Modelling the Energy Transition: Towards an Application of Agent Based Modelling to Integrated Assessment Modelling

Oscar Kraan, Gert Jan Kramer, Telli van der Lei, and Gjalt Huppes

Abstract To attain a better understanding of the energy transition we have applied Agent Based Modelling (ABM) to Integrated Assessment Modelling (IAM) in an abstract model with which we developed a proof of concept model of society's response to a changing climate and energy system. Although there is no doubt that large scale neoclassical IAMs have provided key insights for business decisions and policy makers, we argue that there is a need for an approach that focuses on the role of heterogeneous agents.

With our abstract ABM based on agents with heterogeneously spread discount rates we were able to give a new perspective on appropriate discount rates in the discussion between mitigation and adaption to climate change. We concluded that applying ABM to IAM yields good prospects to the further development of the implementation of society's response to a changing environment and we propose future additions of the model to include adaptive behaviour.

Keywords Integrated assessment modelling • Agent based modelling • Cost–benefit analysis • Mitigation • Adaptation • Climate change

1 Introduction

Since we only have one Earth and hence no possibilities to experiment, we use energy models and their resulting scenario's to understand the dynamics of the energy transition from a fossil fuels based to a zero-carbon emission energy system and quantify narratives about how this transition could evolve [1]. The response

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of society to a warming climate with its associated unclear consequences on the economy and biosphere are substantially uncertain because it is faced with difficult trade-offs that have different time horizons to address the problem [2].

With this in mind it is not surprising that there is a growing scientific recognition that there is a need to focus attention to model the economy, the energy system and its environment from the bottom up concept of complex adaptive systems (CASs) [3–5]. CASs are systems that are shaped by decision by heterogeneous adaptive agents on different levels such as countries, companies and individuals. We have applied this concept with the use of agent based modelling (ABM) with which we could focus our attention to the integration of society's response to a changing climate and energy system into integrated assessment models.

At the moment, most large scale top down models that combine climate and economy, the so-called integrated assessment models (IAM), rely on more or less elementary forms of the prevailing neoclassical theory of economic growth modelled with computer equilibrium models. Although there is no doubt these IAM and other neoclassical energy models (for an overviews look at [6]) have provided key insights for business decisions [7] and policy makers, "a basic problem is the underlying paradigm of an intrinsically stable economic system that follows an optimal growth path governed by the investment of perfectly informed rational actors maximizing a universal intertemporal utility function" [8]. Other researchers have distinguished the same problem [9, 10].

The development of behavioural economics in the field of economics [11] and the development of the field of complexity science in computer science has given rise to increased attention to the integration of society's response to the energy transition in IAM with ABM [3, 8, 9, 12]. ABM is used to simulate complex adaptive systems (CAS) such as the energy system [12] and is well suited to model adaptive heterogeneous agents that, based on their decisions, can be part of emergent system behaviour. Whereas previous studies such as [13] used ABM to show the role of adaptive change of agents this study focuses on the heterogeneity of agents.

To address the need for a better understanding of the energy transition and to quantify narratives of worldviews on how this transition can happen based on heterogeneous adaptive agent decisions, the conceptualization of an ABM should start with the simplification of the energy transition to its key characteristics and the assumption on how agents make decisions.

This study shows the results of a proof of concept agent based model of the energy transition within which heterogeneous agents apply a classical cost–benefit analysis (CBA) to the problem of mitigation versus adaptation. Future adaptive behaviour aspects to add to this model are proposed.

2 Background

2.1 CBA and Discounting

Research has put a lot of attention to the timing of mitigation versus adaptation [14] with the use of CBA [15]. CBA is an economic analysis to evaluate options generating costs and benefits on different time-scales [15]. These costs and benefits are evaluated on their present value by multiplying them with the discount factor which depends on the applied discount rate. The assumption that humans and animals discount the future has been proven by empirical studies in economics and behavioural ecology [16]. The large time lag between when society incurs the cost and reaps the benefits of decisions by agents to mitigate climate change makes a CBA sensitive to the discount rate.

Because of the non-linear characteristics of earth's climate the exact relationship between GHG emissions and a warming climate (the climate sensitivity) and the effect of a warming climate on our economy (the socio-economic sensitivity) [2] and biosphere are for a large part uncertain. This gives rise to different ethical worldviews about how to solve the problem of a warming climate. These different worldviews translate to some extent to the different discount rates researchers apply.

Researchers have questioned how these different worldviews should be incorporated in IAMs and what discount rates would be appropriate [16–18]. The spectrum is stretched by on the one hand Stern applying a near zero pure rate of social time preference, and Nordhaus applying a market conform discount rate. However there is general consensus among scholars that total climate change damages are larger with larger cumulative CO_2eq stabilization levels [19].

Our ABM can account for these different worldviews by modelling heterogeneous agents that apply different discount rates in their individually applied CBA. Other scholars have argued that CBA is of limited use to evaluate decisions to mitigate climate change because of deep uncertainty in the climate and socio-economic sensitivity [20]. By acknowledging their contribution to the discussion on CBA in IAM, we argue that by addressing the uncertainty with sensitivity analysis on key variables, the model is fit for purpose.

3 Conceptualisation of the Model

3.1 Purpose

The purpose of the model is to simulate the energy transition and quantify narratives about how such a transition can evolve by narrowing the system down to its main characteristics. More specific we try to give a new perspective on the appropriate discount rate in models that discuss mitigation and adaptation to climate change. The emergent system is described by the CO_2eq emission level and the system costs at the end of the runtime of the model. The model is written in the software environment of Netlogo. Its code and the exact equations for the variables can be made available by the author upon request. The model has been validated with recording and tracking behaviour, single-agent testing and multi-agent testing as proposed by Van Dam [21].

3.2 Agents and Their Environment

The system is composed by one type of agent, that represent members of society in all its forms, business decision makers, country representatives or individual consumers that use fossil fuels and can make a decision to invest in a GHG-mitigating technology based on individually performed CBA. The timescale is arbitrary but notionally equivalent to the year 2100.

Agents are assumed to emit a standard unit of CO_2eq emissions which over time results in cumulative stock of CO_2eq emissions. Agents have a binary choice to mitigate these emissions completely. This decisions results in a cumulative investment in mitigation technology. The investment costs of a mitigation technology are assumed to go down exponentially based on the learning curve of these technologies.

How the adaptation costs, in our model equivalent with the climate change damage costs, actually will evolve is faced with uncertainty. The model assumes a climate change damage function which represents the adaptation costs agents have to make. This damage function is a function of cumulative CO_2 emissions with a large parameter bandwidth reflecting the deep uncertainty on climate and socio-economic sensitivity. This parameter bandwidth is expressed with the curvature of the adaptation-cost function, as well as it's begin and end points. When referred to the "normal" adaptation-costs function, we refer to an exponential upward curve as other researchers have identified as most probable [16].

The worldview of an agent on how adaptation costs will evolve is expressed by the discount rate which translates in a discount factor that exponentially depends on time and the discount rate. The discount rate is randomly given to agents based on an exogenous discount rate distribution, is fixed to the agent and is uncorrelated to their.

The summation of the present value of benefits an agent will gain by mitigating now is the summation of the present value of avoided climate change damages over the years, reflecting the difference between climate change damages with or without the cumulative emissions an agent would have emitted when he would not have made the investment (business as usual (BAU)) (Fig. 1).

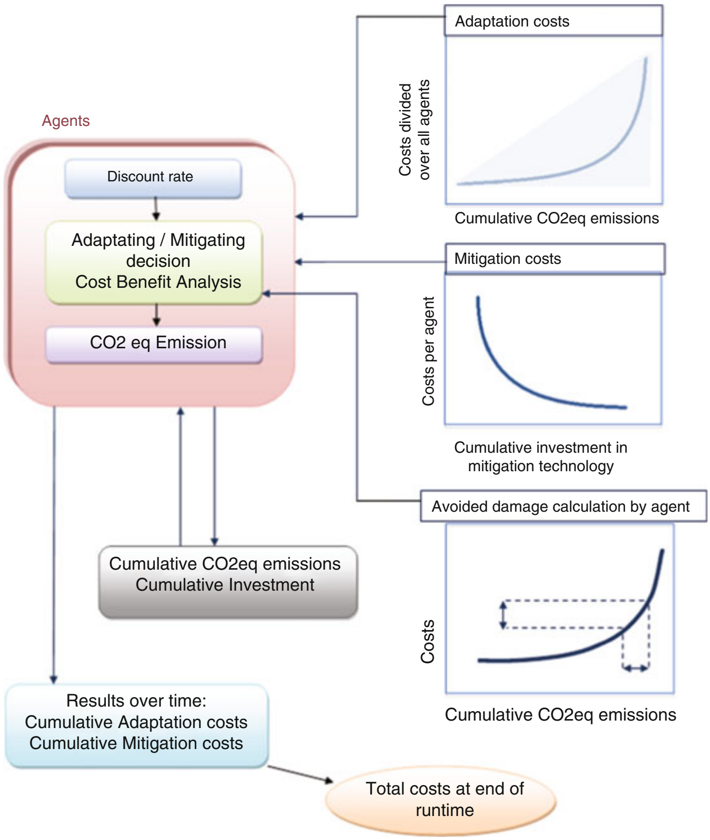


Fig. 1 System description

4 Narratives

The conceptualisation of the models finds it origin by agents in reality at different levels. Individual consumers will realistically not take into account the specific adaptation costs they prevent when they invest in solar panel because of the large sensitivity in the climate and socio-economic system. However, mitigating agents intuitively do understand that they make a small contribution to a better world.

If we look at country level we could argue that agents will take the benefits for avoided climate change adaptation more seriously as they can mitigate a larger percentage of the total cumulative GHG emissions in the BAU scenario by imposing policies and regulation on to their agents. However, due to the political lifetime in the different political systems they will have a longer or shorter foresight which they take into account.

The trade off between mitigating and adaptation is difficult because of their different time horizons. If agents mitigate now because they apply a low discount rate, agents will possibly avoid GHG emission which will not have a large influence on the economy for later generations. Due to the high uncertainty in climate and socio-economic sensitivity mitigation can been seen as insurance for more influential adaptation. However, by investing to late because of a worldview that supports a low climate change damage function, climate change damages can hardly be avoided because relatively small contribution mitigating will have on the cumulative CO_2eq emissions and of the large time lag in the climate system.

5 First Results

In Figs. 2 and 3 the first results of our model with 10 runs on each setting of 100 agents are presented. On the first row on the left hand side we see the typical analysis by Stern; all agents applying a discount rate of zero. On the first row on the right hand side we see the typical analysis by Nordhaus, all agents applying a relative high discount rate. Further down the rows, we have introduced heterogeneity among the agents by enlarging the standard deviation of the discount rate distribution which are depicted in Fig. 4.

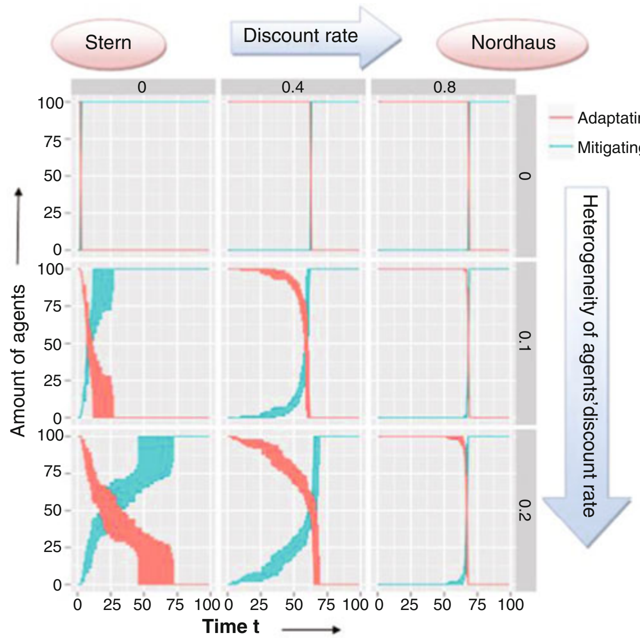


Fig. 2 Development of types of agents over time

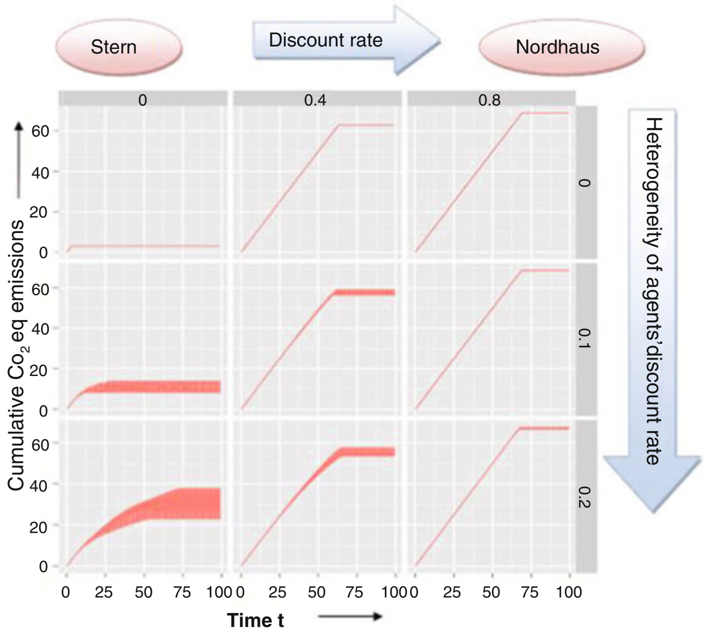
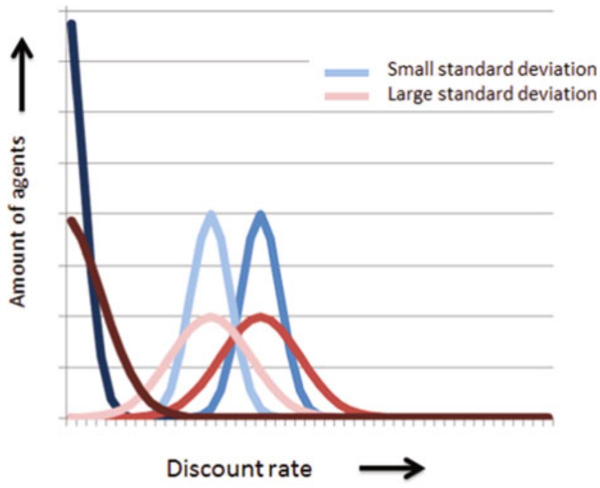


Fig. 3 Development of cumulative CO_2 eq emissions of all agents over time

Fig. 4 Distribution of discount rates



This resulted in a bandwidth of pathways as indicated by the coloured area in Fig. 3. The actually figures are arbitrary but we can distinguish behaviour features of our model. As expected, with no heterogeneity, all agents move together, the higher discount rate they apply, the later they move from adaptation to mitigation.

In the cumulative CO_2 equivalent curves, Fig. 3, we see that under our assumptions about the climate change damage function and mitigation technology costs, mitigating later yields a higher cumulative CO_2 equivalent level stabilization level, as expected.

6 Future Additions

We have used heterogeneous agents within a neoclassical IAM model of the energy transition and with that we have made a start with introducing ABM within IAM. To get a more realistic simulation, we propose to add adaptive behaviour to our agents. Agents worldviews, represented by applied discount rates would not only be heterogeneously spread, but could also made dynamic, individual worldviews could change under influence of different factors. Here we propose two options.

6.1 Agents Within Agents

We can argue that the energy system and its decision makers are actually agents within agents. Ostrom supported a polycentric approach to battle climate change in which she argued that policies and regulations should be discusses at various levels, not only from top down [22]. Individual consumers make up the decision structure within in a country which is an agent at the negotiator table on international conferences. More concrete, if a large enough critical mass of agents supports mitigation, an agent at the second level will decide that all agents at the first level will have to mitigate. This structure of agents within agents can of course be stretched to include city councils, companies, provinces, and NGOs. but fact is that agents can be formed at different levels. In this way agents will influence each other and the evolution of institutions on various levels can be investigated.

6.2 Multi-criteria Analysis

Decisions between mitigating and adaptation are a combination of economic considerations and societal and political judgments. Therefore we propose another way to implement adaptive behaviour and bounded rationality in to agents with which we can let agents make decisions between mitigating and adaptation on more arguments than only our classic CBA. Ostrom and other scholars have tried to distinguish several design features of systems where this group rationality has the biggest chance to flourish [22].

The integration of different criteria on which agents make decisions can be done with the use of multi-criteria analysis. In multi-criteria analysis agents can give weight to different aspects which are scored from 1 to 10. The result of the overall score gives a measure for decision making.

Factors that could be included are the fact that agent are motivated by leadership, non-monetarily expresses ecosystem services, reciprocity of their network and reputation.

7 Conclusion

Like other researchers before us, we have argued that models that try to simulate the energy transition should use integrated assessment modelling combined with agent-based modelling to more realistically model society's response to climate change. Although the results can be discussed in view of the many uncertainties, simplifications and assumptions, we do feel that with the conceptualization of our model we have presented some basic aspects of behaviour of members of society which are present in the real world. We have done this by given a new dimensions to the ethical discussion on the use of appropriate discount rates to use in the light of possible consequences of climate change by distributing heterogeneous discount rates among the agents within the ABM.

Our model gives a first proof of principle of the use of agent based modelling within integrated assessment modelling with the aim to further develop models with more realistic agent behaviour.

We can conclude that applying ABM to IAM yields good prospects to the further development of the implementation of society's response to a changing climate and energy system.

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