

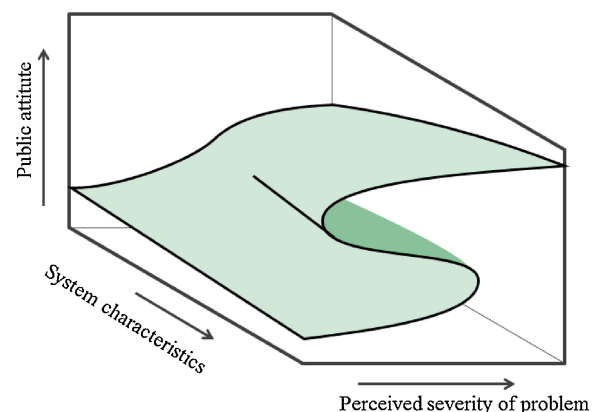


Fig. 1. The catastrophe fold. System characteristics can lead to different types of transitions.

different types of transitions in the context of the energy transition.

The ability of the atmosphere to absorb greenhouse gases can be understood as a *common pool resource dilemma* [46,24]. Common pool resources (CPRs) are defined as open resources for which the physical exclusion of potential users of the resource is difficult (low excludability), while the increased consumption of a user implies that less resource is available for others (high subtractability/rivalry).

The relevant actor behaviour is thus decision-making process in CPR-dilemmas. Work of Elinor Ostrom [45] has highlighted conditions under which a Tragedy of the Commons [28] can be overcome without requiring top-down regulation. Two key aspects that can be distinguished from these conditions and which we will use as model requirements are the following:

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

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

### 2.3. Modelling critical transitions

*Phase transitions* in physics, *critical transitions* in ecology, *non-marginal change* and *regime shifts* in socio-economic literature all share the feature of structural change, often with a perceived sense of abruptness [21]. Although these concepts are discussed in different contexts with different vocabulary, the models that study these dynamics are closely related to each other.

While researchers are usually aware of the limitations, there is a long tradition in applying insights from these different fields of research to structural change in response to societal problems. As a first approximation, Ball [3] showed with examples ranging from ecology, social choice, to (business) economics and political science, that modelling these systems from the viewpoint of statistical physics does seem capable of capturing some of the important features of these social systems.

Several ecologists have applied concepts from ecology to study structural change in socio-ecological systems [30,65,83,29]. One of these, Scheffer and his colleagues, presented the concept of critical transitions and devised a mathematically simple but conceptual rich model of the dynamics of opinion in a society. This concept has been the subject of several influential studies [65,63,66,62,64,7] and has been applied in various other fields such as finance and medicine [10,44]. Although the model is based on ecological dynamics and there is recognition of the difference between societal systems and ecological systems, Scheffer et al. argue that fundamentally these dynamics are similar to processes that determine the character of societal transitions.

Scheffer et al. characterise three types of transitions in the relationship between public attitude about the need to take action against a problem and the perceived severity of the problem: (i) an almost

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

All these models are based on an application of bifurcation theory, [34] which has its foundation in mathematics. They also share the same sort of conclusion; the reaction of system to its changing external conditions can be slow, resulting in hysteresis, a discontinuous shift from one regime to another [3,65].

These conceptual models have been criticised in various reviews stating that these kinds of models “impose over-simple behaviour... and don’t validate strongly against unseen data. Thus whilst such models may have interesting behaviour there is little reason to suppose that they do in fact represent observed social behaviour.” [13] and that “the problem is that they treat social influence in a trivial way” [12].

Although we recognise that conceptual models simplify the complex reality of human behaviour, in standard (techno-economic) energy models they are not treated at all. In Section 6 we will come back to this discussion, discuss critiques in more detail and reflect whether these models can be possibly valued differently. For now we will show in the next section how an existing conceptualisation (MFA) of the concept of critical transitions that focuses on overall system dynamics can be extended and enhanced by incorporating relevant actor behaviour.

## 3. Methods

Inspired by the existing conceptualisation (MFA) of the concept of critical transitions by Scheffer et al. [65] and the requirements identified in Section 2 we developed ACT: Agent-based model of Critical Transitions. With ACT, we altered, extended and implemented, the existing conceptualisation (MFA) to develop an actor approach of the concept of critical transitions. It is conceptual in nature; it is not focussed on a specific location, situation or isolated case but is centered around a conceptual framework (the concept of critical transitions) to reason about the role of human behaviour in the energy transition.

To include this actor behaviour, we designed ACT as an agent-based model. Agent-based modelling (ABM) is a modelling method with which actors, agents in a particular system, can be modelled. In these systems the overall system behaviour emerges from the behaviour and interaction of constituent heterogeneous agents. By applying ABM we could include the relevant actor behaviour and study its influence on the overall system dynamics [80]. With ACT we could depart from the mean-field approach (the assumption that the average attitude of all individual agents influences the action-level of the individual) by simulating more realistic and relevant actor behaviour.

The model is written in the software environment of Netlogo and is accessible online<sup>1</sup> together with a more detailed model description following the ODD protocol [25,26]. This ODD protocol is also available as Supplementary Online Material, see Appendix A.

### 3.1. Model conceptualisation

In ACT agents represent actors in the energy system that faces the problem of climate change. The relevant actor behaviour with which we extended the existing model conceptualisation (MFA) is based on the described actor behaviour which we deduced from actor behaviour in global CPR dilemmas as described in Section 2. This relevant actor behaviour was conceptualised as follows:

<sup>1</sup> <https://www.comses.net/codebases/5836/releases/1.1.0/>.

## Interaction

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

## Heterogeneity

Heterogeneity in ACT consists of two elements:

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

## Non-binary action-level

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

These model elements are well suited to represent relevant elements in the energy system. Table 1 shows how the mentioned elements subsequently are related to the energy transition, the mean-field approach and ACT.

## 3.2. Model design

The conceptualisation translated in the following model design. Discussing this model design we stay close to the original model (MFA) description, and focus on aspects that differentiates ACT from the

**Table 1**

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

Energy transition	Scheffer et al. [65] (MFA)	ACT
Heterogeneity in perceived seriousness of climate change	Heterogeneity in attitude using law of large numbers	Heterogeneity in action level between agents
Social influences by peers	Mean-field interaction	Interaction via networks
Leaders in the energy transition	Not explicitly modelled	Explicit modelled leaders
Continuous action level	Binary action level	Non-binary action level
Uncertainty about climate change	Complete information	Heterogeneous perceived severity of the problem

original model (MFA) and apply it to the problem of climate change. Details on the original model design (MFA) can be found in [62], how we applied this original model (MFA) to the problem of climate change is shown in Table 2.

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

$$V(a_i) = U(a_i(t)) - c(a_i(t) - A_i(t))^2 \quad (1)$$

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

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

When networks or leaders are introduced, the overall influence of agents is normalised following Eq. (2) in which  $n$  is the number of agents within an exogenous determined radius  $r$  of the agent (i.e.  $r = \infty$  for mean-field) and the weight factor  $w_{ij}$  normalises the influence on an agent.

$$A_i(t) = \sum_{j=1}^n a_j w_{ij} \quad (2)$$

Following Scheffer et al. [65] the probability  $P$  of an agent becoming either active or passive ( $a$ ) is defined as:

$$P(a) = \frac{e^{\frac{U(a)}{s}}}{e^{\frac{U(+1)}{s}} + e^{\frac{U(-1)}{s}}} \quad (3)$$

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

$$h_t = \frac{U_t(+1) - U_t(-1)}{2} \quad (4)$$

In the original model (MFA) a parameter  $s$  was defined to incorporate heterogeneity on the perceived severity of the problem. In ACT heterogeneity has been modelled directly via an uniform distribution on  $h$  with bandwidth  $b_h$  to explore the effect of heterogeneity in the perceptions on the severity of climate change (in Eq. (3),  $s = 1$ ). By substituting the current action level of an agent ( $U(a)$ ) with its individual preference of being either active or passive (which is partly based on its peers ( $V(a_i)$ ) in Equation (3), the average tendency for action of the system  $A_{system}(t)$  becomes:

$$A_{system,t} = \tanh(h(t) + 2cA_{system,t-1}) \quad (5)$$

Then solving Eq. (5) for  $A_{system,t} = A_{system,t-1}$ ; giving all the agents the possibility to balance their own concerns with that of their peers, gives the equilibrium overall tendency for action as a function of the severity of climate change  $h(t)$ . Fig. 2 shows a graphical representation of the model structure.



**Table 2**  
Application of mean-field model to the energy transition in ACT.

Abbreviation	Scheffer et al. [65]	ACT
$U_i(t)$	“Utility of being active or passive”	Concern about climate change of individual $i$ at time $t$
$A_{system}(t)$	“Overall tendency for action”	The tendency of the system as a whole to engage in an energy transition
$A_i(t)$	$A_i(t) = A_{system}(t)$	The average tendency of peers of an individual $i$ to engage in an energy transition
$V(a_i)$	“Perceived utility of individual $i$ at time $t$ to become active or passive”	Preference of being either active or passive based on agents’ $i$ concern and that of its peers
$P(a)$	“Probability of action $a$ ”	Probability of becoming active or passive
$h(t)$	“Perceived severity of the problem”	Perceived severity of climate change
$c$	“Cost of taking a deviating position”	Factor that scales social aspects

#### 4. Experiments and results

With ACT several experiments have been conducted with regards to the described relevant actor behaviour. Experiments were conducted with the parameter setting given by Table 3.

Results from these experiments are depicted in Fig. 3. In the three rows of figures, the peer pressure  $c$  between agents has been increased. Figures show the results of 30 model runs. The experimentation of a selection of experiments with 100 runs showed that the experimentation with 30 runs was sufficiently representative with regards to the median and standard deviation of the model outcomes. Depicted are the first and second quartile on both sides of the median (shaded) while the thick lines show the median. Figures were obtained with two scenarios to show the hysteresis of the system behaviour; the perceived seriousness of the problem  $h$ , is exogenously and linearly increased in steps of 0.05, from  $-1$  to  $1$  and subsequently decreased back to  $-1$ , waiting for 20 ticks to reach equilibrium.

Table 4 gives a quantification of the difference between the original mean-field approach and the experimental results. In this table we compared the experimental results (for all  $h$ ) with the mean-field approach, and show the value of  $c$  (in steps of 0.05) at which  $\sigma_e$  is minimal following Equation (6) in which  $A_{system,mf}$  is the result of the mean-field experiment and  $A_{system,e}$  the result of the subsequent experiments

$$\sigma_e = \sum_{h \in H} (A_{system,mf} - A_{system,e})^2 \quad (6)$$

##### 4.1. Mean-field

Our first results showed that with ACT, in which we parameterised the actor interaction as a mean-field, we could replicate the results from the original conceptualisation (MFA) as described by Scheffer’s [65]. With ACT we could explore the effect of additional elements that will be subsequently discussed.

##### 4.2. Network interaction

A key element we distinguished in Section 2.2 is actor interaction. Departing from mean-field interaction, we experimented with nearest neighbor interaction ( $n = 4$ ) as this network is the largest deviation from the MFA with regards to the number of connected agents. The

weight-factor  $w_i$  normalised the influence, simulating energy communities as physical neighborhoods.

Results show the system reacts faster and that a critical transition is less likely but is still possible. Similar results were obtained when experimenting with interaction within the small-world network.

##### 4.3. Heterogeneity

Experiments have been carried out with regards to heterogeneity in the perceived severity of the problem. Agents were given an individual perceived severity of the problem  $h$ , based on an uniform distribution with bandwidth  $b_h$ .

Results from these experiments show that heterogeneity of agent opinions has an influence on model outcomes if we compare those results with the mean-field experiment. Heterogeneity makes the system react faster to a worsening problem and a critical transition is less likely but still possible. This reflect the fact that allowing for a larger heterogeneity, actors are included that change relatively early from inactive to active (or vice versa).

##### 4.4. Influence of leaders

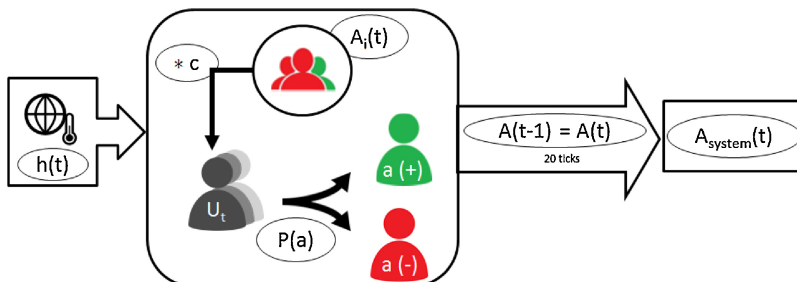
The second aspect of heterogeneity we explored is the influence of leaders. We experimented with the heterogeneous influence  $l_i$  of agents in the system which were normalised with the weight factor  $w_i$  (see Table 3).

Results show the experiment where 10% of agents are leaders with 5 times ( $l_i = 5$ ) as much influence as normal agents. These results show that leaders cause inertia; a critical transition is then more likely. This result contradicts existing literature on the effect of leaders with regards to critical transitions concept. This is due to a difference in conceptualisation of leaders. We will come back to this issue in Section 5.

##### 4.5. Non-binary action level

To explore the effect of the restriction to a binary action level, we experimented with the possibility for a non-binary action level by allowing for a third option  $a = 0$ .

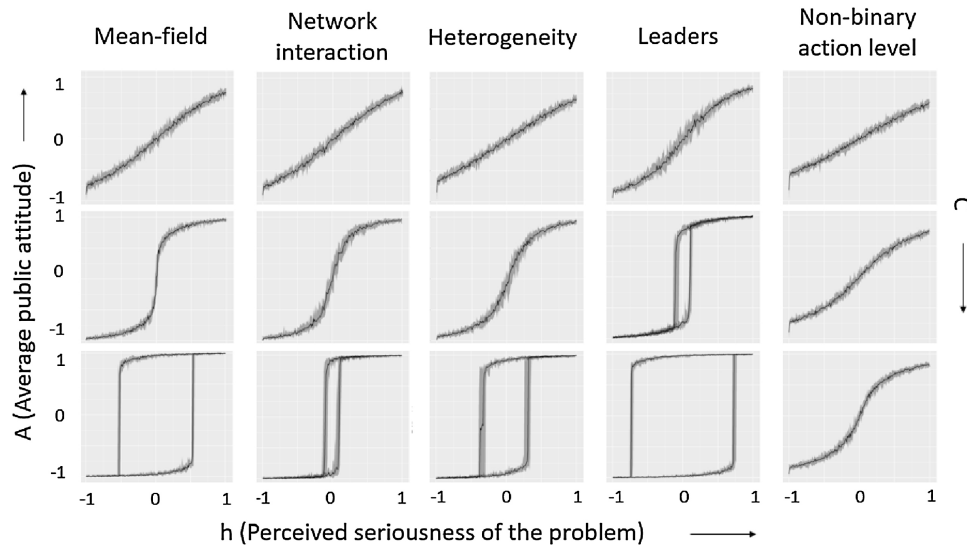
Results show that if we allow for a neutral action-level the critical transition disappears completely.



**Fig. 2.** Model structure. The chance ( $P(a)$ ) of an agent becoming active or passive depends on their current concern about the climate ( $U_i(t)$ ), the perceived severity of climate change ( $h$ ), the average tendency of its peers ( $A_i(t)$ ) and  $c$ , an factor that scales social aspects. Each agents makes a choice to be become active or passive which results in a new equilibrium  $A_{system}(t)$ .

**Table 3**  
Experimental design.

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



**Fig. 3.** Results of the ACT model. The most left column shows the replication of the mean-field experiment. Subsequently the results for network interaction, heterogeneity, leaders and non-binary action level experiment are depicted.

**Table 4**

Comparison between mean-field experiment and subsequent experimental results.

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

## 5. Reflection on model results

The concept of critical transitions highlights several aspects of the energy transition. It argues why society so far has been slow to respond to the dangers of climate change and highlights aspects we should keep an eye on as they can trigger a future critical transition. The model results as they have been presented in Section 4 give rise for the following observations:

### 5.1. Complexity of the problem

Scheffer et al. argue that the increased complexity of a problem decreases the pace in which society will take action. When a problem is very complex, the perception of individuals of that problem is diffuse and the perceived effectiveness of action is low. This makes that individual's opinion will depend more on the opinion of its peers and authorities [65]. Modelling the increase of complexity thus boils down to modelling an increase in peer pressure. Increasing peer pressure in ACT confirms this view; a slow response to an increasing worsening of the problem and a higher change for a critical transition.

### 5.2. Influence of leaders

Scheffer et al. [65] argue that in highly centralised/more authoritarian decision making structures, leaders are a positive driving force for the prevention of a critical transition. Our research however nuances this view. With the use of a richer model, results shows that the 'real world' emergence of champions of change will naturally bring forth champions of status quo representing vested interests. Either leaders can be understood as actors that initiate action (as Scheffer et al. argue, "once the central authority is convinced of the need for change"), or as simply more influential actors that can possibly represent vested interests and can obstruct action. We therefore conclude that when the role of leaders in the energy transition is discussed, an clearer understanding of the role of leaders is necessary.

### 5.3. Collective action problem and the importance of energy communities

Model results from our network experiments confirm insights from economists [45] and game theoretic modellers (e.g. [2]) that address the collective action problem. They distinguish *noticeability* as important aspects to promote action in groups. This also relates to *observability* of innovations, as Rogers [57] suggests that "the observability of an innovation as perceived by members of a social system, is positively related to its rate of adoption". Our model results are in line with this thinking; decreasing the radius of peer-influence increases the ability of the whole system to take early action. In societies where decision making power is decentralised the existence and action readiness of local communities therefore become a critical element [82]. Relating this to an observed practise in the energy transition we have seen that in Germany local communities triggered the German *Energiewende* [43,76,85,31,4]. Copying this success has shown to be

difficult [36] but has highlighted the importance of specific aimed policies [11] and the need for time to build up momentum [43]. This is recognised in the concept of critical transitions; it highlights the problem of slow response of society to the problem of climate change. In decentralised systems, local communities however have proven to be able to initiate a positive shift to a more sustainable system [32,67,4].

#### 5.4. Polarization

Several key players (i.e. the United States and Western Europe) in the energy transition have shown increased polarization of their society not in the least on the issue of global warming and climate change [39,6]. It can be argued that polarizing societies will have less heterogeneity of opinions, the result of which we showed in experiments looking at heterogeneity. Decreased heterogeneity can lead to group-think. The effect of group-think in problems such as climate change has been explained as cognitive dissonance; the tendency to ignore contradictory information from an individual own opinions [20,75]. Our results confirm the idea that polarised societies will decrease their ability to act upon problems such climate change and the need for an energy transition.

#### 5.5. Modelling critical transitions

##### 5.5.1. Modelling non-linearity in the energy system

We distinguish three sources of non-linearity in the energy system. Firstly, there is the cost decline of technology due to technical progress and economies of scale. This leads to so-called tipping points where new technologies outperform incumbent technologies, leading to accelerated (non-linear) change. Secondly, there are ‘events’ that change – in colloquial terms – the rules of the game, i.e. from one moment to the next the actor's outlooks have changed as do (consequently) behaviours. Related to climate change such events are for instance (climate induced) natural disasters and pivotal political moments (the signing of the Paris accord might be a candidate). Thirdly, there is the iterative bidirectional interplay between system elements such as actors. Simulating the non-linear character of the energy system and the energy transition would require modelling these three elements. Modelling of ‘events’ is illusive; this can only be brought in exogenously, and must be supported by a narrative. The second element is outside of the scope of this paper. But our model and the concept of critical transition gives us the mathematical as well as qualitative construct to simulate the last point: how iterative actor interaction influences their behaviour, changing over time as the external environment develops. This goes a long way to model the emergent behaviour in this complex system.

##### 5.5.2. Energy scenarios

The results of such experiments and the experiments in this paper can be related to energy scenario studies. In the latest New Lens Scenarios [60], earlier described as example of scenario development studies, a qualitative storyline is shown to which we can relate to with ACT. The study presented two possible pathway lenses: Room to Manoeuvre where an early crisis leads to punctuated reform, and a Trapped Transition where no action is taken until an existential crisis leads to either ‘write-off reset’ or ‘decay/collapse’. These abstract narratives were the basis for the two scenarios Mountains and Oceans that apply these narratives to assumptions on the possible evolution of the energy system. Fig. 4 shows a summary of the results of the experiments and how the critical transition theory would be applicable to the Shell's pathway lenses.

## 6. Reflection on modelling approach

The energy system is a multi-dimensional complex system that consists of many interacting subsystems. ACT on the other hand is a

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

To formulate an answer to that question, let's for a brief moment look at the discussion around one of the first and maybe the most criticised global energy system modelling study: The Limits to Growth (LtG) [40]. The (compared to its scope) relatively simple model was used to support a narrative on the limitations of a finite planet and its consequence for population and economic growth and in this way illustrated an argumentation that the authors of LtG had about the world and its future development. The LtG study is a part of a broad tradition of energy system models. As we argued earlier (Section 1.2, the scenario development process of Shell and many other scenario studies can also be seen in this context.

Since the publication of the LtG study four decades ago, it has been the subject of wide range of criticism and even recently has been used as an example of over-hyping model success [14]. Although various categorisations of critique exist [5], we will focus on two main types, technical and epistemological, in order to later reflect on the results we deduced from ACT.

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

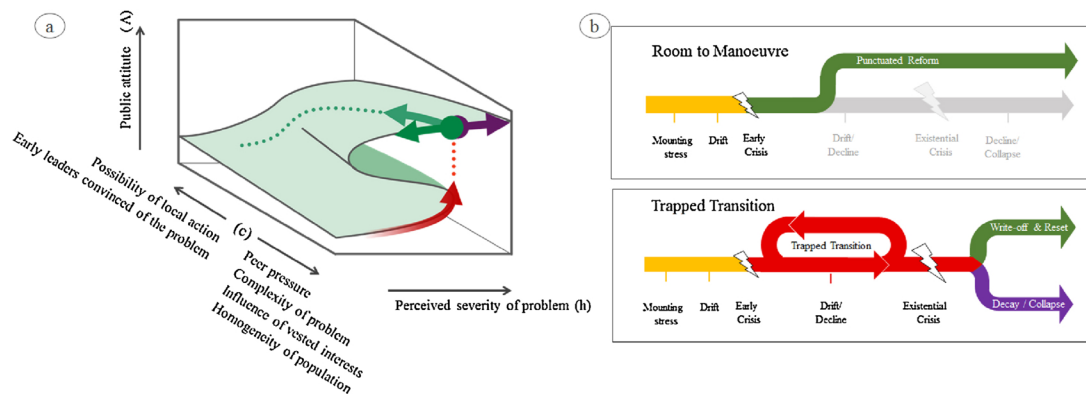
The epistemological criticism has focused on whether anything can be learned from highly aggregated and abstract models. Edmonds [14] has characterised LtG as an analogical way of modelling that is not scientific as it made the impression of being predictive while unsupported by evidence. Although the authors of LtG themselves were aware of these limitations,<sup>2</sup> the model has been perceived by the general public as a prediction.

This epistemological criticism shows the danger of this type of modelling which can be brought down to its duality of means: (i) convince with a particular line of argumentation formulated in a narrative and (ii) illustrate with a quantification by the use of a model and its outputs. Although LtG was published with unpretentiousness with regards to its quantification, its purpose with regards to its narrative was to convince the general public about the limits to growth. Critics however focused on the weakest link, namely the quantification, and interpreted it as a detailed forecast. This is an often seen reaction to scenarios; quoting Michael Liebreich: “if it looks like a forecast, swims like a forecast and quacks like a forecast, it is a forecast... And if that is not the intention, why publish it at all?” [41]

Similar to Edmonds [14], Ehrenfeld [16] distinguishes *analogical modelling* and the use of *metaphors*. Ehrenfeld argues that whereas metaphors are figures of *speech* and suggestive, an analogy is a *practical notion* that compares two cases and suggests an alternative way of

<sup>2</sup> Quoting LtG [40]: “Can anything be learned from a highly aggregated model? Can its output be considered meaningful... The data we have to work with are certainly not sufficient for such forecasts, even if it were our purpose to make them” And stating that the outputs “are not predictions of the values of the variables at any particular year in the future. They are indications of the systems behavioral tendencies only.”.





**Fig. 4.** Summary of results and comparison with the Shell Scenarios. (a) Shows relationship between average public attitude ( $A_t$ ), the perceived seriousness of the problem ( $h$ ) and social aspects described by the parameter  $c$ . Figure shows relationship between critical transition theory and Shells “Pathway Lenses” (b) as building blocks for energy scenarios (adapted from [60]).

addressing the situation based on the presumption that they share similar properties and dynamics. However, completely different mechanisms may be at play. Therefore, while a metaphor can never be wrong (although its usefulness can be questioned), an analogy can be objectively false.

Ehrenfeld observes that often a metaphor is used as a useful starting point of analysis. When the system understanding comes from the source of the metaphor ‘learning by analogy’ has occurred. Learning by analogy is different from the normal scientific method (as shown in Fig. 5) and has been disputed as Ehrenfeld argues that learning by analogy is not necessary as the rules can be invented by independent observation and deduction of the system at hand. The application of the concept of critical transitions to a societal system is an example of learning by analogy; originally applied to analyse ecological systems a metaphor has been deduced which was applied to construct a model of society.

The usefulness of these conceptual models based on analogies is in doubt. Some researchers claim that although they “are extremely useful things... this is not scientific knowledge... reliable conclusions have to be based on evidence so they can be relied upon” [14]. This reflects the thought that science is supposed to be about exact reasoning, leading to certainty. This scientific method requires falsifiability [49]; and thus the process of validation. The process of learning by analogy can therefore be classified as non-scientific as the argument that a certain analogy is appropriate is a subjective qualification.

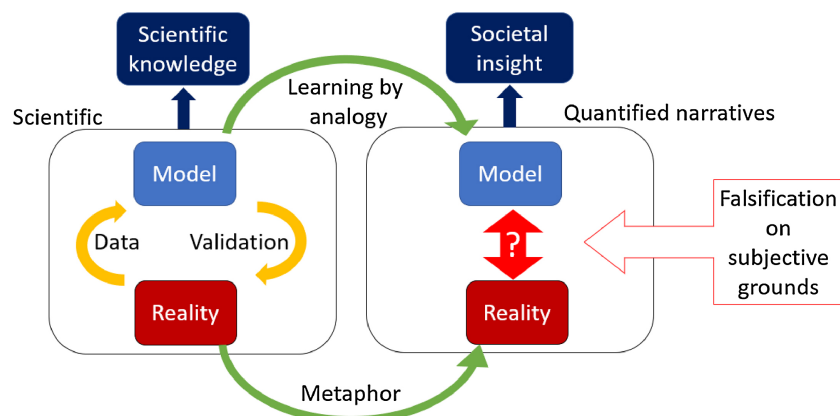
However, in cases where facts are uncertain, values in dispute, stakes are high and decisions urgent, scientists have argued that traditional science as puzzle-solving is “at best irrelevant and at worst a diversion” [52]. Falsification in these cases can only be done on

subjective grounds, as there are no objective grounds to falsify on. (Fig. 5 shows the relationship between a normal scientific modelling study and what the role is of metaphors, analogies and falsification on subjective grounds.) In fact Ehrenfeld [16] recognises that this ‘unknowability’ demands a whole different kind of science and decision making process.

Researchers therefore have advocated the use of post-normal science [22,23]. They argue that, as the future is fundamentally unknowable especially on longer time scales, scientific models can be used as having a metaphorical function [53,9], designed to teach us about ourselves and our perspectives under the guise of describing and predicting the future state of the planet. Although this approach is different from the traditional understanding of scientific knowledge, it can help science to adapt and being useful for sustainability challenges in a complex world.

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

Based on this argumentation and reflecting on this modelling study we therefore would argue that the application of the concept of critical



**Fig. 5.** Learning by analogy. Left-hand figure shows a methodology that can be qualified as scientific where data informs a model which can be validated and falsified. Right-hand figure shows learning by analogy where insights can be generated but where the falsification is done on subjective grounds.

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

## 7. Conclusion

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

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

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

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

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## Supplementary Online Material.

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