EVS30 Symposium
Stuttgart, Germany, October 9 - 11, 2017

Electric mobility in view of Green Growth

Sarah Wolf[1], Steffen Fürst[1], Andreas Geiges[1], Gesine A. Steudle[1],
Jette von Postel[1], Carlo C. Jaeger[1,2]
[1]*Global Climate Forum, Berlin; Sarah Wolf (corresponding author) sarah.wolf@globalclimateforum.org*
[2]*Arizona State University*

Executive Summary

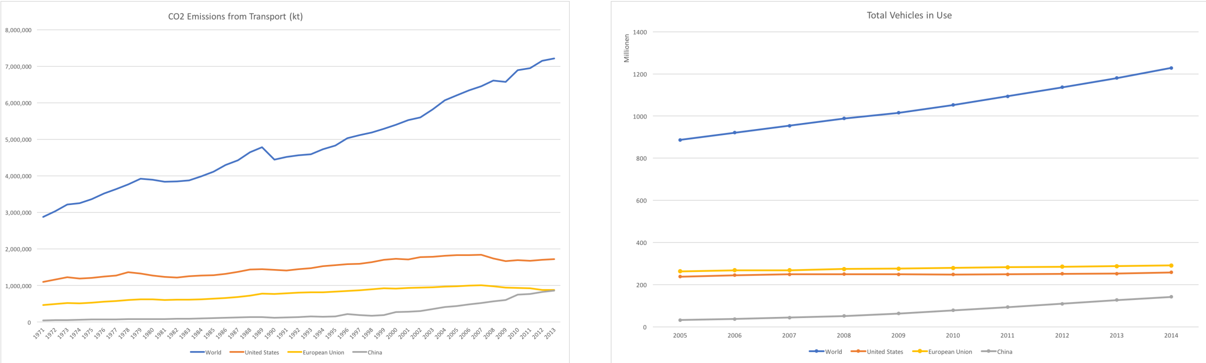
A transition of the global car market towards electric mobility can play a part in turning the risk of climate change into an opportunity of green growth, that is, in increasing environmental, economic, and social well-being. This paper presents work in progress on a global-scope high-resolution simulation model for analysing potential evolutions of the gobal car fleet, and in particular the diffusion of electric vehicles within it. Grounded in Global Systems Science, the approach takes a systemic perspective, draws on the framework of extended evolution, and uses agent-based modelling. Our aim is to engage with, and invite feedback from, the experts on various aspects of electric mobility gathering at this symposium.

Keywords: modeling, car, EV (electric vehicle), consumers

1 Introduction

"Green growth" is described by the OECD as a "twin challenge: expanding economic opportunities for all in the context of a growing global population; and addressing environmental pressures that, if left unaddressed, could undermine our ability to seize these opportunities."[1]
The global car fleet, counting more than 1.2 billion vehicles and growing, is expected to reach 2 billion by 2030 [2]. It contributes to environmental pressures, in particular, in terms of air pollution and CO_2 emissions; in the US, the transport sector has superated the power sector to become the number one emitter [3]. Currently, about 2 million cars, that is, much less than one percent of the global car fleet, are electric vehicles [4].
With increasing pressure to reduce CO_2 emissions of the transport sector, following from policies for avoiding climate change, with millenials not buying as many cars as previous generations did [5], and with the "3 revolutions" of vehicle electrification, automation and shared mobility [6] in sight, the global car market seems to be facing a transition. Traditional car manufacturers acknowledge this: Mary Barra, CEO of General Motors, believes "the auto industry will change more in the next five to 10 years than it has in the last 50" [7] and Volkswagen's CEO Matthias Müller has announced the company's deepest transformation since its foundation in the wake of its diesel emissions scandal [8]. The fact that Tesla has recently superated both Ford and GM in terms of market capitalisation, while producing a fraction of a percent both of the number of cars and of revenue in comparison with either of the traditional manufacturers, points to a strong belief of investors in the future of electric mobility [9].
Our research question on electric mobility in view of green growth is how a transition of the global car market can be achieved in such a way as to realise economic and environmental benefits at the same time, that is, to turn the risk of climate change into an opportunity of green growth. Therefore, we work on analysing potential future evolutions of the car centered global system. Rooted in Global Systems Science, our approach takes a systemic perspective, draws on the framework of extended evolution, uses agent-based modelling, and considers stakeholder engagement essential. In particular, we here present work in progress on a global-scope high-resolution simulation model for analysing the diffusion of electric vehicles in order to engage with and invite feedback from the experts on all kinds of aspects of electric mobility gathering at this symposium.
The remainder of this paper is organized as follows: Section 2 briefly introduces concepts and methods employed. Section 3 specifies the car centered global system, and Section 4 presents the modelling

Figure 1: Trends in CO_2 emissions from transport (left) and numbers of total vehicles in use (right)



work in progress with first results. Section 5 sketches two directions of further work, before Section 6 concludes.

2 Concepts and methods

This section briefly discusses the concept of green growth in general and with reference to the car centered global system. It sketches the field of Global Systems Science (GSS) in which this work is rooted, and some helpful concepts from the field of extended evolution. Finally, the tool of synthetic information systems is briefly introduced.

2.1 Green growth

The concept "green growth" comes with many definitions in the literature (see, e.g., [10, 11] for a collection and a review, respectively); however, this paper is not the place to go into these. Here, we define green growth with respect to "business as usual" (BAU) or "brown" growth. For simplicity, given a plausible growth path of the world economy in the 21st century, we may consider "green growth" those growth paths where at any point in time GDP growth is greater and greenhouse gas emissions are lower than along the brown path. Similarly, such a "relative" definition can be given in terms of other or more indicators for environmental, economic, and social characteristics of the world's development path. "Inclusive green growth" [12] can be defined by adding that inequality should also be lower than in the reference BAU path at any point in time, etc.

This paper is to be seen in the context of previous work [13, 14, 15] which has shown that climate policy, together with a set of other policies, has the potential to trigger a shift to green growth via the following mechanisms: given the current, fossil fuel based economy, a serious decarbonisation requires large investments. Large investments entail growth, jobs, and technical progress. However, no single economic actor has the potential to provide such large investments alone, and incentives for investing into a green economy are little as long as there is not a coordinated move towards it. Strict climate policy, combined with a credible investment impulse, can be the signal needed to re-coordinate investors' expectations towards green growth. Once triggered, the virtuous circle of investors' expectations, investments, technical progress and growth can keep the economy on a green growth path with larger investments, lower unemployment, higher growth, and lower emissions than in the BAU case.

Moving from the macro-economic view to a certain sector (transport) or activity (mobility), as is the case here, definitions cannot be adapted by simply replacing the economy by this sector in a one-to-one manner. While emissions reductions achieved within a sector can be considered separately, the accompanying transition in economic terms may go beyond this sector. For example, jobs lost in a "brown" sector may be replaced by jobs in other sectors rather than in a "green" counterpart of the original sector. A macro-economic view is therefore still necessary to consider green growth opportunities arising from a certain sector.

Considering green growth from a mobility perspective, emissions from the transport sector (about 70% of which are produced by road transport) are of particular interest. In contrast to important other sectors, the global trend is increasing ([16], and see Figure 1 (left)). In a plausible BAU growth path for the 21st century, this trend is likely to continue, not least because global numbers of cars are likely to keep increasing (see Figure 1 (right)). This trend reflects increasing wealth of the population in large parts of the world; at the same time, increasing income generally comes with increasing mobility needs [17],

which constitutes a feedback effect that stabilises the trend in global car numbers. Reversing the trend in transport emissions without curbing benefits (e.g., in terms of growth or employment) that relate to the existing trend in car numbers would lead to a green growth path with respect to mobility; with the above relative definition, slowing down the emissions trend compared with the BAU scenario is a sufficient criterion for "green".
However, one exact definition is not the point in this work. The global systems perspective and modelling tools used here (described below) allow for observing a large number of indicators in model runs. For example, in a model with high spatial resolution, the numbers of cars with an internal combustion engine can be aggregated to the level of cities, municipalities, etc. This allows to estimate, for example, not only greenhouse gas emissions, but also levels of air pollution in some areas of interest such as megacities. "Green growth" can then be defined on a case to case basis in terms of those indicators most relevant for a given study.

2.2 Global Systems Science

Global Systems Science (GSS) is an emerging research field that combines data-driven computer simulation modelling with engagement of stakeholders and citizens to support decision makers faced with global challenges (see, e.g., [18]). Green growth is such a global challenge due to the long-term and global-scope effects of (local) greenhouse gas emissions from the activities of up to 7 bn people.
On global challenges, a systemic perspective needs to be taken to develop evidence and understanding on the underlying global system and its potential future evolutions, in particular for looking at potential effects of alternative decisions.
GSS has a policy informatics side – it describes global systems with the help of computational tools (see Section 4 below) – and an engagement side: ongoing dialogues between modellers and decision makers help shape a simulation model in the most useful directions, so that it can address the questions decision makers have. Further, and more importantly, many of the details in addressing a global challenge involve value judgements and human behaviour. Understanding a global system and evaluating policy options includes engaging citizens in the policy-making and policy evaluation process at an early stage.
Global systems are complex systems, made up of a multitude of heterogeneous actors and other elements interacting in complex networks at multiple scales, giving rise, for example, to feedbacks in and path-dependency of the system evolution. This evolution is non-deterministic; the open future not only results from the systems' complexity which prohibits knowing all the details that would be necessary to describe such a system exactly, but also from its reflexivity: actors in the system can react to predictions made about the system, thus potentially invalidating these.
A first step in analysing a global challenge is therefore to identify the global system to be studied. The car centered global system considered here will be sketched in Section 3.

2.3 The framework of extended evolution

In conceptualising the open future of the car centered global system, the framework of extended evolution [19] provides a useful anchor. This framework considers not only random mutations of genes and natural selection according to fitness, but also regulatory networks (which determine the sequence and intensity in which genes are activated) and niches (the environment an organism lives in, that has often been shaped by earlier generations of the same kind of organisms) as important factors in the evolution of species.
Analogies between biological and technological (or, more generally, cultural) evolution have been studied (see, e.g., [20]). We think it is helpful to add the ideas of regulatory networks and niches when considering the car centered global system. Together, these restrain the space of possibilities that the system may realize in its further evolution, while keeping its dynamics in a non-deterministic mode with an open future.

2.4 Synthetic information systems

Having identified and defined the global system under consideration, one then represents a (usually much simplified) version of this system on the computer to run simulations, which allow one to explore, as in a virtual laboratory, possible scenarios of the system's future evolution and related uncertainties.
An agent-based model (ABM, see, e.g. [21]) represents many heterogeneous actors in this system as agents, their environment, and the complex networks in which they interact in model code. A model simulation run then carries out such interactions repeatedly, giving rise to a trajectory displaying potential overall system dynamics. Generally, many runs are carried out to account for uncertainty.
We speak of a synthetic information system when the ABM's agents are initialised by a synthetic population – a set of virtual agents that, for relevant characteristics, statistically match the corresponding

distributions found in the real-world population (see, e.g., [22] and references therein). Analysis and interactive visualisation of simulation results of the synthetic information system allow to analyse the system and various alternative decisions for gaining a deeper understanding and a better overview.
In particular, the work presented here is carried out in the context of enhancing GSS modelling through High Performance Computing (HPC) and Data Analytics (HPDA), for example by enabling the use of high-resolution data sets, by allowing models to grow in complexity and grow towards global scales, and by facilitating deeper analysis of larger sets of output data from model simulation runs (see coegss.eu). On the potential of agent-based models in addressing grand challenges of global scope see also [23].

3 The car centered global system

This section describes the car centered global system, drawing system boundaries and categorising elements as seen best fit for our overall research question. While the modelling work on this system (Section 4) does not represent all points introduced here, a structured description of the system (in terms of agents, environment, and interaction networks, but also thinking about regulatory networks and niches) is a fist step to analysing this – or really any – system.

3.1 A description of the system's elements

Viewing electric mobility from a systemic perspective requires the consideration of a large number of heterogeneous, spatially distributed agents.
The system first of all includes a global population of actual and potential consumers; we consider households as potential car buyers. Properties of households that are relevant here include the number of people in a household and their ages, the household's location, its mobility needs, its income, the number and properties of cars owned, and many more. In buying (or also in re-selling) a car, a household's decisions may be influenced by various factors. One of these is the local environment, that can include infrastructure (charging stations, public transport, etc.), or regulation at the level of their city or state. For example, some Chinese megacities have a quota policy to control car ownership growth: in Beijing the right to buy a conventional car has to be won in a lottery, in Shanghai such rights are auctioned [24]. Another factor influencing decisions is the local interaction with other agents, for example in terms of congestion and accidents. Last but not least, social influence can shape decisions, in networks between agents that can go beyond local interactions, and that are typically characterised by hubs, clusters, assortativity, as well as community and hierarchical structures [25].
Another type of agents in our system are firms in the car industry, with car manufacturers operating in a global market (as just one example, among Volkswagen sales in 2016, Europe accounted for about 41%, closely followed by about 39% in China [26]) and suppliers of car components. From a green growth perspective, the large numbers of people employed by the car industry, especially if the suppliers of car components are included, also play a role. For example, Volkswagen has about 600'000 employees worldwide, nearly half of which in Germany, where the company is the single largest private employer.
Key public authorities, in particular those of Germany, the U.S., China and Japan could be considered as yet another type of agents. However, it seems more useful here to think of the regulations they pass as part of the environment that households and firms interact in. Hence, this environment includes an administrative layer with laws and procedures governing the admission of cars on the road, the insurance of cars, and standards they have to meet (including the clean air standards violated in the recent diesel scandal). It also includes a geographically anchored layer with rural and urban areas and transport infrastructure like roads and gas or charging stations. The thus defined environment in the car centered global system co-evolves with the global car fleet, but changes at much longer time scales than that of car sales.
The car centered global system is an open system whose evolution is in turn influenced by what surrounds it, such as the global oil industry or geopolitical arrangements in climate policy. Like for the question of whether to include regulator agents or a regulation layer in the environment, the system boundaries are up to definition, and it may be useful to draw them differently when other questions are asked.

3.2 An extended evolution perspective on this system

Attention to regulatory networks and niches helps to understand the remarkable inertia of the car centered global system. Laws and regulations stabilise the car as a fundamental element of mobility in contemporary society. A "regulatory network" shapes the evolution of the car centered global system: regulations passed by different administrations are the nodes, or vertices, in this network. Car manufacturers, that have to consider the regulations in all places where they want to be in the market, constitute the links, or edges, between these nodes. As regulation can be passed at different and nested levels (e.g., the EU or the US, countries or states, and cities), this can be considered a multiscale network. Configurations

in this network may influence the evolution of the global car fleet (by specifying which manufacturer needs to meet which regulations) and may at the same time co-evolve with it (e.g., if some manufacturer withdraws from some market).
Prices can also be viewed as part of the regulatory network; they can play an important role in the process by which a given innovation survives and spreads, or shares the fate of most innovations: to disappear. Carbon prices on the one hand and battery prices on the other will shape the space of possibilities for a transition to electric mobility.
At the same time, the global oil industry is part of the niche that maintains a central role for the internal combustion engine in today's world society. Spatial regions with fully developed charging infrastructures can be niches from which electric mobility may eventually spread.

4 Simulating potential evolutions of the global car fleet

To start simple and add complexity step by step, we have not defined an agent-based model including all of the above system elements from the start, but focus on households and the demand side first. Also, we first defined and implemented a spatially explicit innovation diffusion model on a global scale.

4.1 A spatially explicit innovation diffusion model

The initial innovation diffusion model operates on grid cells in a global map, with a resolution of 2.5 arc-minutes, corresponding to about 5km by 5km at the equator. Scenarios for the evolution of total car numbers are provided as an exogenous input. The model considers only two classes of cars, "brown" and "green" ones. For now, we consider green cars to correspond to battery electric vehicles due to data availability; however, the model structure allows to easily replace this assumption with others, for which the required data is available. A diffusion of green cars takes place within the ranges set by total car sales per time step. This model can be considered a geographic cellular automaton: spatially differentiated input data and a basic transition rule determine the number of green cars in each next step taking into account the neighbouring cells. We run model simulations for a 2009–2025 timeframe.

4.1.1 Scenarios of the total number of

The input data required by the model consists of maps of cars bought per cell per time-step. These have been prepared by combining gridded population data and scenarios from [28] with a rate of car scrappage and numbers of cars per 1000 people per country. For the latter, we used data from OICA [29] for the first decade of the timeframe under consideration. To obtain scenarios for the second decade, car ownership scenarios were computed, on the one hand, by extrapolating current trends and, on the other hand, with the help of a model by Dargay and colleagues [27]. This model estimates numbers of cars per 1000 people based on a country's GDP per capita, population density, level of urbanisation, and a country specific saturation level. The necessary input data and scenarios were obtained from standard data sources [30, 31, 32, 33, 34]. Details can be found in [35].
Figure 2 shows resulting projections of total car numbers by continent, Figure 3 shows the same numbers in spatially explit manner for two points in time. While in 2009, cars were primarily concentrated in three world regions – North America, Europe and Japan with South Korea – fast growth in the numbers of

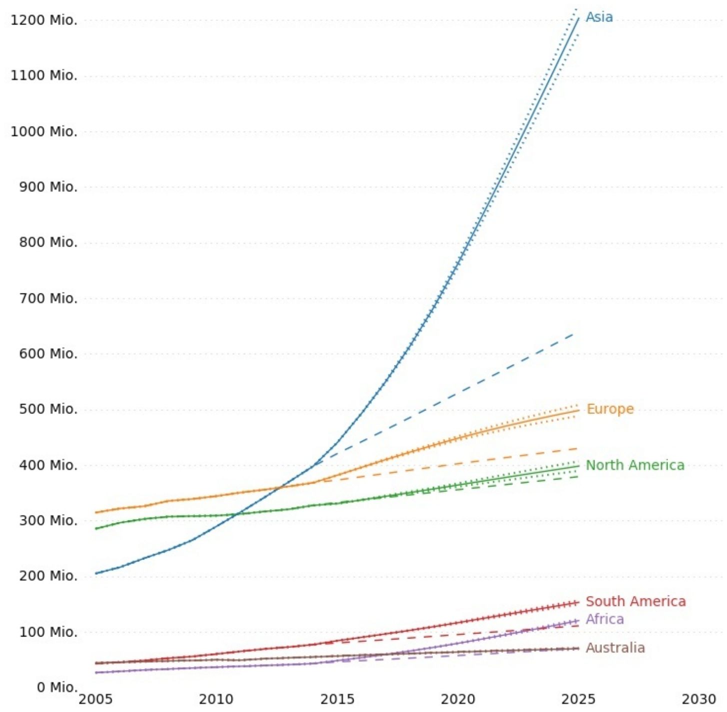


Figure 2: Scenarios for total numbers of cars Numbers by continent: Linear trends, and the model by Dargay et al with high, medium, and low population estimates [27]

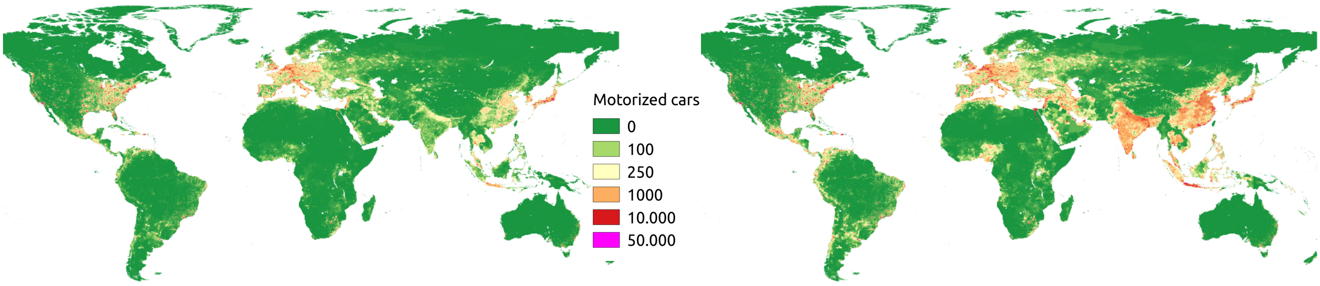


Figure 3: Total number of cars 2009 (left) and Dargay et al model scenario for 2025 (right)

cars happens primarily in China, India and Indonesia. Therefore, the future of the car industry will depend to a large extent on what will happen in this part of the world.

4.1.2 The diffusion mechanism

Given the spatially explicit dynamics for the total number of cars, each car bought in a model simulation can be a green or a brown car. The diffusion dynamics for green cars has an innovation and an imitation component.

- Innovation: as electric cars are already on the market, from time to time somebody will buy such a car for a variety of reasons, modelled as a random variable. However, to buy an electric car people need a certain income. Other factors being equal, the higher the relative GDP in the cell's country, the higher the probability that they will do so. Also, countries differ quite extensively in the level of policy support provided for electric mobility, in the form of subsidies, privileged access to lanes or parking spots, and many more. Therefore, the innovation component includes a policy factor, determined by calibrating model output to electric vehicle sales data.

- Imitation: the more electric cars are present in a given neighbourhood, the higher the probability that a consumer chooses one. This represents observations by this consumer and takes the number of green cars already present in this neighbourhood as an indicator of the existence of an electric-car-friendly infrastructure. In the current model version, the neighbourhood consists of 2 rings of cells around a given cell, and the respective numbers are weighted with inverse distance between the cells.

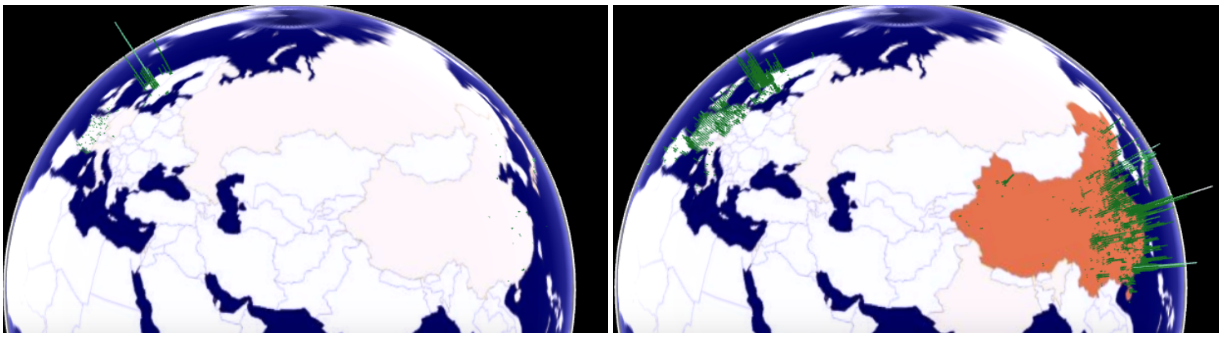
4.2 First results

Exploring with our work, at the same time with model development, the use of HPC tools for agent-based modelling, the model was programmed using Pandora [36] and run on the fine spatial grid of the population data with global scope. The country-specific policy parameter for the innovation component has been calibrated for the 15 countries listed in Table 1, according to data availability. It allows to compare country-specific incentives on the basis of a common model which takes the countries' GDP and spatial population structure into account. When analysing those policies that exist in each of these countries (see [37, 38]), together with the respective dates when these policies were enacted, the range of values spanned by this parameter, and the relative value for one country as compared to another can help structure the study of the effectiveness of certain policy mixes in certain economic, cultural and societal backgrounds. A step of model refinement which would calibrate the model to smaller sub-areas, for example in the US, could then be confronted with study results as in [39] to gain a better understanding of the diffusion of electric vehicles in various circumstances.

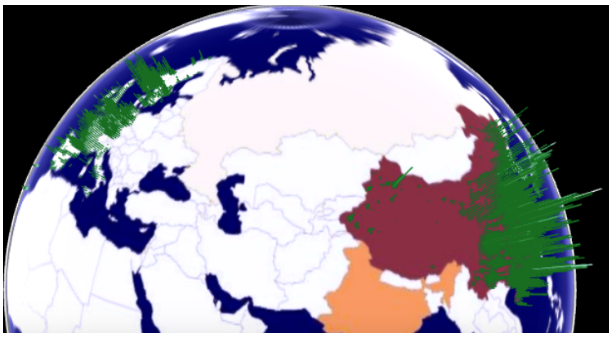
Table 1: Policy factors calibrated

factor	country
0.06667	Korea
0.2	Italy, Spain
0.26667	Canada
0.4	Japan
0.53333	United Kingdom, Portugal, South Aftrica
0.66667	United States, Germany, Netherlands
1.66667	China
2	Sweden, France
10	Norway

Figure 4: Shares (spike height) and total numbers of BEV (spike colour), and total number of cars (country colour)



2009 2017



2025

Model results can be visualised in global maps. Figure 4 shows screenshots on the results from these 15 countries obtained with an interactive visualisation tool that is based on R and shiny [40]. In the maps, the height of spikes depicts the share, and colour the total numbers of electric vehicles. In addition, total numbers of cars in the country are displayed by colouring the underlying country map.

In simulation results for 2009, Norway stands out as the lonely innovator for electric vehicles. The picture for 2017 shows that total numbers of cars in China have increased with respect to other countries, where electric vehicle shares are growing and the largest total amounts (white spikes) occur. Finally, the simulation for 2025 shows the largest EV shares and total numbers in China, and we see that total numbers of cars have massively increased in China, and are increasing also in India. To take a closer look at electric vehicle shares, which are picking up in urban areas both in China and in several places in Europe, the tool allows to zoom into certain areas and to move the globe.

In two dimensions, the map in Figure 5 shows that the Chinese coastline is likely to play an important role in the diffusion of electric vehicles. Three megalopolis, defined by the Chinese leadership around three key cities, Beijing, Shanghai and Shenzhen (next to Hong Kong), have the potential to become territorial niches for the initial stage in the evolution of individual mobility based on electric cars. Against this background, one can begin to evaluate strategic choices by relevant actors: for example, the Volkswagen decision to engage with leading Chinese IT firms like Huawei in view of the digitalisation of car traffic, rather than partnering with American companies like Apple or Google, makes perfect sense [41]. So does the recent announcement by Volvo (owned by the Chinese Geely Automobile Holdings) to introduce only hybrids or battery electric vehicles as new models from 2019 on [42], especially when viewed in the Chinese context.

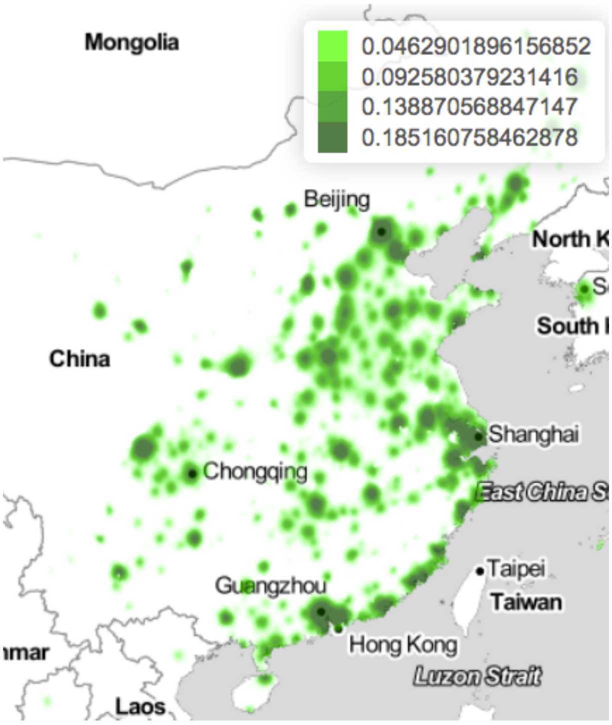


Figure 5: Detail from simulation output for China: share of electric vehicles in 2025.

A similar map for Northwestern Europe, Figure 6, shows a large urban chain from England, through the Benelux countries, Germany, Switzerland and France, connecting Manchester with Marseille and the French Mediterranean coast, with the Rhine valley as its backbone. If one wants to establish a powerful regional niche facilitating the transition to e-mobility in the midst of Europe,

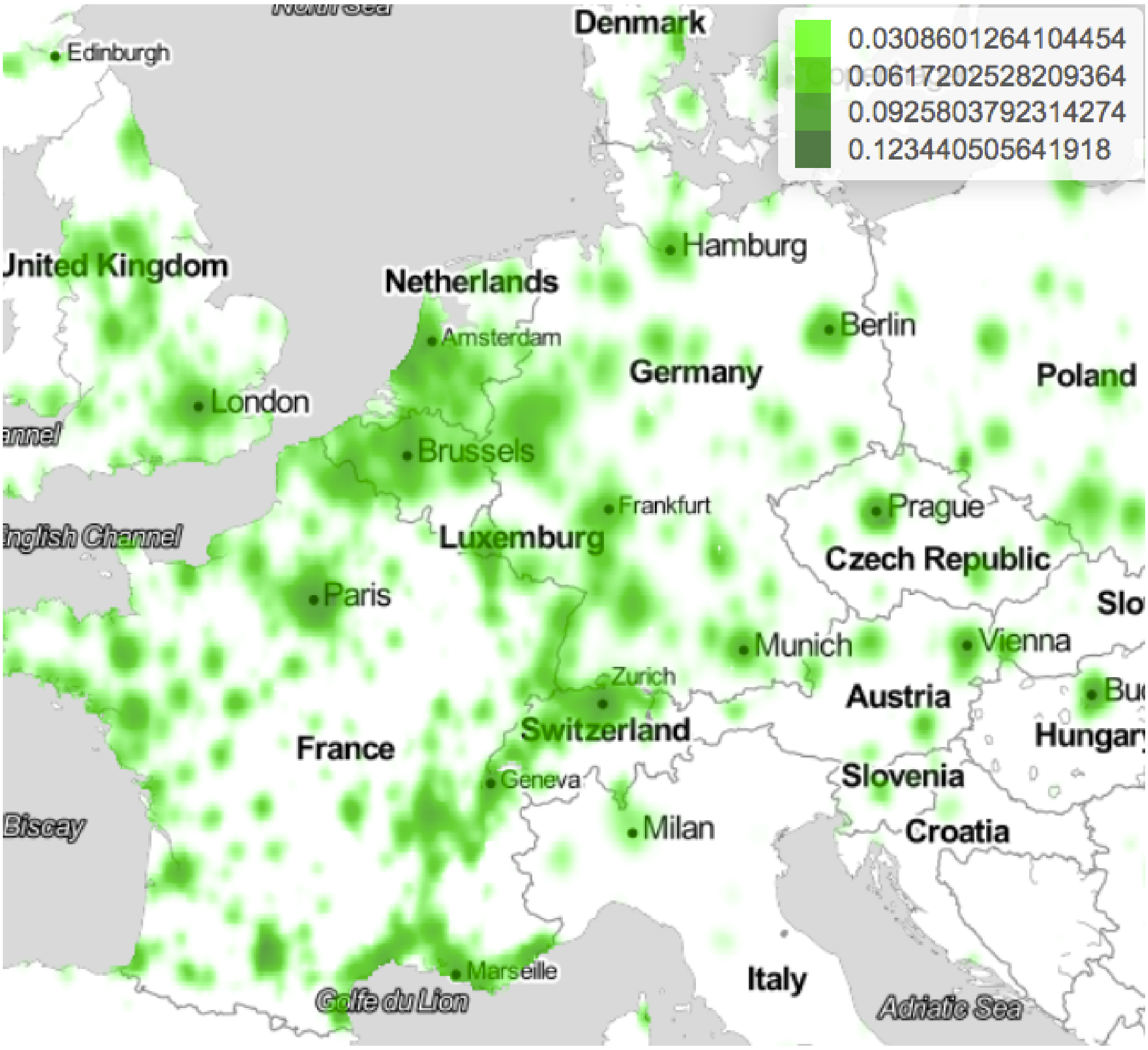


Figure 6: Detail from simulation output for Northwestern Europe: share of electric vehicles in 2025.

this corridor deserves special attention by policy makers. In addition, the ambitious project of the energy transition in Germany – with the explicit goal of shutting down nuclear energy and bringing greenhouse gas emissions close to zero – sets a context in which electric mobility can offer a possibility of using digitised electric cars not only as mobility devices, but also as media of energy storage. Returning to the framework of extended evolution, this corresponds to an enlargement of functional characteristics, which can open up favourable spaces for an innovation in a fitness landscape that initially was not well suited for this particular innovation.

5 Further work in progress

To refine the model from the previous section in the spirit of Section 2.4, currently two complementary strands of work are in progress.

5.1 Basic agent dynamics with a refined synthetic population

Innovation diffusion models with a discrete time-step can be be disaggregated into agents (see, e.g., [43]). This is a next step we are undertaking with the model presented above. Without going into complex decision making procedures of the agents in a first step, the decisions will still be based on innovation and imitation probabilities. However, feeding the model with an existing detailed synthetic population, we can begin to differentiate agents by their properties, such as household size, income, mobility needs, and an indicator for environmental concern. This shall be done in cooperation with a group that is specialised in producing synthetic populations. Also, the network between the agents can then be taken into account, which vanishes in the aggregate version. Network structures can make important differences in the diffusion of innovations (see, e.g., [44]), and social networks in the real world show quite a few particularities, such as a heavy tailed degree distribution (many nodes have very many connections), a high clustering coefficient (i.e., a large number of closed patterns: the friend of my friend is likely to also be my friend), assortativity (agents link predominantly to similar agents), community structures (clusters of agents much more linked to other agents within the group than to those outside) and hierarchical structures (subgroups of groups) [25]. Therefore, as one of the next steps in work with this model, networks shall be explicitly considered. This will allow us to analyse commonalities and differences with the cell-wise aggregate model, in order to explore at which points an explicit agent-based model can provide information on the underlying global system that a more aggregate model is unable to provide.

5.2 A basic synthetic population with refined agent dynamics

At the same time, we are working on a model that does take into account more complex decision making processes of the agents. In particular, we consider agents that take their decisions by optimizing expected utility, using subjective probabilities that they update based on information from other agents within their network. To initialise this model version, we updated and extended an existing synthetic population. Details, first results on how the mechanisms in this model play out in terms of overall system dynamics, and a discussion on data analytics tools for model analysis are presented in [45] and are beyond the scope of this text.

6 Conclusions and outlook

Obtaining green growth is one of the grand or global challenges society is currently facing. A transition to sustainable mobility is part of what needs to be achieved for this. The car centered global system, and the diffusion of electric mobility within this system, are elements that can play a crucial role. Vice versa, the idea of green growth can play a role in achieving a transition to sustainable mobility: in a world where cars largely resemble welfare, freedom, status, etc., and where conventional cars come with internal combustion engines, an alternative narrative, that may help switch to another convention, is wanting. Green growth puts the focus on benefits to be obtained from reducing emissions (by using electric vehicles and renewable transport, such as bikes, by sharing cars and rides, and so on) such as reduced air pollution or urban space freed up for other uses than traffic and many more. In this vein, this paper has presented an approach to and tools (under construction) for analysing electric mobility in view of green growth.

An important part of constructing these tools is the development of agent-based simulation models. This work can benefit from interaction with experts on various aspects of electric mobility: first, to shape the model into the most relevant directions, it is of interest to us which questions potential users of such a tool would like to see answered. Second, to fill in details into the current, still basic, model, expertise from the field is required. The present paper is intended to initiate dialogues with experts in relation to the Electric Vehicle Symposium.

While work in progress, the above examples of first results indicate how a simulation model and its (visualised) output can foster structured thinking about a global challenge, and enhance one's understanding of a given system by pointing out potential evolutions. Making oneself aware of potential futures in a given system is a first step in shaping its future evolution by then evaluating which of these futures are desirable, or which should be avoided, and which measures help steer the system in the direction of the former.

Acknowledgments

We thank two anonymous reviewers for helpful comments. Funding from the EU under grant 676547 (Centre of Excellence for Global Systems Science) is gratefully acknowledged.

References

[1] OECD, "What is green growth and how can it help deliver sustainable development?" 2017. [Online]. http://www.oecd.org/greengrowth/whatisgreengrowthandhowcanithelpdeliversustainabledevelopment.htm

[2] D. Sperling and D. Gordon, *Two billion cars: driving toward sustainability*. Oxford University Press, 2009.

[3] J. DeCicco, “Tailpipes top smokestacks as nation’s largest CO2 emitters,” http://www.carsclimate.com/2016/09/tailpipes-top-smokestacks.html, 2016.

[4] N. Lutsey, “The rise of electric vehicles: The second million,” ICCT blog, published 2017.01.31, 2017. [Online]. http://www.theicct.org/blogs/staff/second-million-electric-vehicles

[5] T. Dutzik, J. Inglis, and P. Baxandall, “Millennials in motion, changing travel habits of young americans and the implications for public policy,” U.S. PIRG Education Fund and Frontier Group, 2014. http://www.uspirg.org/sites/pirg/files/reports/Millennials%20in%20Motion%20USPIRG.pdf

[6] L. Fulton, J. Mason, and D. Meroux, “Three Revolutions in Urban Transportation,” May 2017. https://www.itdp.org/wp-content/uploads/2017/04/UCD-ITDP-3R-Report-FINAL.pdf

[7] M. Barra, “GM 2015 Sustainability Report Chairman & CEO Message: To Our Stakeholders,” https://media.gm.com/dld/content/dam/Media/images/US/Release_Images/2016/05-2016/Sustainability/GM-Sustainability-MaryBarra-Letter.pdf, 2016.

[8] Volkswagen, “Matthias Müller: We have launched the biggest change process in Volkswagen’s history,” Volkswagen press release, https://www.volkswagen-media-services.com/en/detailpage/-/detail/Matthias-Mller-We-have-launched-the-biggest-change-process-in-Volkswagens-history/view/3710903/7a5bbec13158edd433c6630f5ac445da?p_p_auth=NcZ61zbL, 2016.

[9] J. B. Stewart and W. Brangham, “Numbers Behind Tesla, GM, Ford, the ”New Big Three”,” 2017. [Online]. http://www.supplychain247.com/article/numbers_behind_tesla_gm_ford_the_new_big_three

[10] UNDESA, “A Guidebook to the Green Economy: Issue 1: Green Economy, Green Growth, and Low Carbon Development - history, definitions and a guide to recent publications,” United Nations Division for Sustainable Development, 2012.

[11] M.-C. Rische, A. Roehlig, and J. Stoever, “Green, greener, grey. Disentangeling different types of green growth,” *HWWI Research Paper*, no. 160, 2014. http://www.hwwi.org/fileadmin/_migrated/tx_wilpubdb/HWWI_Research_Paper_160.pdf

[12] The World Bank, “Inclusive Green Growth. The Pathway to Sustainable Development,” The World Bank, 2012. http://siteresources.worldbank.org/EXTSDNET/Resources/Inclusive_Green_Growth_May_2012.pdf

[13] C. C. Jaeger, L. Paroussos, D. Mangalagiu, R. Kupers, A. Mandel, and J. D. Tábara, “A New Growth Path for Europe – Generating Prosperity and Jobs in the Low-Carbon Economy,” Synthesis Report, A study commissioned by the German Federal Ministry for the Environment, Nature Conservation and Nuclear Safety, Berlin, 2011. http://www.globalclimateforum.org/fileadmin/ecf-documents/publications/reports/A_New_Growth_Path_for_Europe_-_Synthesis_Report.pdf

[14] C. C. Jaeger, F. Schütze, S. Fürst, D. Mangalagiu, F. Meißner, J. Mielke, G. A. Steudle, and S. Wolf, “Investment-Oriented Climate Policy: An opportunity for Europe,” A study commissioned by the German Federal Ministry for the Environment, Nature Conservation, Building and Nuclear Safety, Berlin, 2015. http://www.globalclimateforum.org/fileadmin/ecf-documents/news-events/2016_0217_Investment-oriented_climate_policy/Investment-oriented_climate_policy-_An_opportunity_for_Europe.pdf

[15] C. C. Jaeger, K. Hasselmann, G. Leipold, D. Mangalagiu, and J. D. Tábara, *Reframing the Problem of Climate Change: From Zero Sum Game to Win-Win Solutions*. Earthscan, 2012.

[16] International Energy Agency, “CO_2 Emissions from Fuel Combustion. Highlights,” 2016. http://www.iea.org/publications/freepublications/publication/CO2EmissionsfromFuelCombustion_Highlights_2016.pdf

[17] D. Kalinowska and U. Kunert, “Ageing and Mobility in Germany: Are Women Taking the Fast Lane?” DIW Berlin Discussion Paper No. 892, May 2009. http://www.diw.de/documents/publikationen/73/diw_01.c.98162.de/dp892.pdf

[18] R. Dum and J. Johnson, “Global Systems Science and Policy” in: *Non-Equilibrium Social Science and Policy*. J. Johnson, A. Nowak, P. Ormerod, B. Rosewell, YC Zhang, Eds. Springer, 2017.

[19] M. D. Laubichler and J. Renn, “Extended Evolution: A conceptual framework for integrating regulatory networks and niche construction,” *Journal of Experimental Zoology (Part B: Molecular and Developmental Evolution)*, vol. 9999, pp. 1–13, 2015. http://pubman.mpiwg-berlin.mpg.de/pubman/item/escidoc:723342:2/component/escidoc:723343/Laubichler_et_al-2015-Journal_of_Experimental_Zoology_Part_B_Molecular_and_Developmental_Evolution.pdf

[20] J. Ziman, *Technological Innovation as an Evolutionary Process*. Cambridge University Press, 2000, ch. Evolutionary models for technological change, pp. 1–11. http://assets.cambridge.org/97805216/23612/sample/9780521623612wsc00.pdf

[21] L. Tesfatsion and K. Judd, *Agent-Based Computational Economics*, ser. Handbook of Computational Economics. North-Holland: Elsevier, 2006, no. 2.

[22] F. Gargiulo, S. Ternes, S. Huet, and G. Deffuant, “An Iterative Approach for Generating Statistically Realistic Populations of Households,” *PLoS ONE*, vol. 5, p. e8828, January 2010. https://doi.org/10.1371/journal.pone.0008828

[23] A. J. Heppenstall, A. T. Crooks, M. Batty, and L. M. See, "Reflections and conclusions: Geographical models to address grand challenges," in *Agent-based models of geographical systems*, A. J. Heppenstall, A. T. Crooks, L. M. See, and M. Batty, Eds. Springer, 2012, pp. 739–747.

[24] F. Suwei and L. Qiang, "Car Ownership Control in Chinese Mega Cities: Shanghai, Beijing and Guangzhou," 2013. [Online]. Available: https://www.lta.gov.sg/ltaacademy/doc/13Sep040-Feng_CarOwnershipControl.pdf

[25] M. S. Granovetter, "The Strength of Weak Ties", *Americal Journal of Sociology*, vol. 78, no. 6, 1973.

[26] Volkswagen AG, "Volkswagen Konzern liefert 10,3 Millionen Fahrzeuge im Jahr 2016 aus," Press Release, January 2017. [Online]. https://www.volkswagen-media-services.com/detailpage/-/detail/Volkswagen-Konzern-liefert-103-Millionen-Fahrzeuge-im-Jahr-2016-aus/view/4447022/657bd2c10865b3dee40ed4dc685c90fb?p_p_auth=AyVxrcS0

[27] J. Dargay, D. Gately, and M. Sommer, "Vehicle Ownership and Income Growth, Worldwide: 1960-2030," *The Energy Journal*, vol. 28, no. 4, pp. 143–170, 2007.

[28] Socioeconomic Data and Applications Center (SEDAC), "Gridded Population of the World, v3," http://sedac.ciesin.columbia.edu/data/collection/gpw-v3/maps/services, 2015, visited December 2015.

[29] OICA, "Vehicles in use," http://www.oica.net/category/vehicles-in-use/, 2015, visited December 2015.

[30] International Monetary Fund, "World Economic Outlook, GDP per capita based on purchasing-power-parity (PPP) in current international dollars," https://www.imf.org/external/pubs/ft/weo/2016/01/weodata/weoselgr.aspx, 2016, visited July 2016.

[31] U.S. Energy Information Administration, "International Energy Outlook 2016, World GDP per capita by region expressed in purchasing power parity," http://www.eia.gov/forecasts/aeo/data/browser/#/?id=47-IEO2016&sourcekey=0, 2016, visited July 2016.

[32] United Nations Department of Economic and Social Affairs, "World Population Prospects, the 2015 Revision," https://esa.un.org/unpd/wpp/Download/Standard/Population/, 2015, visited July 2015.

[33] World Bank, "Land area (sq. km)," http://data.worldbank.org/indicator/AG.LND.TOTL.K2, 2015, visited July 2016.

[34] United Nations Department of Economic and Social Affairs, "World Urbanisation Prospects, the 2014 Revision, File 21: Annual Percentage of Population at Mid-Year Residing in Urban Areas by Major Area, Region and Country, 1950-2050," https://esa.un.org/unpd/wup/CD-ROM/, 2014, visited July 2016.

[35] S. Wolf, M. Dreyer, M. Edwards, S. Fürst, A. Geiges, J. Hilpert, J. von Postel, F. Saracco, M. Tizzoni, and E. Ubaldi, "CoeGSS Deliverable D4.4: First Status Report of the Pilots," 2016. http://coegss.eu/wp-content/uploads/2016/02/D4.4.pdf

[36] X. Rubio-Campillo, "Pandora: A Versatile Agent-Based Modelling Platform for Social Simulation," in *SIMUL 2014: The Sixth International Conference on Advances in System Simulation*, 2014.

[37] EAFO (European Alternative Fuels Observatory), "Battery electic vehicles for European countries," http://www.eafo.eu, 2017, visited December 2017.

[38] IEA, "Global EV Outlook 2016," https://www.iea.org/publications/freepublications/publication/Global_EV_Outlook_2016.pdf, 2016, visited December 2016.

[39] Z. McDonald, "Comparing the Top 10 Cities for Electric Vehicle Adoption," Posted August 11, 2016. [Online]. http://www.fleetcarma.com/top-cities-electric-vehicle-sales

[40] "shiny," 2017. [Online]. https://shiny.rstudio.com

[41] Huawei Technologies Co., Ltd., "Huawei and Volkswagen Collaborate to Connect Automobiles and Smartphones," Press Release, May 2015. [Online]. https://www.huawei.eu/media-centre/press-releases/huawei-and-volkswagen-collaborate-connect-automobiles-and-smartphones

[42] J. Ewing, "Volvo, Betting on Electric, Moves to Phase Out Conventional Engines," The New York Times, July 2017. [Online]. https://www.nytimes.com/2017/07/05/business/energy-environment/volvo-hybrid-electric-car.html?emc=edit_nn_20170706&nl=morning-briefing&nlid=77854954&ref=business&te=1

[43] E. Kiesling, M. Guenther, C. Stummer, and L. M. Wakolbinger, "Agent-based Simulation of Innovation Diffusion: A Review," *Central European Journal of Operations Research*, vol. 20, pp. 183–230, June 2012.

[44] M. Edwards, S. Huet, F. Goreaud, and G. Deffuant, "Comparing an individual-based model of behaviour diffusion with its mean field aggregate approximation," *Journal of Artificial Societies and Social Simulation*, vol. 6, no. 4, 2003.

[45] A. Geiges, O. Allerbo, S. Fuerst, and S. Wolf, "Modeling consumer- and innovation-driven transitions of the car market: Modeling and analysis concepts," 2017, prepared for the 2nd Workshop on Agent-based modelling at ESCP Europe Berlin. Available upon request.

Authors

Sarah Wolf has a background in mathematics, in particular, probability. She obtained a PhD in mathematics from Freie Universität Berlin with interdisciplinary work relating to climate change. Since 2009, her focus is on economic and agent-based models for understanding a transition to green growth. Currently, she leads the pilot studies workpackage of the Centre of Excellence for Global Systems Science (CoeGSS), which makes High Performance Computing available to Global Systems modelling.

Steffen Fürst is a staff scientist at GCF. He holds a Diplom (equiv. to M.Sc.) in mathematics with emphasis on economics and social sciences. His research interests include agent-based computational modelling, with a focus on a computer science view. He currently contributes to the Green Growth pilot study of the Centre of Excellence for Global Systems Science.

Andreas Geiges studied Environmental Engineering in Stuttgart and received his PhD in the related field of stochastic modeling, uncertainty quantification and optimized data acquisition for environmental systems. He contributes to the Centre of Excellence for Global Systems Science (CoeGSS). Within an interdisciplinary researcher team, he develops large-scale agent-based models (ABM) for modelling complex global systems. His interests are modeling of environment-related systems, the energy market with a special focus on renewable energies, and energy efficiency as well as possible paths towards sustainable mobility.

Gesine A. Steudle studied physics in Berlin and Granada (Spain) with a focus on optics and statistical physics. She obtained her PhD from Humboldt-University Berlin in the field of experimental quantum optics. Before she joined GCF she was working at a private consulting company in the area of energy efficiency and renewable energies. At GCF she works mainly in the development of mathematical models to understand the transition dynamics between economic equilibria, as for example a possible transition between a brown and a green growth path.

Jette von Postel is a research assistant at GCF. She obtained a B.Sc. in mathematics from Freie Universität Berlin and is now doing a master's program in mathematics with focus on probability theory. She has been working within the Green Growth pilot study of the Centre of Excellence for Global Systems Science (CoeGSS) since summer 2016.

Carlo C. Jaeger is an economist working on global systems, in particular on the role of financial markets in addressing – or exacerbating – the problem of climate change. He is co-founder and chairman of the Global Climate Forum, Professor at Potsdam University, Germany, Visiting Professor at the Julie Ann Wrigley Global Institute of Sustainability, Arizona State University (ASU), and the Beijing Normal University (BNU), China, where he has been appointed as an outstanding foreign expert to the Chinese government. Jaeger's current research is focused on problems of global coordination, especially in view of sustainable development.