Global Climate Forum

Working Paper 3/ 2017

Electric mobility in view of Green Growth

Sarah Wolf[α*] · Steffen Fürst[α] · Andreas Geiges[α] · Gesine A. Steudle[α] · Jette von Postel[α] · Carlo C. Jaeger[αβ]

[α] Global Climate Forum
[β] Arizona State University
*E-mail: sarah.wolf@globalclimateforum.org

Electric mobility in view of Green Growth

Sarah Wolf · Steffen Fürst · Andreas Geiges · Gesine A. Steudle · Jette von Postel · Carlo C. Jaeger

November, 2017

Abstract Achieving green growth, that is, improving environmental, economic, and social well-being at the same time, is one of the global challenges society is currently facing. A sustainable mobility transition is an important element in shifting to a green growth path. This paper outlines an approach to analysing electric mobility in view of green growth that is grounded in Global Systems Science. It presents an initial synthetic information system developed for investigating the diffusion of electric vehicles in the global car fleet and sketches first simulation results.

Keywords Green growth, electric mobility, Global Systems Science

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."(OECD 2017)

The global car fleet, counting more than 1.2 billion vehicles and growing, is expected to reach 2 billion by 2030 (Sperling and Gordon 2009). It contributes to environmental pressures, in particular, in terms of air pollution and CO_2 emissions; in the US, the transport sector has surpassed the power sector to become the number one emitter (DeCicco 2016). Currently, about 2 million cars, that is, much less than one percent of the global car fleet, are electric vehicles (Lutsey 2017).

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 (Dutzik et al 2014), and with the "3 revolutions" of vehicle electrification, automation and shared mobility (Fulton et al 2017) 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" (Barra 2016) – some have announced plans for transformation (Volkswagen 2016). Earlier this year, Tesla has exceeded 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. This points to a strong belief of investors in the future of electric mobility (Stewart and Brangham 2017).

Against this background, the future evolution of mobility is an interesting research topic. We concentrate on potential evolutions of electric mobility, and on the research question how a transition of the global car market can be achieved in such a way as to simultaneously realise economic and environmental benefits, that is, to turn the risk of climate change into an opportunity for green growth. Therefore, we develop tools for analysing potential future evolutions of the car centred 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. This paper presents this research perspective together with a first step undertaken in model development: a global-scope high-resolution simulation model for analysing the diffusion of electric vehicles.

The remainder of this paper is organized as follows: Section 2 briefly introduces concepts and methods employed. Section 3 specifies the car centred global system, and Section 4 presents initial modelling work in progress with first results. Section 5 sketches directions for 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 centred global system. It sketches the field of Global Systems Science (GSS) in which this work is grounded, 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., UN-DESA 2012; Rische et al 2014, 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 as "green growth" those growth paths in which 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" (The World Bank 2012), for example, 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 (Jaeger et al 2011; Schütze et al 2017; Jaeger et al 2012) 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 small unless there is 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 necessary also when considering green growth opportunities arising from a certain sector.

Emissions from the transport sector (about 70% of which are produced by road transport) increased by over 70% from 1990 to 2014 (International Energy Agency 2016a). 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, e.g., data by OICA 2015).

This trend reflects the increasing wealth of the population in large parts of the world; at the same time, increasing income generally comes with increasing mobility needs (Kalinowska and Kunert 2009), which constitutes a feedback effect that stabilises the trend in the size of the global car fleet. Along a green growth path with respect to mobility, the trend in transport emissions would need to be reversed without curbing benefits (e.g., in terms of growth or employment) that currently relate to increasing numbers of cars. Emissions of electric vehicles depend on how electricity is produced, confirming the need to look beyond the transport sector alone.

The global systems perspective and modelling tools used here (described below) allow to observe a large number of indicators in model runs, and thus to analyse many aspects of potential mobility transitions. For example, in a model with high spatial resolution, the number 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 which are 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., Dum and Johnson 2017). Green growth is one such challenge due to the long-term and global-scope effects of (local) greenhouse gas emissions from the activities of up to 7 bn people.

When it comes to global challenges, a systemic perspective needs to be taken to develop evidence and understanding about the underlying global system and its potential future evolutions, in particular for analysing 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 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 them.

A first step in analysing a global challenge is, therefore, to identify the global system to be studied. The car centred 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 centred global system, the framework of extended evolution (Laubichler and Renn 2015) provides a useful anchor. This framework considers not only random mutations of genes and natural selection according to fitness, but adds regulatory networks and niches as important factors in the evolution of species. The former determine the sequence and intensity in which genes are activated, the latter are parts of the environment an organism lives in, that has often been shaped by earlier generations of the same kind of organisms.

Analogies between biological and technological (or, more generally, cultural) evolution have been studied (see, e.g., Ziman 2000). We think it is helpful to add the ideas of regulatory networks and niches when considering the car centred global system. Together, they constrain the space of possibilities that the system may realize in its 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. Tesfatsion and Judd 2006) represents many heterogeneous actors in this system (agents), their environment, and the complex networks in which they interact in model code. A model simulation run then carries out these 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 matches the corresponding distributions found in the real-world population (see, e.g., Gargiulo et al 2010, and references therein). Analysis and interactive visualisation of simulation results of the synthetic information system allow to gain a deeper understanding and a better overview over the system's potential evolutions, and about possible consequences of various alternative decisions.

In particular, the work presented here was carried out with a focus on enhancing GSS modelling through High Performance Computing (HPC) and Data Analytics (HPDA), for example by enabling the use of high-resolution data sets, allowing models to grow in complexity and grow towards global scales, and facilitating deeper analysis of larger sets of output data from model simulation runs[1]. On the potential of agent-based models in addressing grand challenges of global scope see also Heppenstall et al (2012).

3 The car centred global system

This section describes the car centred global system, drawing system boundaries and categorising elements as seen fit for our overall research question. While the model of 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, keeping in mind also regulatory networks and niches) is a fist step to analysing this – or any – global 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 the respective city or state. For example, some Chinese megacities have a quota policy to control car ownership growth:

---

[1] See coegss.eu.

in Beijing the right to buy a conventional car has to be won in a lottery, in Shanghai such rights are auctioned (Suwei and Qiang 2013). 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. The networks between agents that play a role here can go beyond local interactions; they are typically characterised by hubs, clusters, assortativity, as well as community and hierarchical structures (Granovetter 1973).

Another type of agents in our system are firms in the car industry, with car manufacturers and component suppliers 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 (Volkswagen AG 2017). From a green growth perspective, employment in the car industry, especially if the suppliers of car components are included, also plays 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 centred global system co-evolves with the global car fleet, but changes at much longer time scales than that of car sales.

The car centred 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. Similarly to 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 inertia of the car centred global system. Laws and regulations, but also the design of cities, stabilise the car as a fundamental element of mobility in contemporary society. Regulations shape the evolution of the car centred global system; the different regulations passed by different administrations can be considered linked by car manufacturers, that have to consider the regulations in all places where they want to be in the market.[2] 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 a 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.

---

[2] More precisely, one may consider regulations and manufacturers as a bi-partite network, consisting of two layers, or types, of nodes (regulations and manufacturers). An edge can be drawn from each manufacturer to all those regulations it has to conform with, thus creating two-step-links also between different regulations.

4 Simulating potential evolutions of the global car fleet

To start simple and add complexity step by step, we did not define an agent-based model including all of the above system elements from the start, but focused on households and the demand side first. As an initial step, we defined and implemented a spatially explicit innovation diffusion model on a global scale that is the focus of this section.

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 which is produced as described in Section 4.1.1. This basic model considers only two classes of cars, "brown" and "green" ones. For now, we consider green cars to correspond to battery electric vehicles for reasons of data availability; however, the model structure allows to easily replace this assumption with others, if 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. The model is programmed using Pandora (Rubio-Campillo 2014) and model simulations represent a 2009–2025 timeframe.

4.1.1 Scenarios for the total number of cars

The input data required by the model consists of maps that record the number of car purchases per cell per time-step. These have been prepared by combining gridded population data and scenarios from SEDAC (2015) with a rate of car scrappage and data on cars per 1000 people per country, from OICA (2015) up to 2015. To obtain scenarios for the decade thereafter, 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 et al (2007).

This model estimates the number 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 (International Monetary Fund 2016; U.S. Energy Information Administration 2016; United Na-
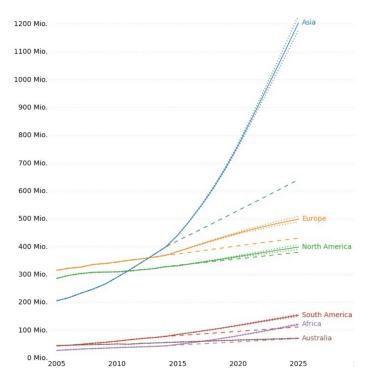

Fig. 1: Scenarios for total numbers of cars by continent: Linear trends (dashed), and the model by Dargay et al (2007) with high (dotted), medium (solid), and low (dotted) population estimates.
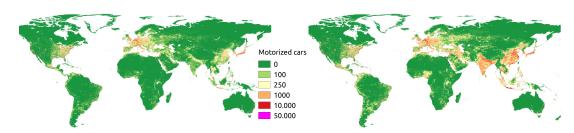
Fig. 2: Total number of cars 2009 (left) and Dargay et al model scenario for 2025 (right)

tions Department of Economic and Social Affairs 2015; The World Bank 2015; United Nations Department of Economic and Social Affairs 2014) – details are presented by Wolf et al (2016).

Figure 1 shows resulting projections of the total car fleet by continent, Figure 2 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, Japan, and South Korea – fast growth in the car fleet 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 would buy such a car for a variety of reasons that escape a deterministic representation. Green car purchases are therefore modelled as a random variable. However, to buy an electric car, people need a certain level of income. Other factors being equal, the higher the relative GDP in the cell's country, the higher the probability that people will do so. Also, countries differ rather 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 there already are in a given neighbourhood, the higher the probability that a consumer chooses one. This takes the number of green cars already present in this neighbourhood as an indicator of the existence of an electric-car-friendly infrastructure and accounts for consumers' awareness based on their observations. 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

Model runs start simulations in 2009, since the numbers of electric vehicles in most countries are negligible before that time. The time horizon of simulations is 2025. The resolution corresponds to the fine spatial grid of the population data and simulations cover global scope – making comparison of results for a set of countries in several continents possible.

4.2.1 Policy parameters

The country-specific policy parameter for the innovation component has been calibrated for the 15 countries listed in Table 1, according to data availability, on electric vehicle sales

up to 2015. 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 European Alternative Fuels Observatory 2017; International Energy Agency 2016b), 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 analyse the effectiveness of certain policy mixes in various economic, cultural and societal backgrounds.

Table 1: Policy factors calibrated

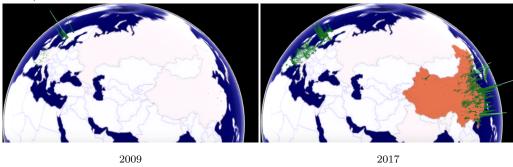| factor	country
0.06667	Korea
0.2	Italy, Spain
0.26667	Canada
0.4	Japan
0.53333	United Kingdom, Portugal, South Aftrica
0.66667	United States, Germany, Netherlands
1.66667	China
2	Sweden, France
10	Norway

For example, policy parameters for Norway, Sweden, France and China reflect large governmental purchase incentives as well as exemptions from registration and ownership taxes (see, e.g., Tietge et al 2016; Hall et al 2017). Further, exempting EV buyers from VAT, Norway takes the lead in levels of policy support for electric mobility; this can also be seen in Norway's policy parameter that is an order of magnitude higher than the others. However, Tietge et al (2016) rate German policies rather low as compared to the UK, and this is not reflected in the parameters as calibrated to EV sales data[3], where the parameter for Germany slightly exceeds that for the UK (see Table 1). This indicates a need for further research into the effectiveness of policies.

Another research direction could be a model refinement so as to calibrate the model to smaller sub-areas, for example in the US, that could then be compared with study results, as those by McDonald (2016), to gain a better understanding of the diffusion of electric vehicles under various circumstances.

4.2.2 Visualisation

Model results can be visualised in global maps. An interactive visualisation tool, based on R and the shiny package[4], was developed together with the model; Figure 3 shows some screenshots. In these maps, the height of the spikes depicts the share, and the colour shows the total number of electric vehicles in each cell. Furthermore, the total number of cars in a country is displayed by colouring the underlying country map.
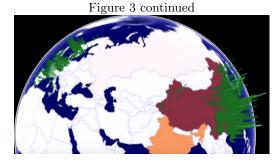
Fig. 3: Shares (spike height) and total numbers of BEV (spike colour), and total number of cars (country colour)

2009   2017

---

[3] Note that the more recent German subsidies for buying electric vehicles started later than the data used for calibration.

[4] https://shiny.rstudio.com

In simulation results for 2009, Norway stands out as the lonely innovator for electric vehicles. The picture for 2017 shows that the total number of cars in China has increased with respect to other countries, and that electric vehicle shares are growing there, while also the largest total amounts (white spikes) occur. This matches the overall pattern in recent data (see, e.g., Lutsey 2017). Finally, the simulation for 2025 shows the largest EV shares and total numbers in

Figure 3 continued

2025

China. Also, the total number of cars has massively increased in China as well as 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 move the globe and to zoom in.

In two dimensions, the map in Figure 4 shows that the Chinese coastline is likely to play an important role in the diffusion of electric vehicles. Three megalopolises, defined by Chinese policy makers around the three key cities of Beijing, Shanghai, and Shenzhen (next to Hong Kong), have the potential to become territorial niches for an initial stage in the evolution of individual mobility based on electric vehicles. 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 sense (Huawei Technologies Co., Ltd. 2015). 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 (Ewing 2017), especially in the Chinese context.
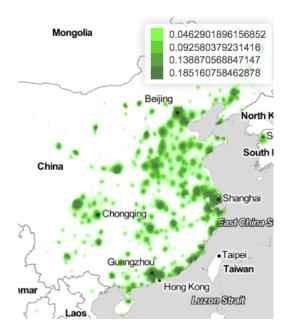

Fig. 4: Detail from simulation output for China: share of electric vehicles in 2025.

A similar map for Northwestern Europe, Figure 5, 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, 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 connected electric vehicles 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.
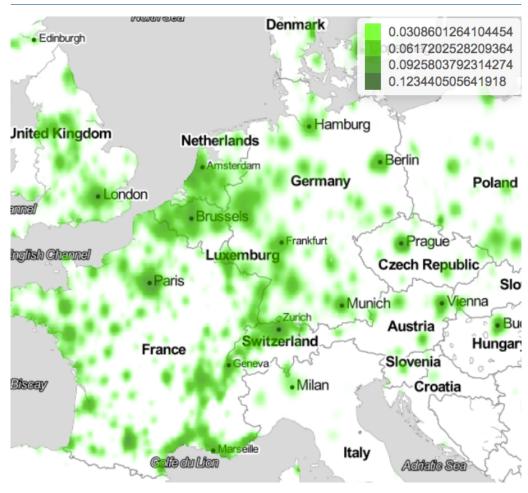
Fig. 5: Detail from simulation output for Northwestern Europe: share of electric vehicles in 2025.

5 Further work

While details are beyond the scope of this text, it should be mentioned that as a follow up to this initial model, the Mobility Transition Model (MoTMo) was developed which represents individuals and households explicitly and takes into account more complex decision making processes of these agents. In particular, they optimize expected utility, using subjective probabilities that they update based on information from other agents within their network. The agents' choices of mobility options (conventional cars, electric vehicles, or other), constitute potential evolutions of private mobility demand. The model uses a synthetic population of Germany. For further information, see Geiges et al (2017); Wolf et al (2017).

6 Conclusions and outlook

Achieving green growth is one of the grand, global challenges society is currently facing. A transition to sustainable mobility is part of what needs to be achieved for this. The car centred 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 reflect welfare, freedom, status, etc., and where conventional cars come with internal combustion engines,

an alternative narrative, that may help switch to another convention, is lacking. Green growth puts the focus on benefits to be obtained from reducing emissions by using electric vehicles and non-motorised transport, such as bikes, by sharing cars and rides: examples are reduced air pollution or urban space freed for other uses than traffic. In this respect, this paper has presented an approach to and tools 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 further develop the models, expertise from practitioners in the field is very valuable. Second, to shape the model into the most relevant directions, it is of interest which questions potential users of such a tool would like to see answered. Therefore, a previous version of this paper was presented at the Electric Vehicle Symposium, with the intention to initiate dialogues with experts from the field.

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.

References

Barra M (2016) 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

Dargay J, Gately D, Sommer M (2007) Vehicle Ownership and Income Growth, Worldwide: 1960-2030. The Energy Journal 28(4):143–170

DeCicco J (2016) Tailpipes top smokestacks as nation's largest CO2 emitters. http://www.carsclimate.com/2016/09/tailpipes-top-smokestacks.html

Dum R, Johnson J (2017) Global Systems Science and Policy. In: Johnson J, Nowak A, Ormerod P, Rosewell B, Zhang YC (eds) Non-Equilibrium Social Science and Policy, Springer, chap 14, pp 209–225, DOI 10.1007/978-3-319-42424-8_14

Dutzik T, Inglis J, Baxandall P (2014) Millennials in motion, changing travel habits of young americans and the implications for public policy. U.S. PIRG Education Fund and Frontier Group

European Alternative Fuels Observatory (2017) Battery electric vehicles for European countries. http://www.eafo.eu, visited April 2017

Ewing J (2017) Volvo, Betting on Electric, Moves to Phase Out Conventional Engines. The New York Times, URL <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>

Fulton L, Mason J, Meroux D (2017) Three Revolutions in Urban Transportation. URL <https://www.itdp.org/wp-content/uploads/2017/04/UCD-ITDP-3R-Report-FINAL.pdf>

Gargiulo F, Ternes S, Huet S, Deffuant G (2010) An Iterative Approach for Generating Statistically Realistic Populations of Households. PLoS ONE 5:e8828, URL <https://doi.org/10.1371/journal.pone.0008828>

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

Granovetter MS (1973) The Strength of Weak Ties. American Journal of Sociology (78):1360–1380

Hall D, Moultak M, Lutsey N (2017) Electric Vehicle Capitals of the World. ICCT White Paper

Heppenstall AJ, Crooks AT, Batty M, See LM (2012) Reflections and conclusions: Geographical models to address grand challenges. In: Heppenstall AJ, Crooks AT, See LM, Batty M (eds) Agent-based models of geographical systems, Springer, pp 739–747

Huawei Technologies Co, Ltd (2015) Huawei and Volkswagen Collaborate to Connect Automobiles and Smartphones. Press Release, URL <https://www.huawei.eu/media-centre/press-releases/huawei-and-volkswagen-collaborate-connect-automobiles-and-smartphones>

International Energy Agency (2016a) CO_2 Emissions from Fuel Combustion. Highlights. URL `<http://www.iea.org/publications/freepublications/publication/CO2EmissionsfromFuelCombustion_Highlights_2016.pdf>`

International Energy Agency (2016b) Global EV Outlook 2016. https://www.iea.org/publications/freepublications/publication/Global_EV_Outlook_2016.pdf, visited December 2016

International Monetary Fund (2016) 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, visited July 2016

Jaeger CC, Paroussos L, Mangalagiu D, Kupers R, Mandel A, Tábara JD (2011) 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

Jaeger CC, Hasselmann K, Leipold G, Mangalagiu D, Tábara JD (2012) Reframing the Problem of Climate Change: From Zero Sum Game to Win-Win Solutions. Earthscan, Abingdon, Oxon / New York

Kalinowska D, Kunert U (2009) Ageing and Mobility in Germany: Are Women Taking the Fast Lane? DIW Berlin Discussion Paper No. 892

Laubichler MD, Renn J (2015) Extended Evolution: A conceptual framework for integrating regulatory networks and niche construction. Journal of Experimental Zoology (Part B: Molecular and Developmental Evolution) 324:565–577

Lutsey N (2017) The rise of electric vehicles: The second million. ICCT blog, published 2017.01.31, URL `<http://www.theicct.org/blogs/staff/second-million-electric-vehicles>`

McDonald Z (2016) Comparing the Top 10 Cities for Electric Vehicle Adoption. Online, posted August 11, 2016, URL `<http://www.fleetcarma.com/top-cities-electric-vehicle-sales>`

OECD (2017) What is green growth and how can it help deliver sustainable development? URL `<http://www.oecd.org/greengrowth/whatisgreengrowthandhowcanithelpdeliversustainabledevelopment.htm>`

OICA (2015) Vehicles in use. http://www.oica.net/category/vehicles-in-use/, visited December 2015

Rische MC, Roehlig A, Stoever J (2014) Green, greener, grey. Disentangeling different types of green growth. HWWI Research Paper (160), URL `<http://www.hwwi.org/fileadmin/_migrated/tx_wilpubdb/HWWI_Research_Paper_160.pdf>`

Rubio-Campillo X (2014) Pandora: A Versatile Agent-Based Modelling Platform for Social Simulation. In: SIMUL 2014: The Sixth International Conference on Advances in System Simulation

Schütze F, Fürst S, Mielke J, Steudle GA, Wolf S, Jaeger CC (2017) The role of sustainable investment in climate policy. Sustainability 9(12):2221, URL `<http://dx.doi.org/10.1007/s00191-006-0026-4>`

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

Sperling D, Gordon D (2009) Two billion cars: driving toward sustainability. Oxford University Press

Stewart JB, Brangham W (2017) Numbers Behind Tesla, GM, Ford, the "New Big Three". URL `<http://www.supplychain247.com/article/numbers_behind_tesla_gm_ford_the_new_big_three>`

Suwei F, Qiang L (2013) Car Ownership Control in Chinese Mega Cities: Shanghai, Beijing and Guangzhou. Journeys URL `<https://www.lta.gov.sg/ltaacademy/doc/13Sep040-Feng_CarOwnershipControl.pdf>`

Tesfatsion L, Judd K (2006) Agent-Based Computational Economics. No. 2 in Handbook of Computational Economics, Elsevier, North-Holland

The World Bank (2012) Inclusive Green Growth. The Pathway to Sustainable Development. The World Bank, URL `<http://siteresources.worldbank.org/EXTSDNET/Resources/Inclusive_Green_Growth_May_2012.pdf>`

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

Tietge U, Mock P, Lutsey N, Campestrini A (2016) Comparison of Leading Electric Vehicle Policy and Deployment in Europe. ICCT White Paper

UNDESA (2012) 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

United Nations Department of Economic and Social Affairs (2014) 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/, visited July 2016

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

US Energy Information Administration (2016) 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, visited July 2016

Volkswagen (2016) 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

Volkswagen AG (2017) Volkswagen Konzern liefert 10,3 Millionen Fahrzeuge im Jahr 2016 aus. Press Release, URL `<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>`

Wolf S, Dreyer M, Edwards M, Fürst S, Geiges A, Hilpert J, von Postel J, Saracco F, Tizzoni M, Ubaldi E (2016) CoeGSS Deliverable D4.4: First Status Report of the Pilots

Wolf S, Edwards M, Fürst S, Geiges A, Rossi L, Tizzoni M, Ubaldi E (2017) CoeGSS Deliverable D4.2: Second Report on Pilot Requirements

Ziman J (2000) Technological Innovation as an Evolutionary Process, Cambridge University Press, chap Evolutionary models for technological change, pp 1–11. URL `<http://assets.cambridge.org/97805216/23612/sample/9780521623612wsc00.pdf>`