Directed Technological Change in a Bottom-Up/Top-Down CGE model: Analysis of Passenger Transport

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Abstract. This study incorporates endogenous and directed technical change in a dynamic, general equilibrium framework, with a bottom-up representation of technologies. On the example of the Austrian transport sector this paper studies the economic impacts of a carbon tax and a subsidy in research and development on innovation and market penetration of alternative, environmentally friendly passenger transport technologies. The model comprises six economic sectors, of which passenger transport is represented by bottom-up activity analysis and can be produced by one dirty technology "conventional fossil fuels" and two clean ones "hybrid" and "pure electricity". At the centerpiece of this modelling approach an innovation possibility frontier defines the technological progress of each technology. Following Aghion et al. (2011), innovation depends on the quantity of skilled labor, the degree of innovation of the previous period and two exogenous technology parameters. In the policy analysis we firstly find that an increasing carbon tax has a key impact on the competitiveness of both clean technologies and leads to a phase out of the dirty technology. However, technological progress and innovation is not affected. Secondly, if the carbon tax revenues are used to subsidize research and development of the clean technologies, technological progress will be promoted. The subsidy leads to a rise in the rate of technological change and to lower input costs within production. Thus, innovation happens more rapidly. Finally, this paper provides a comprehensive modelling approach that can be used for the quantitative analysis of climate policy on innovation and competitiveness by considering technology details.

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1 Introduction

Transport is currently responsible for around a quarter of EU greenhouse gas emissions making it one of the prime polluters. According to the European Commission road transport, foremost passenger transport, accounts for more than two-thirds of EU transport-related greenhouse gas emissions (European Commission 2011; International Transport Forum 2010). Moreover, with an increase of 36% between 1990 and 2007, transport shows by far the highest increase in greenhouse gas emissions (while those from most other sectors are generally falling). Although a variety of mitigation strategies to reduce passenger transport such as road pricing, fuel taxation and enhancement of public transport exist, the increasing trend continuous. According to the EU (European Union 2012) and IEA (IEA 2008) a promising approach to reduce greenhouse gases from passenger transport is technological, i.e. to change the propulsion technology used. Alternative propulsion technologies use alternative energy sources and do not depend on fossil fuels, such that some alternative technologies are even nearly CO2 neutral. Several alternative, environmentally friendly propulsion technologies, such as pure electricity and hydrogen have been developed for passenger cars, but have not succeeded market penetration and competitiveness yet.

Therefore this paper aims to study the technological progress of alternative, environmentally friendly passenger transport in a dynamic, general equilibrium framework in order to analyze (i) policy instruments that foster endogenous and directed technical change and (ii) to assess the resulting economic impacts. Thereby this study fills a gap not covered by the literature so far by linking two strands of modelling techniques: a detailed bottom-up representation of passenger transport technologies (following Böhringer (1998)) and accounting for endogenous and directed technical change (following Aghion et al. 2011).

The incorporation of bottom-up technologies in an economy-wide top down model is frequently used for the energy sector in order to assess energy policy scenarios (Böhringer and Rutherford 2009a; Wing 2006). The idea is that sectors whose technological options and details are of major importance for policy analysis are represented by bottom up activity analysis. The production possibilities are captured by discrete Leontief technologies that are active or inactive in equilibrium depending on their profitability. For the purpose of this study this approach enables the consideration of all available technologies, even those that are currently not competitive and cost-efficient. Within transport policy so far only Schäfer and Jacoby (2005) consider both transport technologies and technological progress in a CGE model. However, in terms of transport technology only conventional fossil fuels are incorporated by these authors, no alternative energy sources are taken into account.

Most studies relying on the incorporation of bottom-up details in an economic top-down model, only account for exogenous technical change based on assumptions about future costs. These assumptions are commonly represented by the AEEI (autonomous energy efficiency improvement) parameter (e.g. see Manne and Richels 1992; Nordhaus 1992) a heuristic measure of all non-price driven improvements in technology (Löschel 2002). The main reason is that induced endogenous technological change is commonly modelled as knowledge accumulation (see Goulder and Schneider 1999; Jaffe et al. 2003; Romer 1990) and achieved by a shift in the neoclassical production functions, via the substitution of inputs with knowledge capital. Therefore the key element of the representation of bottom-up activities - fixed input-output relation of Leontief technologies - is not suitable for induced endogenous technological change as for instance developed by Goulder and Schneider (1999).

In order to answer the addressed issues and to link technology details with endogenous technical change in a dynamic, CGE framework we use the approach of endogenous, directed technical change of Aghion et al. (2011) as modelling guidance. Aghion et al. (2011) focus in their study on the endogenous response of technological change to environmental policy and how it relates to innovation and resources. Their definition of an innovation possibility frontier is used as our linking device.

2 Literature review on technical change

This section subsumes the fundamentals and challenges of modelling technological change, both exogenous and endogenous, and the representation of technology details in a computable general equilibrium framework for energy and climate policy analysis.

2.1 Bottom up vs. top down

In order to assess and model the interaction of energy, environment and economy a gap between bottom-up engineering models and top-down macroeconomic models arises. Generally bottom-up models simulate a large number of individual technologies to capture substitution possibilities of energy carriers, energy efficiency and technological development. Within this approach technological change occurs as one technology is substituted by another. In contrast top-down models show technologies on a highly aggregated level with a standard, simplified neoclassical CES production function capturing substitution possibilities and do not rely on the description of individual technologies. Technological change is modelled as a shift in the costs of production at commodity or industrial level (for an overview see Wing 2006; Löschel 2002). Hybrid models integrating technological details in a top-down macroeconomic framework overcome the shortcomings of both approaches and are wide-spread within energy policy analysis (Böhringer and Rutherford 2009b; Sue Wing 2008; Frei et al. 2003). Technological options and details that are of major importance for policy analysis are represented by bottom up activity analysis, modelled by a set of Leontief technologies. Thus, the factors of production are used in fixed proportions and there is no substitutability between factors. In contrast, all other production activities in top-down models are represented by some form of CES nest cost functions that capture substitution possibilities on the input side as well as transformation possibilities on the output side (Böhringer 1998; Löschel 2002).

The hybrid (bottom-up in top-down) approach enables dealing with transitional technologies and future technologies, not competitive in the benchmark case. Technologies that are not active in the benchmark, run losses at benchmark prices, however might turn active if the relative price system changes (e.g. policy interference, energy improvements). Turning to the transport sector and the adressed issue of this paper, the hybrid model formulation is most suitable. The reason is that currently only fossil fuel based passenger transport and with governmental subsidies, biofuels of the first generation are competitive and cost efficient. However a range of alternative propulsion technologies exists which might either enter the market in the near future, such as hybrid vehicles, or in the long run such as pure electricity, hydrogen and biofuels of the second generation, because those technologies are in early development stages only. Whether these technologies succeed depends on policy support and whether they are competitive in prices. Moreover the hybrid (bottom-up in top-down) approach enables the simulation of classical transitional technologies such as hybrid vehicles, that will play an important role in the near future, but will disappear in the long run (Kloess et al. 2009; IEA 2004; Offer et al. 2010).

2.2 Exogenous technological change

A bulk of studies in climate policy research treat technological change as exogenous. On the one hand it can be introduced as a non-price driven improvement in technology (AEEI parameter) and on the other hand by assumptions about future costs of technologies (backstop). The index of "autonomous energy efficiency improvement" (AAEI) may present structural changes in the economy or changes in the energy use per unit output. It simply consists of augmentation coefficients ,α, applied to inputs of the production function, whose values normally grow over time (Sue Wing 2008; Löschel 2002):

$$Y_t = F(\alpha^K K_t, \alpha^L L_t)$$

Changes in energy intensity depend on the degree to which energy can be substituted by other commodities and factors and is thus determined by the elasticity of substitution between energy and all other inputs. The incremental technological change of the AEEI parameter is generally used to illustrate empirically-observed development of expanding output accompanied by declining energy intensity. However there are several shortcomings. First and most important the rate and direction of technological change are predefined by the modeler, thus there is no endogenous feedback. Secondly the AEEI parameter enables only incremental improvement and no radical technical change synonymous for the appearance of completely new technologies (Sue Wing 2006; Löschel 2002).

One way to account for radical technological change is to provide discrete new technologies, so called backstop technologies. Basically those are alternative production functions, not commercial in the benchmark, which switch on in future periods in response to increasing prices. Thereby the initially relative high costs reflect investment in research and development. Energy-economic models generally include fossil as well as non-fossil backstop technologies. Examples are carbon-free electric power generation, full cells and advanced fossil fuel generation technologies (Sue Wing 2006). In order to incorporate backstop technologies in macroeconomic models the hybrid top down and bottom-up is very common (see prior section). The advantage of both ways of exogenous technological change is to analyze the impacts and macroeconomic effects of replacing the existing capital stock with more energy efficient as well as environmentally friendly technologies. However, innovation or diffusion can not be assessed.

2.3 Endogenous technological change

2.3.1 Induced technological change: The stock of knowledge approach

Tracing back to Romer (1990) and Grossman and Helpman (1994) a newer class of modelling approaches focuses on investment in R&D. Its centerpiece is the stock of knowledge H_t, an explicit input in production, to capture the link between investments in R&D (accumulation of knowledge) and technological progress. Thereby, it implies that R&D is the source of technological progress and investments to R&D improve the state of knowledge, thus innovation (Sue Wing 2006; Löschel 2002; Jaffe et al. 2003). Goulder and Schneider (1999) give one example to incorporate induced technological change with sectoral spillover in a dynamic general equilibrium model. Their model comprises four intermediate industries and three industries that produce *investments goods*, *R&D services* and a *consumption good* as final goods. R&D services are produced with labor and intermediate inputs in order to generate technical information. The key assumption is that R&D services have a positive price, reflecting that education, personal and other costs are required to offer knowledge-services. Every sector produces with labor, capital, energy and material inputs [1]. In terms of capital Goulder and Schneider (1999) differ between physical capital (K) and knowledge capital (H), which is rival but not excludable (spillover).

Each stock of capital accumulates according to:

$$K_{t+1} \geq (1 - \delta_t)K_t + I_t$$

$$H_{t+1} \geq H_t + \epsilon \cdot R_t$$

Investment in new physical capital ,I_t, and expenditure in R&D activities ,R_t, expands the respective stock of capital and allows firms to produce more output with the same

[1] $X_j = f_j(\bar{H}_j, H_j, K_j, L_j, E_j, M_j, IM_j)$ with $\bar{H}_j$ denoting knowledge spillover

amounts of inputs. Expenditure on R&D underlies induced technological change. While physical capital depreciates at rate δ_t, knowledge capital does not.

This approach is used in a variety of studies concerning climate policy and abatement, however not suitable in order to analyze the addressed issues of this paper. The approach is only suitable for CES-type technologies, because the driving force of induced technological change is the substitution of inputs with knowledge capital (expenditure in R&D activities ,R_t, expands the respective stock of capital and reduces input requirements for the other industries). Therefore it does not fit the requirements of our hybird, bottom-up in top-down, approach where technologies are represented by a Leontief-style production function with a fixed input-output relation.

2.3.2 Directed technological change

The fact that technological change is not neutral, but directed and biased has not been the focus of climate policy research so far. Acemoglu (2002) and Aghion et al. (2011) address the issue that some factors of production or economic forces benefit technological change more than others. The centerpiece of the analysis is the endogenous response of technological change to environmental policy and how it relates to innovation and resources. Aghion et al. (2011) construct a general equilibrium framework to study the endogenous response of different types of technologies to certain policies and propose a simple two-sector model of directed technical change. They consider an infinite horizon discrete time economy (Ramsey-style) inhabited by a continuum of households comprising workers, entrepreneurs and scientists:

$$\sum_{t=0}^{\infty}(1/(1+\rho))^t \cdot U(C_t, S_t)$$

The utility at time t depends on the consumption of the final good (C_t) and on environmental quality (S_t), with $\rho \gg 0$ as the discount rate.

In terms of production, there is a unique final good, produced competitively by two different technologies "clean" (Y_{Ct}) and "dirty" (Y_{Dt}):

$$Y_t = (Y_{Ct}^{\frac{\epsilon-1}{\epsilon}} + Y_{Dt}^{\frac{\epsilon-1}{\epsilon}})^{\frac{\epsilon}{\epsilon-1}}$$

Aghion et al. (2011) state that the elasticity of substitution ϵ between both technologies plays a crucial role for policy response of technological change.

Both technologies are produced using labor and a continuum of sector-specific machines and are as follows:

$$Y_{Ct} = L_{Ct}^{1-\alpha} \int_0^1 A_{Cit}^{1-\alpha} x_{Cit}^{\alpha} di \quad \text{and} \quad Y_{Dt} = R_t^{\alpha_2} L_{Dt}^{1-\alpha} \int_0^1 A_{Dit}^{1-\alpha_1} x_{Dit}^{\alpha_1} di$$

Dirty production (Y_{Dt}) also uses a natural exhaustible resource (R_t). In terms of directed technological change, the quality of machine of type i used in sector $j \in (C, D)$ at time t, defined as A_{jit}, is of key importance. The quantity of machines is denoted by x_{jit}. Innovation starts at the beginning of every period t, when a scientist ,s_t,[2] decides whether to direct her research to clean or dirty technology. She is then randomly allocated to at most one machine, with $\mu_j \in (10, 1)$ being the probability of a successful innovation for each technology. Thereby innovation increases the quality of a machine by a factor $1+\gamma$, with $\gamma \gg 0$ characterizing some kind of exogenous learning rate. In terms of specification of the innovation possibility frontier a successful scientist gains a one-period patent and becomes the entrepreneur for the current period in the production of machine i. In sectors where innovation is not successful, monopoly rights are allocated randomly to an entrepreneur drawn from the pool of potential entrepreneurs who then use the old technology. All these assumptions imply the centerpiece of this approach, the evolution of A_{jt} over time:

$$A_{jt} = (1 + \gamma \cdot S_j t \cdot \mu_j) \cdot A_{jt-1}$$

We just presented the highlights and main assumptions that are of key importance for the purpose of this study (for a complete description see Aghion et al. (2011)). Although this approach is highly stylized, the definition of the innovation possibility frontier gives the opportunity to introduce endogenous technological change linked with its endogenous policy responses in an integrated bottom-up, top-down framework.

3 The model

The dynamic CGE model developed in this paper aims to study the technological progress of alternative propulsion technologies for passenger transport and to analyze the impacts of policy instruments to foster endogenous and directed technological change. In order to keep the degree of complexity as simple as possible we follow the closed economy assumption. The model further comprises six economic sectors: Passenger transport (PT), fossil fuels (FF) - subsuming coal, oil and gas , electricity generation & distribution (ELY), agriculture, food and textile (AFT), services (SERV) and manufacturing, metal- and non metal industries (MI). Passenger transport can be produced by one dirty technology “conventional fossil fuels” and two clean ones “hybrid” and “pure electricity”. On consumption side households are endowed with capital (K), labor (divided by skilled, LS, and unskilled, LU) and a natural resource (R) used within the production of fossil fuels.

[2] with the number of scientists normalized to 1

3.1 Model formulation

In terms of dynamics the model adopted here is based on a simple Ramsey growth model. It is taken as the benchmark model for modern dynamic macroeconomics and optimal inter-temporal allocation of resources and is thus used in a variety of studies concerning climate policy.

In the production of industrial activities[3] ,$Y_t(IA)$, firms minimize costs of producing output subjected to a nested CES function that describes the price-dependent use of factors and intermediate inputs. In the upper nest intermediate domestic inputs (all $IA \neq ES$) trade off with the value added – energy composite, which is specified by a trade off between value added and energy inputs on mid-level. Within energy inputs fossil fuels and electricity trade off, while in the value added capital and skilled as well as unskilled labor trade off.

- Industrial activity $Y_t(IA)$

$$\pi_t^{Y(IA)} = p_t^{Y(IA)} - \left\{ \theta_{YALL}^{Y(IA)} \cdot \sum_{ES \neq IA} \left[\theta_Y^{Y(ES)} \cdot \left(p_t^{Y(ES)} \right)^{\sigma_Y^{y(ES)}} \right]^{\frac{\sigma_{YALL}^{y(IA)}}{1-\sigma_Y^{y(ES)}}} + \left(1 - \theta_{YALL}^{Y(IA)}\right) \cdot \left(\left(p_t^{VA(IA)} \right)^{\sigma_{VAE}^{y(IA)}} \cdot \left(p_t^{ENG(IA)} \right)^{1-\sigma_{VAE}^{y(IA)}} \right)^{\sigma_{YALL}^{y(IA)}} \right\}^{\frac{1}{1-\sigma_{YALL}^{y(IA)}}} \tag{1}$$

with the value added composite:

$$\pi_t^{VA(IA)} = p_t^{VA(IA)} - \left\{ \theta_{kl}^{Y(IA)} \cdot \left(\left(p_t^{LS(IA)} \right)^{\sigma_l^{y(IA)}} \cdot \left(p_t^{LU(IA)} \right)^{1-\sigma_l^{Y(IA)}} \right)^{1-\sigma_{kl}^{Y(IA)}} + (1 - \theta_{kl}^{Y(IA)}) \cdot \left(r_t^{K(IA)} \right)^{1-\sigma_{kl}^{Y(IA)}} \right\}^{\frac{1}{1-\sigma_{kl}^{Y(IA)}}}$$

and the energy composite:

$$\pi_t^{ENG(IA)} = p_t^{ENG(IA)} - \left\{ \left(p_t^{FF(IA)} \right)^{\theta_e^{Y(IA)}} \cdot \left(p_t^{ELY(IA)} \right)^{1-\theta_e^{Y(IA)}} \right\}$$

From here on σ always denotes the elasticity of substitution between the respective inputs, while θ accounts for the according share parameter in a CES-nesting.

Passenger transport technologies are incorporated as bottom-up activities. Therefore production possibilities are captured by discrete Leontief technologies that are active or inactive in equilibrium depending on their profitability. The unit profit function for passenger transport (PT) for technology *tec* is as follows:

[3] the set IA with alias ES comprises AFT, SERV and MI

- Passenger Transport PT(tec)

$$\begin{aligned}\pi_t^{PT}(tec) = p_t^{PT} - \Big\{&\theta_{ls}(tec)\cdot p_t^{LS} + \theta_{lu}(tec)\cdot p_t^{LU} + \\ &\theta_{y(IA)}(tec)\cdot A_t(tec)\cdot p_t^{Y(IA)} + \\ &\theta_k(tec)\cdot r_t^K + A_t(tec)\cdot\theta_{ff}(tec)\cdot p_t^{FF} + \\ &\theta_{ely}(tec)\cdot A_t(tec)\cdot p_t^{ELY}\Big\}\end{aligned} \tag{2}$$

Following Aghion et al. (2011) $A_t(tec)$ denotes the quality and efficiency of the intermediate as well as energy inputs. Hence, $A_t(tec)$ defines the level of technological change (for the innovation possibility frontier see Equation 6).

Fossil fuels (subsuming oil, coal and gas) are produced within a CES nesting, however the natural resource (R) is essential for production. On top level natural resource trades off with a fixed share (Leontief) to the energy-value added-intermediate composite. On mid-level Y(IA), ELY and value added trade off. On the lower nest, within value-added, L (composite of skilled and unskilled labor) and K are linked through a Cobb-Douglas production function. The unit profit function is as follows:

$$\pi_t^{FF} = p_t^{FF} - \Big\{\theta_{ffr}\cdot\left(p_t^R\right)^{1-\sigma_{ffr}} + (1-\theta_{ffr})\cdot\left(p_t^{IEVA}\right)^{1-\sigma_{ffr}}\Big\}^{\frac{1}{1-\sigma_{ffr}}} \tag{3}$$

with the following energy-value added-intermediate composite:

$$\begin{aligned}\pi_t^{IEVA} = p_t^{IEVA} - \Big\{&\theta_{klely_1}\cdot\left(\left(\left(p_t^{LS}\right)^{\theta_{ls}}\cdot\left(p_t^{LU}\right)^{1-\theta_{ls}}\right)^{\theta_l}\cdot\left(r_t^K\right)^{1-\theta_l}\right)^{1-\sigma_{klely}} \\ &+ (1-\theta_{klely_2})\, p_t^{IEVA}\cdot\left(p_t^{ELY}\right)^{1-\sigma_{klely}} \\ &+ (1-\theta_{klely1}-\theta_{klely2})\cdot\sum_{IA}\left[\theta_Y^{Y(IA)}\cdot\left(p_t^{Y(IA)}\right)\right]^{\sigma_{klely}}\Big\}^{\frac{1}{1-\sigma_{klely}}}\end{aligned}$$

Electricity is produced within a 3-level nesting CES function comprising FF, L, K and Y(IA):

$$\begin{aligned}\pi_t^{ELY} = p_t^{ELY} - \Big\{&\theta_{REVA}\cdot\sum_{IA}\left[\theta_Y^{Y(IA)}\cdot\left(p_t^{Y(IA)}\right)\right]^{1-\sigma_{IFFVA}} \\ &+ (1-\theta_{REVA})\cdot\left(p_t^{FFVA}\right)^{1-\sigma_{IFFVA}}\Big\}^{\frac{1}{1-\sigma_{IFFVA}}}\end{aligned} \tag{4}$$

with

$$\begin{aligned}\pi_t^{FFVA} = p_t^{FFVA} - \Big\{&\theta_{ffva}\cdot\left(p_t^{FF}\right)^{1-\sigma_{FFVA}} \\ &+ (1-\theta_{ffva})\cdot\left(\left(\left(p_t^{LS}\right)^{\theta_{ffls}}\cdot\left(p_t^{LU}\right)^{(1-\theta_{ffls})}\right)^{\theta_{lff}}\cdot\left(r_t^K\right)^{1-\theta_{lff}}\right)^{1-\sigma_{FFVA}}\Big\}^{\frac{1}{1-\sigma_{FFVA}}}\end{aligned}$$

Finally a consumption good C is produced by CES technology where industry activities Y(IA), PT, FF and ELY trade off. On top level energy-composite and consumption-composite trade off. The unit profit function for the production of the final consumption good is:

$$\pi_t^C = p_t^C - \left\{ \theta_{CE} \cdot \left(p_t^{RIPT}\right)^{1-\sigma_{CE}} + (1-\theta_{CE}) \cdot \left(p_t^{ENG}\right)^{1-\sigma_{CE}} \right\}^{\frac{1}{1-\sigma_{CE}}}, \tag{5}$$

with the consumption composite given by:

$$\pi_t^{RIPT} = p_t^{RIPT} - \left\{ \theta_{RIPT} \cdot \sum_{IA} \left[\theta_Y^{Y(IA)} \cdot \left(p_t^{Y(IA)} \right) \right]^{(1-\sigma_{RIPT})} + (1-\theta_{RIPT}) \cdot \left(p_t^{PT}\right)^{1-\sigma_{RIPT}} \right\}^{\frac{1}{1-\sigma_{RIPT}}}$$

The energy-composite is as follows:

$$\pi_t^{ENG} = p_t^{ENG} - \left\{ \theta_{ENG} \cdot \left(p^{ELY}\right)^{(1-\sigma_{ENG})} + (1-\theta_{ENG}) \cdot \left(p_t^{FF}\right)^{1-\sigma_{ENG}} \right\}^{\frac{1}{1-\sigma_{ENG}}}$$

The centerpiece of this study is the evolution of $A_t(tec)$, following the specification of the innovation possibility frontier of Aghion et al. (2011). Analogous to Aghion et al. (2011), skilled labor (modelled as share on total employment) determines innovation, in particular the level of research to clean or dirty technology. Thus the higher the share of skilled labor on total employment, the higher is the possibility of innovation. Innovation also depends on the previous quality and efficiency ($A_{t-1}(tec)$). Furthermore, the parameter $\mu(tec) \in (10, 1)$ defines the probability of success of an innovation and $\gamma(tec)$ characterizes the increase in quality (the so-called learning rate) for technology tec. The difference equation is given by:

$$A_t(tec) = \left(1 - \gamma(tec) \cdot \left(\frac{LS_t(tec)}{L_t(tec)}\right) \cdot \mu(tec)\right) \cdot A_{t-1}(tec) \tag{6}$$

Thus, Equation 6 allows for directed endogenous technical change and its endogenous policy responses[4].

In terms of evolution, capital accumulates as follows:

$$K_{t+1} \geq (1-\delta_t)K_t + I_t \tag{7}$$

The next period capital stock is built from investment and capital less depreciation.

[4]In contrast, to Aghion et al. (2011) we define quality and efficiency as $A_t(tec) < 1$, in order to define the improvement and progress as changes in the energy use per unit output.

In terms of factors, we assume full employment. Thus skilled labor and unskilled labor present total employment of the economy:

$$\bar{L_t} = LU_t + LS_t \tag{8}$$

A representative household receives its income (M) from providing the primary factors capital, labor and natural resource.

$$M = p_0^{LS} \cdot LS_0 + = p_0^{LU} \cdot LU_0 + p_0^K \cdot K_0 + p_0^R \cdot R_0 \tag{9}$$

Following the Ramsey model, a representative consumer maximizes the present value of his life-time utility:

$$W = max \sum_{t=0}^{\infty} (1/(1+\rho))^t \cdot U(C_t) \tag{10}$$

The instantaneous utility function with a constant inter-temporal elasticity of substitution (ϕ) of 0.5, consistent with the steady state, is given by:

$$U(C_t) = \frac{C_t^{(1-\phi)} - 1}{1-\phi} \tag{11}$$

Prior to the numerical example we define the following: It is not possible to solve for an infinite number of periods numerically. Therefore a finite horizon model is used. However, this approximation poses some problems with respect to capital accumulation. A common approach in order to avoid those problems is the introduction of terminal capital (Paltsev 2004; Lau et al. 2002). Without terminal capital all capital would be consumed in the last period and nothing would be invested. The terminal condition forces investment to increase in proportion to final consumption demand. Following Lau et al. (2002) the post terminal capital (K_{T+1}) is introduced as an endogenous variable and the terminal condition is as follows:

$$I_T / I_{T-1} = 1 + gr \tag{12}$$

Equation 12 sets the terminal investment growth rate equal to the steady state growth rate.

4 Numerical example

In this section, we illustrate the use of our hybrid bottom-up/top-down model with endogenous, directed change for the assessment of different policy options promoting technological progress and innovation on the example of Austria. In 2009 the Austrian transport sector was around 27% above the greenhouse gas emission reduction target of the EU and furthermore emissions from passenger transport are still increasing. Thus, the technological approach (to change the propulsion technology used) id particularly suitable for Austria, since a large part (62%) of the Austrian population lives in rural areas and relies on the car, due to long distances and poor public transport. Finally, Austria shows a high degree of technical knowhow ready to be used in the fields of alternative propulsion technologies (Anderl et al. 2009; Kloess et al. 2009). The CGE model is programmed in the General Algebraic Modelling System (GAMS) by using the Mathematical Programming System for General Equilibrium Analysis (MPSGE) as pre-processing subsystem (Rutherford and Paltsev 1999).

4.1 Benchmark data

The reduced social accounting matrix of Table 1 summarizes the data to which the model is calibrated. The data relies on the GTAP data set (Center for Global Trade Analysis 2004) and input-output table for Austria (Statistics Austria 2005) in order to account for the relations and levels of factors and production activities.

Table 1: Social accounting matrix [in million $]

	FF	ELY	SERV	AFT	MI	PT	C	W	HH
FF	3604	-640	-400	-300	-300	-880	-1084		
ELY	-67	6801	-1600	-1200	-1262		-2672		
SERV	-959	-984	350832	-100237	-100237	-920	-147493		
AFT	-191	-196	-116944	263124	-75362		-70429		
MI	-767	-787	-116944	-75178	263370	-736	-68956		
PT						4454	-4454		
C							295089	-295089	
W								295089	-295089
L	-519	-1571	-53504	-40128	-40128	-960			136810
K	-732	-2622	-61440	-46080	-46080	-958			157912
RS	-367								367

Table 2 and Table 3 show the cost structure of both, clean and dirty passenger transport technologies. Within the production of conventional passenger transport fossil fuels show a relatively high cost share. According to (Kloess et al. 2009) fuel costs are responsible for 20% of the annual costs of conventional gasoline based passenger transport. Also note that the benchmark output of conventional passenger transport represents the economy wide demand for passenger transport, since hybrid and pure-electricity are not competitive, yet. Within the production of hybrid based passenger transport capital costs, in particular battery costs, account for the largest part of production costs. Within the production of electricity based passenger transport capital costs present by far the highest cost fraction. The reason are also very high battery costs (Kloess et al. 2009). In this example unit-output of hybrid is listed as 10% more costly than the price

Table 2: Cost structure of active technologies

	conventional
PT	4454
FF	-880
SERV	-920
MI	-736
L	-960
K	-985

Table 3: Cost structure of inactive technologies

	Hybrid	Electric
PT	1	1
FF	-0.3	
ELY	-0.2	-0.3
SERV	-0.1	-0.1
MI	-0.1	-0.2
L	-0.1	-0.1
K	-0.4	-0.6

of passenger transport in the base year. Electricity based passenger transport is 40% more costly. Further assumptions regarding the technological process and development are derived from a literature review (Kloess et al. 2009; Offer et al. 2010; IEA 2008).

For calibration we assume an annual interest rate as well as factor growth rate of 2%. Furthermore the annual discount rate is 7% (see also Nordhaus (1992)). Finally the model is calibrated to the steady state, activity levels are rising over time and prices are falling over time.The price of capital differs from all other prices by $(1 + r, 2\%)$. The benchmark is replicated and all (active) quantities and prices grow at a constant rate of 2%. The period of analysis lasts from 2005 to 2050.

4.2 Reference scenario

The reference scenario is defined by no policy intervention. However, there is technological change in pure-electricity and hybrid based passenger transport, with the learning rate γ of 3.5% and the associated rate of success ,μ, of 80% (for both technologies)[5]. Furthermore we follow the assumption of exhaustible resources and constrain the growth of the natural resource (R_t). Thus, the annual growth rate is about half of the growth rate of all other factors. Results show, that in the reference scenario pure-electricity based

[5]Within this simple numerical example both clean technologies (hybrid and pure-electricity) are defined by the identical technological progress. Dirty technologies do not experience an increase in quality or efficiency.

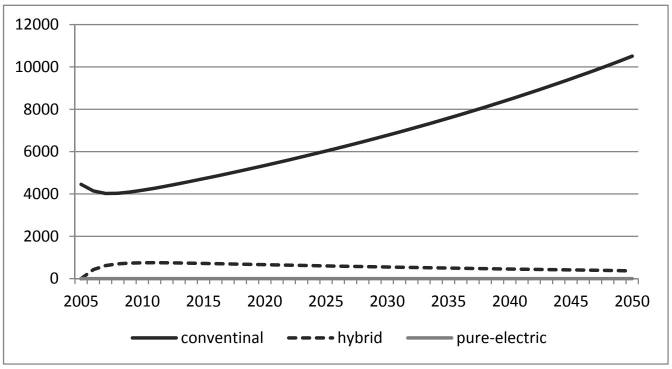

Figure 1: Passenger transport supply

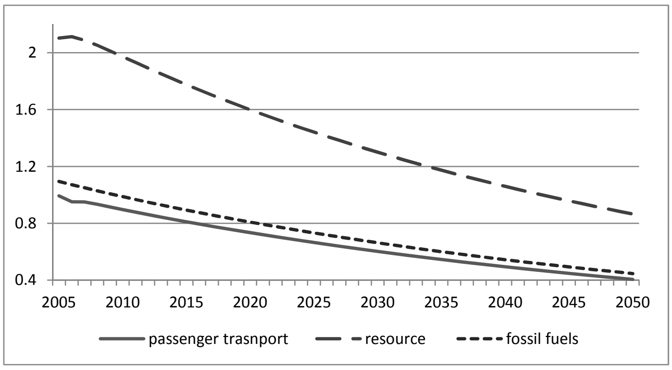

Figure 2: Price development until 2050

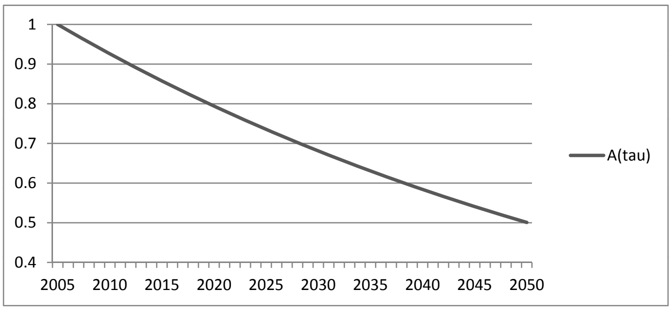

Figure 3: Technological change

passenger transport is not competitive and hence inactive. Although we assume technological change (increase in quality, A_t) and an exhaustible resource, pure-electricity based passenger transport is not able to overcome the initial cost difference and to break even. Conventional based passenger transport remains market leader and increases its production significantly until 2050. Hybrid based passenger transport gets active in 2006, however maintains a substantially low level of production (see Figure 1).

The resource constraint implies a substantially higher price of the natural resource. Turning to our model assumptions, since the natural resource is essential for production of fossil fuels, its price is also affected. The resulting price of passenger transport is well below the treshold at which pure-electricity based passenger transport would break even.

In terms of technological change Figure 3 illustrates the evolution of A_t (quality/effecience parameter).

Sensitivity analysis shows that the assumptions of exhaustible resource is essential for this result. By not following this assumption and assuming the same growth rate as for all other factors (2%) hybrid-based passenger transport is continuously increasing and soon market leader. In contrast, the dirty technology, conventional based passenger transport, experiences a continuous phase-out and nearly disappears at the end of our analysis period. The results for pure-electricity based passenger transport do not change, the technology is not able to break even. Thus, the increasing price of fossil fuels caused by the resource constraint, is most beneficial for the dirty technology and hinders the competitiveness of hybrid based passenger transport, since the input share of fossil fuels is 27%.

4.3 Policy simulations

In this section we illustrate the use of our hybrid bottom-up/top-down model with endogenous technological change to assess the economic impacts of different policy options aiming to foster technological change. Therefore we follow a two-step approach:

1. Apply an increasing carbon tax on fossil fuels and
2. use the revenue of the carbon tax to subsidize research and development

Within policy arenas a carbon tax has been the most favored policy intervention in order to reduce greenhouse gas emissions from fossil fuel combustion. A bulk of EU-member states introduced some kind of carbon tax. Austria, the focus of our policy analysis, currently charges a fuel tax on gasoline, benzene and fuel oil. However, the impacts have been modest, since we still observe increasing fossil fuel consumption. Therefore, in a second step of our analysis we use the carbon tax revenues to subsidize research and development of alternative passenger transport technologies in order to foster technological progress.

4.3.1 Carbon tax

Fossil fuels are an important input for several production activities. In this simulation we apply an additional carbon tax on fossil fuels. Starting with an initial tax of 10% and

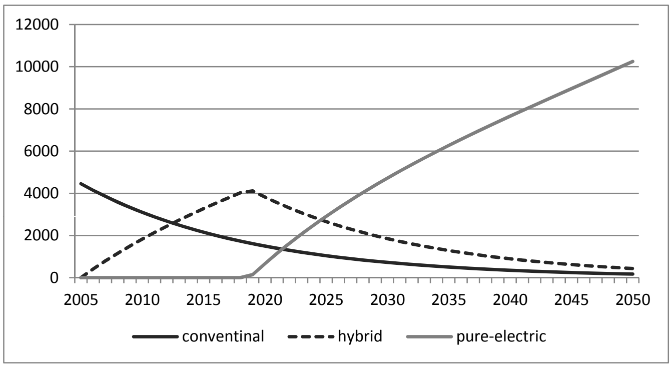

Figure 4: Passenger transport supply

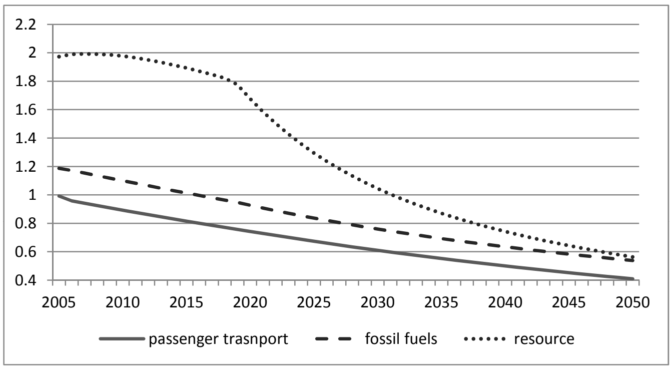

Figure 5: Price development until 2050

an annual growth rate of 1.8%, the tax will be around 22% in 2050. As illustrated in Figure 4, the increasing carbon tax leads to a continuous phase out of conventional fossil fuels. Hybrid based passenger transport experiences a substantial increase until 2019, afterwards (when pure-electricity is competitive) it is continuously decreasing and nearly disappeared in 2050. By the time, pure-electricity based passenger transport gets active, its production rises substantially and gains market leadership in 2025. Summarizing, a fuel tax significantly promotes environmentally friendly passenger transport.

In terms of prices, Figure 5 illustrates that the carbon tax is responsible for a significantly higher price of fossil fuels compared to the reference case (see Figure 2). Prices of passenger transport and the natural resource are not affected. Moreover, the rate of technological progress ($A_t(tec)$) is not affected (at the level of reference case, see Figure 3) since the carbon tax has no impact on skilled labor or on the learning parameters. In addition to conventional passenger transport, the output level of sectors with a high fuel-intensity (e.g. ELY, MI) is also falling compared to the reference case.

4.3.2 Subsidy in Research and Development

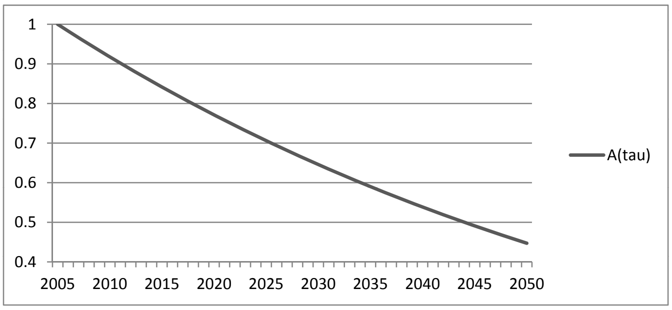

Figure 6: Technological change

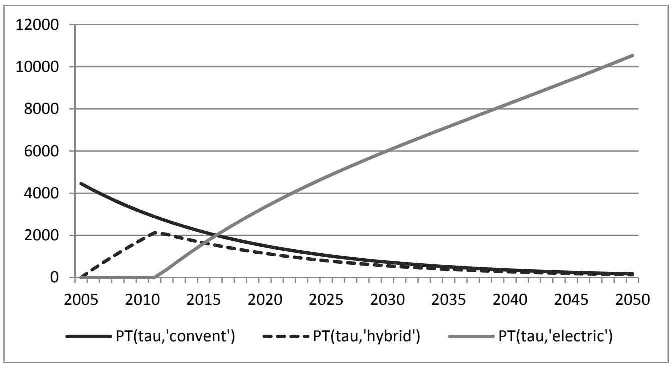

Figure 7: Passenger transport supply

In contrast to the carbon tax, we are also interested in policy options that promote technological progress. Therefor we aim to subsidize research and development in order to affect technical progress. Thereby the revenues of the fuel tax are used to finance the subsidy. In terms of modelling specification, the subsidy is applied to skilled labor, one driving force of directed technological change (see Equation 6). Pure-electricity shows with an CO_2 coefficient[6] of 120g per kilometer driven, by far the highest environmental effectiveness, compared to conventional fossil fuels (240g per kilometer driven) and hybrid (180g per kilometer driven). Therefore in order to foster technological progress of the most sustainable and environmentally friendly technology we subsidize pure-electricity, only.

Compared to the previous scenario, subsidizing research and development of pure-electricity based passenger transport fosters technological progress. The subsidy implies

[6]The CO_2 coefficients are based on Kloess et al. (2009) and calculated for Austria (e.g. high share of renewable energy in electricity production)

that the price of skilled labor within the production of pure-electricity based passenger transport falls and thus promotes the competitiveness. Furthermore A_t is also affected by the subsidy and the efficiency improvement is substantially higher than in the prior scenarios (see Figure 3). Both, the rise in the rate of technological change and the lower costs of skilled labor, imply that pure-electricity beaks even in 2010, already (see Figure 7). Conventional fossil fuel passenger transport experiences a continuous phase-out similar to the prior scenarios. The role of hybrid based passenger transport on the market is also limited. The rapid market entrance of pure-electricity leads to a substantial fall in the output level of hybrid based passenger transport, compared to the carbon tax scenario.

5 Conclusion and Discussion

This study incorporates endogenous and directed technical change in a dynamic, general equilibrium framework, with a bottom-up representation of technologies. On the example of the Austrian transport sector this paper studies the economic impacts of a carbon tax and a subsidy in research and development on technological progress and market penetration of alternative, environmentally friendly passenger transport technologies.

The dynamic CGE model developed in this paper comprises six economic sectors: passenger transport, fossil fuels , electricity generation & distribution, agriculture, food and textile, services as well as manufacturing, metal- and non metal industries. Thereby passenger transport is represented by bottom-up activity analysis and can be produced by one dirty technology “conventional fossil fuels” and two clean ones “hybrid” and “pure electricity” (not active in the benchmark). On consumption side households are endowed with capital, labor (divided by skilled and unskilled) and a natural resource. The centerpiece of this modelling approach is the evolution of the quality and efficiency of each technology, following the innovation possibility frontier of Aghion et al. (2011). Skilled labor determines innovation, in particular the level of research to clean or dirty technology. Thus the higher the share of skilled labor on total employment, the higher is the possibility of innovation. Innovation also depends on quality and efficiency of the previous period. Furthermore, two exogenous parameters (probability of success of an innovation and a learning rate) also influence innovation. The modelling approach introduced in this study fills a gap not covered by the literature so far and incorporates endogenous technological change linked with its endogenous policy responses in an integrated bottom-up, top-down framework.

In our policy analysis we follow a two-step approach: First, we apply an increasing carbon tax on fossil fuels and secondly we use the revenue of the carbon tax to subsidize research and development of clean technologies. Policy results are compared to a reference scenario, with no policy intervention. However, there is technological change in pure-electricity and hybrid based passenger transport and we follow the assumption of exhaustible resources and constrain the growth of the natural resource.

Results suggest that an increasing carbon tax leads to a continuous phase out of conventional fossil fuels. Both clean technologies break even, in particular production of pure-electricity based passenger transport rises continuously and takes over market-leadership. Analogous to technology studies (see Kloess et al. 2009; IEA 2008) hybrid based passenger transport represents a classical transition technology and disappears in the long run. However technological progress is not affected compared to the reference scenario. Thus there is no endogenous feedback or policy response of technological change. In contrast, subsidizing research and development of pure-electricity based passenger transport, in the second policy scenario, fosters technological progress. The subsidy leads to a rise in the rate of technological change and to lower input costs within production. This implies that pure-electricity based passenger transport breaks even nearly right away, compared to the carbon tax scenario.

Although there are several limitations of the numerical example (i.e. simplified data set and assumptions, limited number of policy scenarios and technologies), our results underline the importance to account for policy instruments that influence technological progress and innovation in favor of environmentally friendly and sustainable technologies. This paper provides a comprehensive modelling approach that can be used for the quantitative analysis of climate policy impacts on innovation and competitiveness by considering technology details. Several future research possibilities appear fruitful: (i) expanding not only the number of technologies also the number of sectors represented by bottom-up activities (e.g. energy sector), (ii) applying an open economy assumption and assess the impacts of trade on innovation and competitiveness and (iii) incorporation of environmental quality and degradation in order to account for emission reduction and environmental effectiveness.

References

Acemoglu, D. (2002). ‘Directed Technical Change’.
In: *Review of Economic Studies* 69.4, pp. 781–809 (cit. on p. 6).

Aghion, P., D. Acemoglu, D. Acemoglu, L. Bursztyn and D. Hemous (Oct. 2011). *The Environment and Directed Technical Change*. GRASP Working Papers 12 (cit. on pp. 1–3, 6, 7, 9, 10, 18).

Anderl, M. et al. (2009). *Klimaschutzbericht 2009*. Tech. rep. Umweltbundesamt (cit. on p. 12).

Böhringer, C. (1998).
‘The synthesis of bottom-up and top-down in energy policy modeling’.
In: *Energy Economics* 20.3, pp. 233–248 (cit. on pp. 2, 4).

Böhringer, C. and T. Rutherford (2009a).
'Integrated assessment of energy policies: Decomposing top-down and bottom-up'.
In: *Journal of Economic Dynamics and Control* 33.9, pp. 1648–1661 (cit. on p. 2).

– (2009b).
'Integrated assessment of energy policies: Decomposing top-down and bottom-up'.
In: *Journal of Economic Dynamics and Control* 33.9, pp. 1648–1661 (cit. on p. 3).

Center for Global Trade Analysis (2004). *GTAP 7 Database*. Tech. rep.
Department of Agricultural Economics, Purdue University (cit. on p. 12).

European Commission (2011). *EU Energy in Figures 2010 - GHG emissions by sector*.
Tech. rep. European Commission Directorate-General for Energy and Transport
(cit. on p. 2).

European Union (2012).
Commission strategy to reduce CO2 emissions from cars and vans (cit. on p. 2).

Frei, C., P. Haldi and G. Sarlos (2003).
'Dynamic formulation of a top-down and bottom-up merging energy policy model'.
In: *Energy Policy* 31, pp. 1017–1031 (cit. on p. 3).

Goulder, L. and S. Schneider (1999).
'Induced technological change and the attractiveness of CO2 abatement policies'.
In: *Resource and Energy Economics* 21.4, pp. 211–253 (cit. on pp. 3, 5).

Grossman, G. M. and E. Helpman (1994).
'Endogenous Innovation in the Theory of Growth'.
In: *Journal of Economic Perspectives* 8.1, pp. 23–44 (cit. on p. 5).

IEA (2004). *Renewable Energy: Market and Policy Trends in IEA countries*. Paris
(cit. on p. 4).

– (2008). *Energy Technology Perspectives 2008*. Paris: OECD & IEA
(cit. on pp. 2, 13, 19).

International Transport Forum (2010).
Reducing Transport Greenhouse Gas Emissions: Trends & data. Tech. rep. OECD
(cit. on p. 2).

Jaffe, A. B., R. G. Newell and R. N. Stavins (2003).
'Chapter 11 Technological change and the environment'.
In: *Handbook of Environmental Economics*. Ed. by K. G. Maler and J. R. Vincent.
Vol. 1. Handbook of Environmental Economics. Elsevier. Chap. 11, pp. 461–516
(cit. on pp. 3, 5).

Kloess, M., A. Weichbold and K. Könighofer (2009). *Technical, Ecological and Economic Assessment of Electrified Powertrain Systems for Passenger Cars in a Dynamic Context (2010 to 2050).* Tech. rep. (cit. on pp. 4, 12, 13, 17, 19).

Lau, M., A. Pahlke and T. Rutherford (2002). 'Approximating infinite-horizon models in a complementarity format: A primer in dynamic general equilibrium analysis'. In: *Journal of Economic Dynamics and Control* 26.4, pp. 577–609 (cit. on p. 11).

Löschel, A. (2002). 'Technological change in economic models of environmental policy: A survey'. In: *Ecological Economics* 43.2-3, pp. 105–126 (cit. on pp. 3–5).

Manne, A. and R. Richels (1992). *Buying Greenhouse Insurance: The Economic Costs of CO2 Emission Limits.* The MIT Press (cit. on p. 3).

Nordhaus, W. (1992). *Managing the Global Commons: The Economics of Climate Change.* The MIT Press (cit. on pp. 3, 13).

Offer, G., D. Howey, M. Contestabile, R. Clague and N. Brandon (2010). 'Comparative analysis of battery electric, hydrogen fuel cell and hybrid vehicles in a future sustainable road transport system'. In: *Energy Policy* 38.1, pp. 24–29 (cit. on pp. 4, 13).

Paltsev, S. (2004). *Moving from Static to Dynamic General Equilibrium Economic Models.* Tech. rep. Joint Program on the Science and Policy of Global Change, Massachusetts Institute of Technology (cit. on p. 11).

Romer, P. (1990). 'Endogenous technological change'. In: *Journal of Political Economy* 98.5, pp. 71–102 (cit. on pp. 3, 5).

Rutherford, T. and S. Paltsev (1999). *From an Input-Output Table to a General Equilibrium Model: Assessing the Excess Burden of Indirect Taxes in Russia.* Tech. rep. Department of Economics, University of Colorado (cit. on p. 12).

Schäfer, A. and D. Jacoby (2005). 'Technology Detail in a multisectoral CGE model: transport under climate policy'. In: *Energy Economics* 27, pp. 1–24 (cit. on p. 2).

Statistics Austria (2005). *Input-Output table for Austria.* Tech. rep. Statistics Austria (cit. on p. 12).

Sue Wing, I. (2006). 'Representing induced technological change in models for climate policy analysis'. In: *Energy Economics* 28.5-6, pp. 539–562 (cit. on pp. 4, 5).

Sue Wing, I. (2008). 'The synthesis of bottom-up and top-down approaches to climate policy modeling: Electric power technology detail in a social accounting framework'. In: *Energy Economics* 30.2, pp. 547–573 (cit. on pp. 3, 4).

Wing, I. S. (2006). 'The synthesis of bottom-up and top-down approaches to climate policy modeling: Electric power technology detail in a social accounting framework'. In: *Energy Economics* (cit. on pp. 2, 3).