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The Circular Economy –

An Economic Impact Assessment

C. Böhringer (University of Oldenburg) and T. F. Rutherford (University of Wisconsin)

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1. Introduction

The paradigm on a Circular Economy (CE) refers to an industrial economy that builds on renewable resources and reduces waste. The fundamental assumption underlying the postulated need for the shift to a CE is that current production and consumption patterns employ scarce resources in an inefficient manner. Prime examples for seemingly inefficient resource use are the transport sector, the building sector, and the food sector. These segments demand for a larger share of consumer income to satisfy the need for mobility, housing, and nutrition. Proponents of the CE postulate that these segments are plagued by substantial "structural waste", in that consumers' needs could be satisfied with much less resources. Improving resource efficiency is portrayed as a win-win strategy since the exploitation of efficiency improvements comes at negative cost – measurable direct economic benefits in terms of higher real income or likewise GDP growth are furthermore accompanied by reduced pressure on the natural environment since a more efficient resource use comes along with less pollution. The line of arguing for a CE resembles can be viewed as a generalization of the more specific debate on energy efficiency over the last decades: In the same vein, there is the claim for huge cost savings through improved energy efficiency – free lunches that have just to be picked up.

Mainstream economics is more cautious on the potential for such free lunches. Rooted in neoclassical assumptions on rational decision making (optimization) of economic agents, the normative yardstick is a competitive market economy which assures the most efficient use of scarce resources subject to consumer preferences, technological options, and initial resource endowments. Resource scarcity is thereby not only driven from the valuation of consumers but likewise from technological change and potential resource endowment shocks. Market prices as the outcome of producer supply and consumer demand thereby reflect the full cost for the economy of providing goods or employing resources at the margin. The relative scarcity of resources (commodities) as reflected in market prices crucially pends on possibilities of substitution – a technological breakthrough may render a previously very scarce resource (commodities) with a high market price to an abundant resource (commodity) whose price falls towards zero. Efficiency is phrased as economic efficiency in terms of the maximum amount of consumer and producer surplus rather than physical efficiency such as the amount of energy required to produce one unit of output. If there is for example abundant supply of a resource with the associated economic valuation being rather low, then an increase of physical efficiency comes at a loss of economic efficiency (welfare) since the economy is "unnecessarily" overly constrained. Policy-induced changes from a competitive market outcome will typically result in a loss of welfare since available resources are no longer used in the most (economically) efficient manner.

The neoclassical paradigm on the efficient performance of competitive markets explains the caveats mainstream economics puts forward with respect to the assorted welfare gains from reducing "structural waste" in sectors such as transport, building, or food. Current economic practice is viewed as the outcome of optimizing consumer and producer choices trading off cost and benefits along multiple dimensions. The underutilization of capacity (capital) identified by CE scholars as waste is then nothing else than a deliberate choice: For example, consumers may draw much more satisfaction from highly powered cars with high investment cost, poor fuel economy, and little capacity utilization (non-shared seats or long periods of garage parking) than going for alternative means of transportation which provide the identical one-dimensional transport service, i.e. kilometers per time, at a much lower cost. The same reasoning can be exemplified along consumer demands for housing and producer decisions on food production.

Beyond the normative yardstick of competitive markets, mainstream economics, however, has fully embraced the notion of market imperfections to explain potentially large inefficiencies in real-word economies. Such imperfections include external effects, public good provision, asymmetric information, or market power. To correct for market imperfections, policy interference can be warranted to improve economic efficiency of resource use. In this vein, regulatory policies may follow suit with three key circular economy principles stated as (i) *preservation of natural capital* by controlling virgin finite stocks and managing renewable flows, (ii) *maintenance of the highest utility of products, components, and materials* by circulating them in the economy, and (iii) *avoidance of leakage* of energy and materials. These three principles echo serious concerns in particular on the magnitude of negative external effects associated with the use of finite resources and non-priced environmental pollution.

In a static setting, policy regulation constitutes a conditio-sine-qua-non for correcting inefficient production and consumption patterns. In a dynamic perspective, technological change may help to resolve the curse of finite resources and environmental degradation. For example, a break-through towards competitive energy supply from renewable energy sources such as wind and solar can relax resource constraints on fossil fuels and at the same time get rid of detrimental greenhouse gas emissions from fossil fuel combustion. At second glance, however, it is not straightforward if technological change will ameliorate or worsen pre-existing inefficiencies of resource uses. More specifically, technological progress such as the digital revolution may unfold additional demands in transport, building, and food sectors with potentially negative implications for the scale of resource and environmental externalities. The resource savings from new technologies thus may be reduced due to behavioral responses on the grounds of income and substitution effects. This rebound or take-back effects has been intensively discussed in the context of energy savings technologies (energy efficiency improvements). As to mobility, increased energy efficiency or lower capital utilization cost may lead to increased transport demand as the “available” income increases or the unit cost for transport services declines compared to the cost for other demanded goods.

Along with the growing interest in circular economic structures, there is the need to assess the economic and environmental impacts of major technology shifts in transport, building and food sector. Likewise, complementary regulatory measures to control resource use such as emission taxes or energy efficiency standards must be investigated. This report summarizes the development and application of a computable general equilibrium model which facilitates the sound representation of complex economic responses to technology shifts and regulatory policy measures. Within the limitations of model assumptions and choices, impact assessment thus can be based on systematic analysis rather than on fuzzy hunches.

The remainder of this report is organized as follows. Section 2 provides a non-technical description of the generic CGE model structure and its parametrization. Section 3 describes extensions of the generic CGE model for the analysis of technological shifts in private transportation, housing, and food production as well as location-specific transportation pricing. Section 4 exemplifies the specification of exogenous technology shift scenarios. Section 5 provides illustrative simulation results. Section 6 concludes. Appendix A includes an algebraic summary of the generic CGE model. Appendix B describes the technique to incorporate exogenous empirical estimates on own-price and income elasticities through a flexible nested constant-elasticity-of-substitution (CES) demand system. Appendix C summarizes the input assumptions to selected technology shift scenarios and macroeconomic results of the report GROWTH WITHIN A CIRCULAR ECONOMY: VISION FOR A COMPETITIVE EUROPE which has been published jointly by the Ellen MacArthur Foundation, the Stiftungsfonds für Umweltökonomie und Nachhaltigkeit (SUN), and the McKinsey Center for Business and Environment.

2. Generic Framework for Impact Analysis: Computable General Equilibrium

Computable general equilibrium (CGE) analysis represents the state-of-the-art method for an economy-wide impact assessment of technology shifts and regulatory policy measures. CGE analysis is rooted in general equilibrium theory that combines assumptions regarding the optimizing behavior of economic agents with the analysis of equilibrium conditions: producers combine primary factors and intermediate inputs at least cost subject to technological constraints; given preferences consumers maximize their well-being subject to budget constraints.

CGE analysis provides counterfactual ex-ante comparisons, assessing the outcomes with a reform in place with what would have happened had it not been undertaken. The CGE framework also facilitates the impact assessment of exogenous shocks such as disruptive technological changes. The main virtue of the CGE approach is its comprehensive microeconomic representation of price-dependent market interactions and income-expenditure circles. CGE analysis quantifies the changes in key macroeconomic indicators (e.g. GDP, consumption, employment) as well as sector-specific economic activities (e.g. production, export, import) as compared to a business-as-usual situation.

Economic activities are directly linked to inputs of physical resources such as energy, material, land or water. To the extent that physical flow data is available and consistently mapped to production, consumption and trade activities, CGE analysis also provides insights into the total (direct and indirect embodied) resource input. For example, the detailed representation of energy flows accommodates the environmental impact analysis of technology shocks and policy regulations on CO_2 emissions as a major driving force of global warming. If CGE models are implemented in a multi-region setting with global trade, they capture the global supply chains of products consumed and can quantify the environmental footprint of production and consumption across regions. A multi-region (global) dimension ensures that important spillover and feedback effects from international markets are consistently taken into account. For example, restrictions on CO_2 emissions in the EU, will affect international trade flows. Highly regulated (and thus more expensive) domestic products may be substituted by less regulated (and thus cheaper) foreign products. A global modeling framework will account for such undesirable leakage effects.

2.1. Non-technical summary of the generic model

The CGE model developed for the current analysis of technology shifts in transport adopts the generic structure of an established multi-region, multi-sector CGE model of global trade and energy use.[1] This section provides a non-technical overview of basic model characteristics. A detailed algebraic summary of the generic model is provided in Appendix A.

Figure 1 provides a diagrammatic structure of the generic model structure. The core model features a representative agent RA_r in each region r that receives income from labor (L) and capital (K). Labor and capital are intersectorally mobile within a region but immobile between regions. In the production of fossil fuels, part of the capital is treated as a sector-specific resource. Primary factors are used together with intermediate inputs for production Y_{ir} of commodities i in region r. Production is specified through constant elasticity of substitution (CES) cost functions with several levels to capture substitution possibilities in domestic production sectors between capital, labor, energy and non-energy intermediate inputs.

Production of commodities other than primary fossil fuels is captured by three-level constant elasticity of substitution (CES) cost functions describing the price-responsive use of capital, labor, energy, and material in production (see Figure 2). At the top level, a CES composite of intermediate material demands trades off with an aggregate of energy, capital, and labor subject to a CES. At the second level, a CES function describes the substitution possibilities between intermediate demand for the energy aggregate and a value-added composite of labor and capital. At the third level, a CES function captures capital and labor substitution possibilities within the value-added composite, whereas different energy inputs (coal, gas, oil, and electricity) enter the

[1] Böhringer, Christoph and Thomas F. Rutherford (2002): "Carbon Abatement and International Spillovers", *Environmental and Resource Economics*, 22 (3), 391–417.

energy composite subject to a CES. As to the formation of the CES energy aggregate, several levels of nesting capture differences in substitution possibilities between primary fossil fuel types as well as substitution between the primary fossil fuel composite and secondary energy, i.e. electricity. The CES composite of primary fossil fuels in turn is defined as a CES function of coal and a CES composite of refined oil and natural gas.

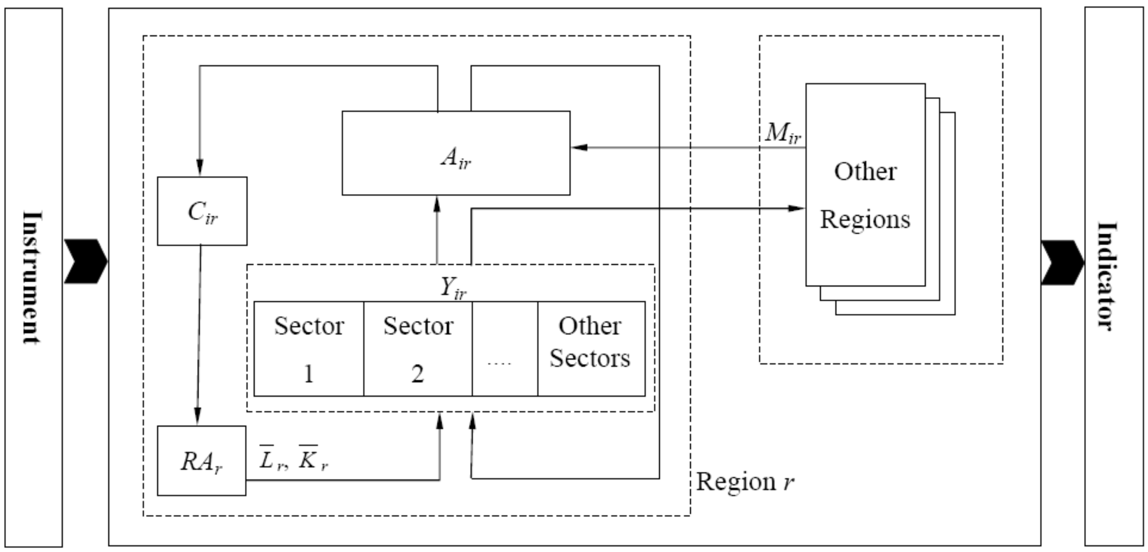

Figure 1: Multi-sector multi-region CGE model of global trade and energy use

In the production of fossil fuels (see Figure 3), all inputs except for the sector-specific fossil-fuel resource are aggregated in fixed proportions. This aggregate trades off with the sector-specific fossil-fuel resource at a CES. On the output side, a firm may have the possibility to produce different outputs (for example, a variety destined for the domestic market and a variety destined for export markets). As a corollary to the CES function on the input side, a constant elasticity of transformation (CET) function describes the trade-off between alternative outputs given relative output prices (the production possibility frontier).

Final consumption demand C_{ir} in each region is determined by the representative household who maximizes utility subject to a budget constraint with fixed investment and exogenous government provision of public goods and services. The household's total income consists of net factor income and tax revenues. In the generic model version, substitution possibilities in consumption are described by a separable nested CES (expenditure) function. At the top level, an energy composite trades off with a non-energy consumption bundle.

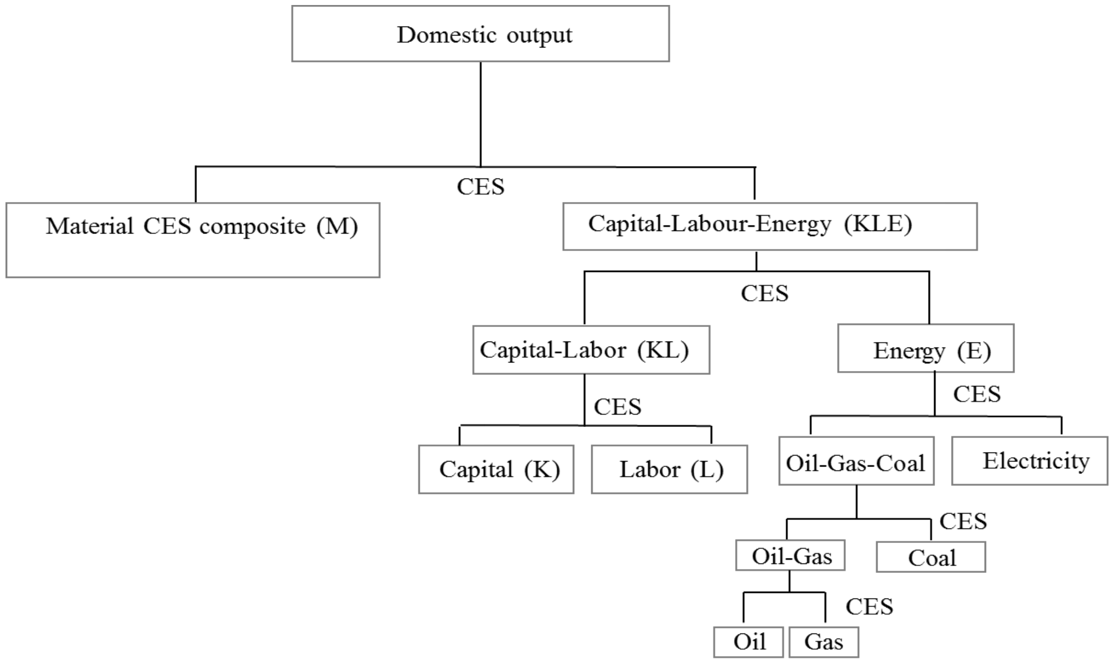

Figure 2: Nesting structure of non-fossil fuel production

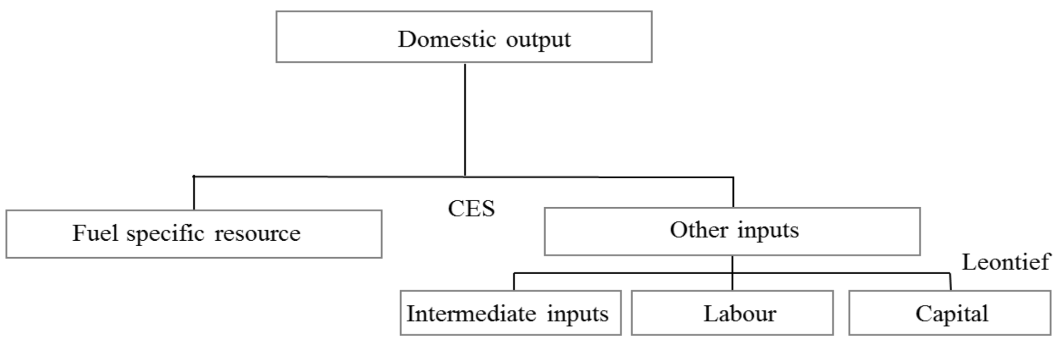

Figure 3: Nesting structure of fossil fuel production

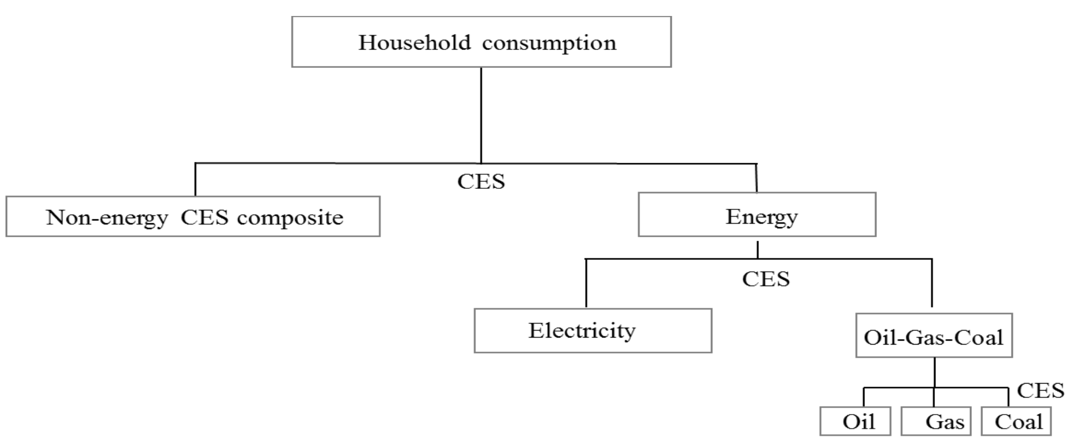

Figure 4: Nesting structure of household consumption

At the next level, the substitution patterns within the non-energy consumption bundle as well as the energy aggregate are described again by nested CES functions (see Figure 4). In the model variant used for the current analysis, the nested separable CES representation of consumption is replaced by a non-separable nested CES function to match empirical estimates on own-price and income elasticities of demand by good category (see 3.4.).

All goods used on the domestic market in intermediate and final demand correspond to a CES composite A_{ir} of the domestically produced variety and a CES import aggregate M_{ir} of the same variety from the other regions, the so-called Armington good. Domestic production either enters the formation of the Armington good or is exported to satisfy the import demand of other regions. The balance of payment constraint, which is warranted through flexible exchange rates, incorporates the benchmark trade deficit or surplus for each region.

The model links carbon dioxide (CO_2) emissions in fixed proportions to fossil-fuel use with fuel-specific CO_2 coefficients. CO_2 emission abatement can take place by fuel switching (inter-fuel substitution) or energy savings (either via energy efficiency improvements or the scale reduction of production and final demand activities). Abatement cost curves are thereby implicit to the aggregate top-down representation of technologies and preferences through nested CES functions.

2.2. Data

Applied large-scale CGE models feature many functional parameters which have to be specified with relatively few observations. Data availability usually prevents the econometric estimation of the model parameters as an econometric system of simultaneous equations. The conventional approach is to determine parameters for the equations in the model by means of a non-stochastic calibration method. Using base-year economic accounts the model is calibrated such that the initial solution to the model exactly reproduces the values of the reference equilibrium. With CES functions characterizing technologies and preferences, there is the need for exogenous estimates on substitution elasticities that determine the responses of economic agents to changes in relative factor and commodity prices. As to the accounting of base-year emission data, environmental satellite accounts on sector-specific energy demands and associated emissions must be aligned with economic input-output data.

The data for base-year calibration is provided by the database of the Global Trade Analysis Project (GTAP) with detailed accounts of regional production, regional consumption, and bilateral trade as well as energy flows and CO_2 emissions.[2] The GTAP database (version 8) has a broad coverage of countries (up to 129) and sectors (up to 57) which can be flexibly aggregated tailored to the specific interests of economic research.

For the current analysis the database is aggregated to a dataset with 5 regions and 16 sectors as listed in Table 1.

Table 1: Model sectors and regions

Sectors and commodities	Countries and regions
Coal	European Union
Crude oil	North America
Natural gas	Other OECD
Refined oil products	China
Electricity	Rest of the world
Air transport	
Water transport	
Other transport	
Other manufactures and services	
Motor vehicles and parts	
Trade incl. repairs of motor vehicles	
Construction	
Dwellings and other business services	
Beverages and tobacco products	
Food	
All other goods and services	

At the regional level, the 129 regions of the GTAP database are summarized to 5 major geopolitical regions: Europe which includes all 28 Member States of the European Union; North America which includes the U.S. and Canada; the composite of all other OECD countries which includes Japan, Mexico, Australia and New Zealand; China; and a composite of the rest of the world (ROW) compromising all the remaining countries. The 57 sectors of the GTAP database are aggregated towards 16 sectors which are central to the assessment of technology shift scenarios in private transportation, housing, and food production. Beyond primary and secondary energy goods (coal, gas, crude oil, refined oil products, and electricity), key inputs to private transportation include motor vehicles and parts as well as repair services while important inputs to housing relate to rents, real estate, construction, and services such as water supply. In food

[2] For more information on the GTAP database (version 8) see Narayanan, G.B., Aguiar, A., McDougall, R. (2012): Global Trade, Assistance, and Production: The GTAP 8 Data Base, Center for Global Trade Analysis, Purdue University.

production, the sectors distinguished are on the one hand beverages and tobacco products, and on the other hand a composite food product (covering crops, animal products, and food processing). All other goods and services are combined towards a composite consumption good.

3. Model Extensions

In order to address specific policy questions with respect to technology shifts and environmental policy regulations, the generic CGE model is extended along various extensions.

3.1. Technology shifts in private transportation, housing and food production

3.1.1 Private transportation

Household transportation is among the more rapidly growing energy uses. Technology shifts in the provision of transportation services are viewed as a key determinant for resource efficiency of future production and consumption patterns. An explicit representation of household transportation is likewise important for the quantitative analysis of regulatory energy and environmental policies.

However, household transportation expenditures related to private automobiles are not represented explicitly in the GTAP data. Thus, the GTAP data is re-arranged in a coherent manner to split out household transportation as a separate demand category. Private households spend a significant share of their income for the purchase of transport services. The private cost categories thereby include expenditures for vehicle purchases, fuel, maintenance (incl. parking and insurance fees), and also the opportunity cost for driving in terms of forgone working time. Exogenous cost estimates on these private transportation expenditures are linked to economic flows of GTAP commodities to final household consumption. For example, fuel cost for gasoline or electricity are split out from the composite final consumption demand flows and then enter an explicit production activity of private household transportation. The latter is characterized as a Leontief technology where inputs enter in fixed proportions.

In the simulations of technology shifts the cost coefficients can be exogenously altered to mimic assumptions on future changes in the input mix. Private transportation services then enter the LES demand system together with all other consumption goods. The choice of income and own-price elasticities for transportation demand critically drives the rebound effect, i.e. the magnitude to which households increase transport demand as technological shifts may decrease specific costs.

In addition to private cost of household transportation, there are external cost related to congestion, pollution, and infrastructure requirements. Estimates for these external cost categories are incorporated in the reference economy. In the absence of more detailed information, the default assumption is that external cost are proportional to the level of transportation.

3.1.2. Private housing

Another major expenditure category for households is housing. As with private transportation, GTAP does not feature an explicit housing activity but keeps track of value flows such as rent payments, construction cost, or water use in final consumption. To mimic explicit technology shocks in housing – e.g., an exogenously assumed decline in capital cost (rents, construction cost) due to new more efficient business models of housing – the major services entering housing are split out from final demand to constitute an explicit Leontief-fixed production activity referred to as housing. Housing then enters the LES demand system subject to empirical estimates of own-price and income elasticities.

3.1.3. Food production

Beyond private transportation and housing, food constitutes a third major expenditure category of households. Potential efficiency improvements in food supply (use) are captured as total factor productivity changes in the provision of food.

3.2. Public sector

A central government in each region collects taxes to finance transfers and the provision of a public good. The public good is produced with commodities purchased at market prices. Besides value-add taxes, income and factor employment taxes the GTAP database features intermediate input taxes, industry-specific output taxes as well as import tariffs and export duties. The economic impact assessment of policy interference involves revenue-neutral tax reforms in order to provide a meaningful welfare comparison without the need to trade off private consumption and government (public) consumption. This is done by keeping the amount of the public good provision fixed and balancing the public budget by means of an equal-yield tax instrument. By default, lump-sum transfers between the government and representative household are chosen as the equal-yield instrument.

The existence of initial distortionary taxes provides scope for economic efficiency improvements through tax recycling of additional revenues that are for example raised as energy or resource taxes to correct for negative environmental externalities. Such environmental (green) tax reforms continue to rank high on the political agenda of many OECD countries and have figures prominently in economic research during the last decades. As green taxes raise revenues which can be used to reduce existing tax distortions, they can present an opportunity to earn a double (or even triple) dividend. They not only improve the environment. They may also contribute to a reduction of the overall excess burden of the tax system and may help to alleviate the unemployment problem.

It should be noted, however, that environmental regulation can also exacerbate rather than alleviate pre-existing tax distortions. This is because environmental levies induce not only market distortions similar to those of the replaced taxes but in addition new distortions in intermediate and final consumption. The negative impacts from imposing additional environmental levies (tax interaction effect) can dominate the positive impacts of using additional revenues for cuts in existing distortionary taxes (revenue recycling effect).

3.3. Involuntary unemployment

In view of pressing unemployment problems in many countries the labor market effects of technology shifts and regulatory measures on resource use are of pre-eminent importance in the policy debate on a circular economy. The generic multi-sector multi-region CGE model captures adjustments in labor demand across sectors triggered by exogenous shocks. However, it does not feature involuntary unemployment as an outcome of imperfectly competitive labor markets. Regional labor markets, however, exhibit frictions with equilibrium unemployment. Labor market rigidities are represented at the regional level through the specification of a wage curve. The wage curve reflects empirical evidence on the inverse relationship between the level of wages and the rate of unemployment which can be derived in analytical terms from wage-bargaining as well as efficiency wage mechanisms.

The standard specification of the wage curve adopts a log-linear relationship between the real wage and the unemployment rate:

$$\log\left(\frac{w}{P}\right) = \gamma_0 + \gamma_1 \log(ur)$$

where w is the nominal wage rate, P denotes a consumer goods price index, γ_0 is a positive scale parameter, γ_1 is the elasticity of the real wage with respect to the unemployment rate (the so-called wage curve elasticity), and ur denotes the unemployment rate. Microeconomic foundations of the wage curve are provided both by theories of efficiency wages as well as union bargaining.[3]

[3] According to efficiency wage theory, the wage influences workers' productivity. A higher unemployment rate then allows firms to pay lower wages, while still keeping the workforce motivated. An alternative

The wage curve summarizes the fact that "A worker who is employed in an area of high unemployment earns less than an identical individual who works in a region with low joblessness."[4]

3.4. Linear expenditure system

The standard nested CES expenditure function imposes unit income elasticities. The latter implies that the budget shares of each good do not vary with the level of income.[5] In order to go beyond this restriction, choosing a linear expenditure system (LES) is helpful as it no longer assume unit income elasticity. A non-separable nested CES function can be calibrated to match exogenous (empirical) estimates on income and (own-)price demand elasticities. In this way, the rebound effect in the context of technology shifts or regulatory policies can be better rooted on empirical grounds. Note that with the LES in place, the separable CES nesting structure for household consumption (see Figure 4) is replaced by a non-separable two-level cost function where each consumption good enters in both a top-level Leontief and a bottom-level CES nest. The generic calibration technique is laid out in Appendix C.

3.5. Location-specific transportation and congestion externalities

For the regulatory policy analysis of congestion pricing, composite private transportation is further decomposed into two location-specific transportation services – rural and urban -- which trade off at a constant elasticity of substitution. Location-specific services are each produced with intermediate inputs (as before: vehicle purchases, fuel cost, maintenance cost, time requirements for driving). Urban transportation is subject to a congestion externality which follows the functional relationship of a network traffic system model and increases exponential in the transport volume.

4. Scenario Design: Caveats and Implementation

The CGE approach explains the allocation of resources in production and consumption as the result of optimizing behavior by economic agents which are subject to technology constraints on the production side and preferences on the consumption side. With static technologies and preferences, changes in observed resource allocation are triggered by policy interference such as

theory is based on union bargaining, where an increase in unemployment tilts a labor union's preferences towards greater concern with the number of jobs vis-a-vis the wage rate of its employed members.

[4] Blanchflower, David G. and Andrew J. Oswald (1994): The wage curve, Cambridge, Massachusetts, The MIT Press.

[5] Households tend to spend a much higher proportion of their income on food at low incomes, for example, than at high incomes.

resource taxes or technology mandates (standards) which affect relative prices and hence the choices in demand and supply of economic agents. The range of economic choices is prescribed through the flexibility of functional forms – most commonly, CES and CET functions which capture local substitution (transformation) possibilities through constant elasticities of substitution (transformation). Notably, however, there is neither technological change nor a shift in preferences. While policy regulation triggers economic adjustment across a given range of technological options (and in view of robust preferences), it does not lead to technological change (nor preference shifts) in standard CGE applications without endogenous growth mechanisms.

Beyond policy regulation another driver for resource allocation is technological change (technological progress). Technological change can substantially increase resource efficiency and thereby spur economic growth. On the other hand, the process of invention, innovation and diffusion demands resources itself and can be viewed as the outcome of entrepreneurial research and development activities. As such, technological change will be also affected through policy regulation such as R&D subsidies. The drivers and mechanisms of (endogenous) technological change are subject to economic research with ambivalent and diverse theoretical as well as empirical findings. Given the complexity of theoretical approaches to explain the endogeneity of technological change and the challenges of empirical foundations the bulk of multi-sector multi-region CGE models abstains from endogenous technological change and instead adopts the drastic assumption of autonomous technical progress which comes along as “manna from heaven”.

While assumptions on exogenous technological change can be rooted in expert opinions of prospective future developments such as the implications of digitization they remain ultimately ad-hoc since they miss a rigorous causal underpinning. Neither the magnitude nor the direction of technological change is addressed in a consistent economic framework which trades off the cost and benefits of R&D activities to effect technological change.

The technological shift scenarios proposed here in the analysis of private transportation follow the notion of exogenous technological change. Instead of describing policy regulations to affect technological change endogenously, the scenarios capture alternate views on how the future of private transportation might look like. The input requirements to transportation services are changed exogenously to reflect prospective technological developments.

Obviously, the specification of exogenous technology scenarios poses challenges in itself. The different cost categories might be inherently linked to each other such that a change of one cost coefficient would imply a “consistent” adjustment in other cost coefficients.

Table 2 illustrates the characterization of input requirements to private transportation for the benchmark equilibrium (BMK) which is given by the base-year economic statistics.

Table 2: Illustrative input assumptions for technology shift scenarios in private transportation

N.B.: BMK data are given in % of total private consumption. Scenario cost assumptions are given as an index of the respective BMK cost (==> BAU index = 1).

	Total private cost						*Total external cost*				*Income and price elasticities*	
	Direct cash out cost - transport				*Private transport time cost*		*External cost*				*Transport*	
Scenario	VehicleCost	OilUse	Electricity	Maintenance (incl. parking, insurance)	PrivateTime	***Private cost index***	Infrastructure and governance cost	Accidents, pollution and noise costs	External time (congestion)	***Total cost index***	Own price elasticity	Income elasticity
	veh_cost	toil_cost	tele_cost	tmaint_cost	ptime_cost	pc_index	infra_cost	poll_cost	etime_cost	tc_index	pelas_trn	ielas_trn
BMK	4.72	2.98	0.01	3.60	9.26		6.10	2.23	3.97		-0.3	0.5
BAU	1.00	1.00	1.00	1.00	1.00	1.000	1.00	1.00	1.00	1.000	-0.3	0.5
Transport	0.93	0.80	1.07	1.00	0.96	0.977	0.97	0.96	0.96	0.975	-0.3	0.5

Annual average expenditures for transportation in the BMK are stated in % of total private consumption. Direct private costs of transportation include the capital costs of vehicles (*veh_cost*), payments for fuel inputs oil and electricity (*toil_cost* and *tele_cost*), maintenance cost incl. parking and insurance (*tmaint_cost*), and the opportunity time cost of driving (*ptime_cost*). While the latter is not reported in economic input-output accounts, it is part of the private resource cost for transportation and can be based on available empirical data of driving time. Furthermore, private transportation involves additional external resource use that are listed in the section "Total External Cost" of Table 1 including external cost for infrastructure and governance (*infra_cost*), accidents, pollution and noise costs (*poll_cost*), and congestion cost (*etime_cost*). All external cost components must be estimated based on pertinent data sources. The benchmark accounts for private cost categories and private plus external cost categories constitute the reference cost of transportation which are indexed to unity for the benchmark (see *pc_index* for private cost and *tc_index* for total cost). The last two columns in Table 1 include estimates for the own-price elasticity (*pelas*) and income elasticity (*ielas*) of transportation demand. These elasticities are important for capturing behavioral responses of economic agents to changes in prices and incomes contributing to the broader rebound effect of technology shifts.

Scenario assumptions on changes in the input requirements to transportation are then indicated as coefficients with respect to benchmark costs. For example, the scenario *BAU* (business-as-usual) in Table 2 for the EU region assumes no change in technology such that all coefficients take the value of unity and the composite cost indices remain unchanged. The illustrative scenario *Transport* in Table 2 prescribes future per-unit transportation to become less resource-demanding across all inputs except for maintenance (which keeps at the benchmark level) and electricity (which increases by 7% indicating a higher share of electric cars).From a partial equilibrium perspective, the assumed changes in coefficients readily translate into a change in the composite cost index. In scenario *Transport* the private cost of transportation would go down by 2.23% (with respect to the total of base-year private transportation cost) while social cost of transportation would decline by 2.25% (with respect to the total of base-year private and external cost). The cost savings in private cost are equivalent to 1.173% of total base-year household consumption expenditures and in social cost equivalent to 1.57% of total base-year household consumption expenditures.

Figure 5 provides a graphical exposition of cost changes. Cost changes are indicated for the different cost categories in private transportation (*veh_cost*, *toil_cost*, *tele_cost*, *maint_cost*, *ptime_cost*, *infra_cost*, *poll_cost*, and *etime_cost*) that go along with the assumption of the illustrative technology shift *Transport* as stated in Table 2. The exogenously imposed cost changes are stated in percent of base-year (2007) final consumption expenditure reported in GTAP. The items *pc_cost* and *tc_cost* state aggregate private cost and social cost savings.

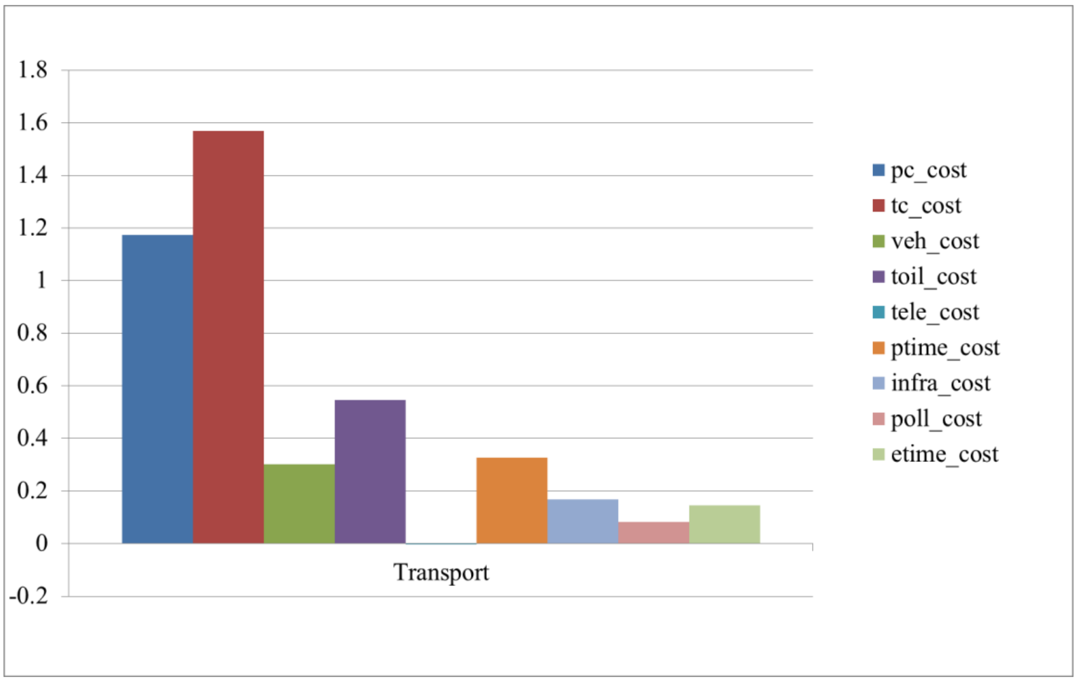

Figure 5: Cost changes in EU private transportation (in% from base-year final consumption expenditure) according to scenario *Transport*

5. Illustrative CGE Simulations[6]

The direct (partial equilibrium) economic effect of a technology shift in transportation can be directly calculated as the product of benchmark cost times the difference between the scenario-

[6] For the parameterization and results of technology shift scenarios referred to in the report GROWTH WITHIN A CIRCULAR ECONOMY: VISION FOR A COMPETITIVE EUROPE see Appendix C.

specific cost index and unity. The simplistic assumption of this back-on-the-envelope calculation is that there is neither an economic response to changes in the demand structure of private transportation nor to the changes in cost of transportation. Empirical socio-economic research, however, highlights the importance of so-called rebound effects which may substantially weaken or strengthen the direct effects. In microeconomic theory such rebound effects can be trace back to income, own-price and cross-price (substitution) effects. Technology shifts which change the cost of good or service supply induce an effective change in income which in turn will affect demand for the supplied good/service. The income elasticity measures the relative change in demand following a relative change in income. For normal goods the income elasticity is positive, i.e., with an increase in effective income the goods demand will increase as well. Likewise, the own-price elasticity indicates the change in demand as the price for the specific good changes – the own-price elasticity for normal goods is negative. Finally, technology shifts imply a change in relative prices which leads to substitution effects capture by cross-price substitution elasticities. The substitution effect is unambiguous in that the demand for the good which gets relatively cheaper increases whereas the demand for the good which gets relatively more expensive decreases.

A first step to adjust the direct cost impacts of technology shifts in transportation for rebound effects would be to apply income and own-price elasticities. A comprehensive assessment of rebound effects, however, calls for economy-wide CGE models which account for complex market interaction and spillover effects.

Against this background, the CGE framework can be used to quantify the relative importance of rebound effects. More generally, the CGE approach allows to trace through how exogenous technology shifts affect overall economic efficiency via changes in factor productivity (factor remuneration) and external effects (e.g. external pollution or congestion cost from transportation). Furthermore, details on structural adjustment in the price-responsive input-output structure of the economy can be provided (e.g. changes in sectoral outputs, exports, or imports).

However, the interpretation of results should not be stretched too far. More specifically, the technology shifts are unconditional, i.e., the transition from the benchmark technology to the future technology is not explained endogenously. Technological change occurs as manna from heaven. Thus, neither the simplistic partial equilibrium accounting nor the complex general equilibrium calculations can be credibly used to claim that technology progress is for free and will bring about larger GDP and economic efficiency gains – the unconditional technology forecasting does not quantify the economic cost (e.g. in R&D) to achieve specific technological change nor the opportunity cost of foregoing other directions of technological change. Scenario assumptions on drastically reduced capital and fuel cost for private transportation are not "innocent" since the cost cuts come for free. To put in another but related context: One can naively point to a renewable energy future which delivers electricity at negligible marginal cost and without CO_2 emissions. But such a view overlooks drastic economic adjustment cost for pushing costly renewable energy sources into electricity production (with annual cost for feed-in tariffs just in Germany at the time being of more than 20 bn €).

Given the disruptive nature of exogenous technology shifts, it is also quite problematic to investigate unemployment effects of disruptive technological shifts based on the conventional approach of a wage curve which relates to established economic patterns and "incremental" shocks through policy regulation in a local environment. When the economy is subjected to technology shocks, the empirical basis for the negative relationship between the levels of unemployment and wages might get substantially flawed. As a consequence, scenarios with unconditional technology forcing are investigated without having the wage curve mechanism active.

The CGE simulations of technology shifts in transportation quantify impacts at the economy-wide level as well as the sector level. Key indicators at the economy-wide level include: efficiency changes measured in terms of the Hicksian equivalent variation in income of the representative agent (*ev_ge* – in non-technical terms this comes down to changes in real consumption)[7] or as a fraction of base-year GDP (*GDP_ev*), the activity level of private transportation (*trn*), and economy-wide CO_2 emissions (*CO2*).[8]

Figure 6 depicts the changes in these indicators triggered by the technology shift scenario *Transport* for the EU region. In addition, Figure 6 reports the partial equilibrium cost savings that can be calculated directly from the exogenous technology shift assumptions (see Table 2) and have been already sketched in Figure 5. The indicator *ev_pe1* refers to the private cost savings as a fraction of total consumption expenditure in the base-year (*pc_cost* in Figure 4). The indicator *ev_pe2* captures the total cost savings including changes in external cost as a fraction of total consumption expenditure in the base-year (*tc_cost* in Figure 4). By definition, *ev_pe2* comes

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[7] The Hicksian equivalent variation (HEV) in income denotes the amount of money that is necessary to add to or deduct from the benchmark income of consumers so that they enjoy a utility level equal to the one in the counterfactual policy scenario (on the basis of ex-ante relative prices). A positive (negative) number thus indicates a welfare gain (loss).

[8] It should be noted that – in the absence of robust estimates on the social cost of global warming – the CO_2 emissions are not evaluated in the current model setting as a negative environmental externality which affects real income (welfare) of the representative household.

closer to the general equilibrium welfare accounting (*ev_ge*) than *ev_pe1* (note that all the three indicators share the same value base, i.e., total consumption expenditure in the base-year).

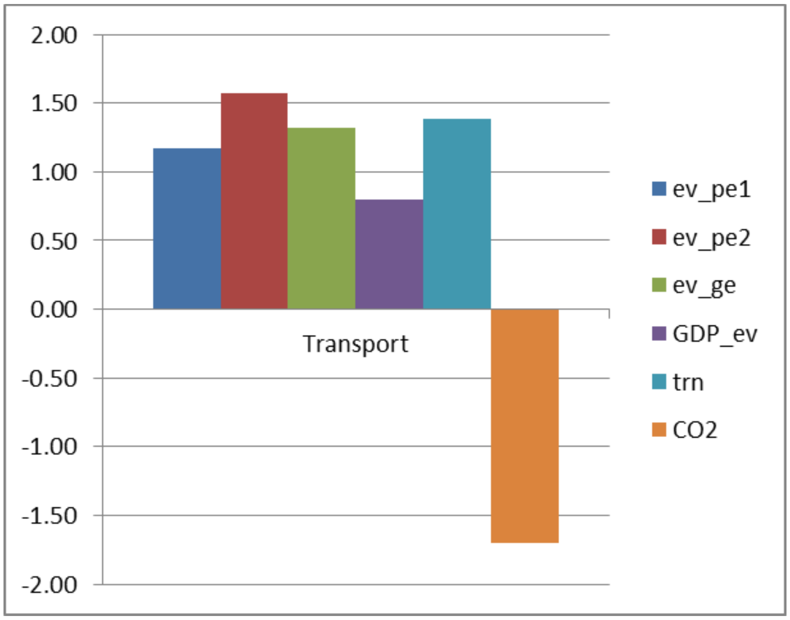

Figure 6: General equilibrium impacts of technology shifts in EU private transportation (% change from base-year) under scenario *Transport*

Apparently, for the specific scenario *Transport* the composite rebound effect is negative. According to the unconditional technology forecasting in scenario *Transport* the exogenously imposed partial equilibrium cost savings amount to 1.57% of base-year consumption expenditure while it drops to 1.32% accounting for general equilibrium rebound effects. The partial equilibrium setting neglects all market interaction and income effects: except for those quantities and prices of goods that are exogenously changed, prices and quantities of all other goods remain constant. The general equilibrium setting on the other hand follows through how the initial shock affects all prices and incomes in the economy which then trigger changes in supply and demand decisions across all markets. Economic adjustment takes place until the fundamental general equilibrium conditions (market clearance, no excess profits, income balance) hold again in the new counterfactual equilibrium. The incidence of policy shocks for the household depends both on preferences and endowments. Therefore, welfare accounting is based on real income which evaluates nominal income changes in terms of the consumption price index. To gain further insights into the relative importance of the different channels for general equilibrium welfare impacts, one can decompose the change in real income triggered by the technology shift scenario following price and quantity impacts. Figure 7 depicts how the exogenously imposed changes in resource inputs affect the different income components of the representative EU household: resource rents (*res*), land rents (*lnd*), capital rents (*cap*), remuneration to skilled labor (*skl*), remuneration to unskilled labor (*lab*), subsistence consumption (*LES*), investment expenditure (*INV*), transfers from the government accounting for transportation infrastructure cost (*TSF*), balance of payment (*BOP*), and external cost of pollution from household transportation (*POL*).

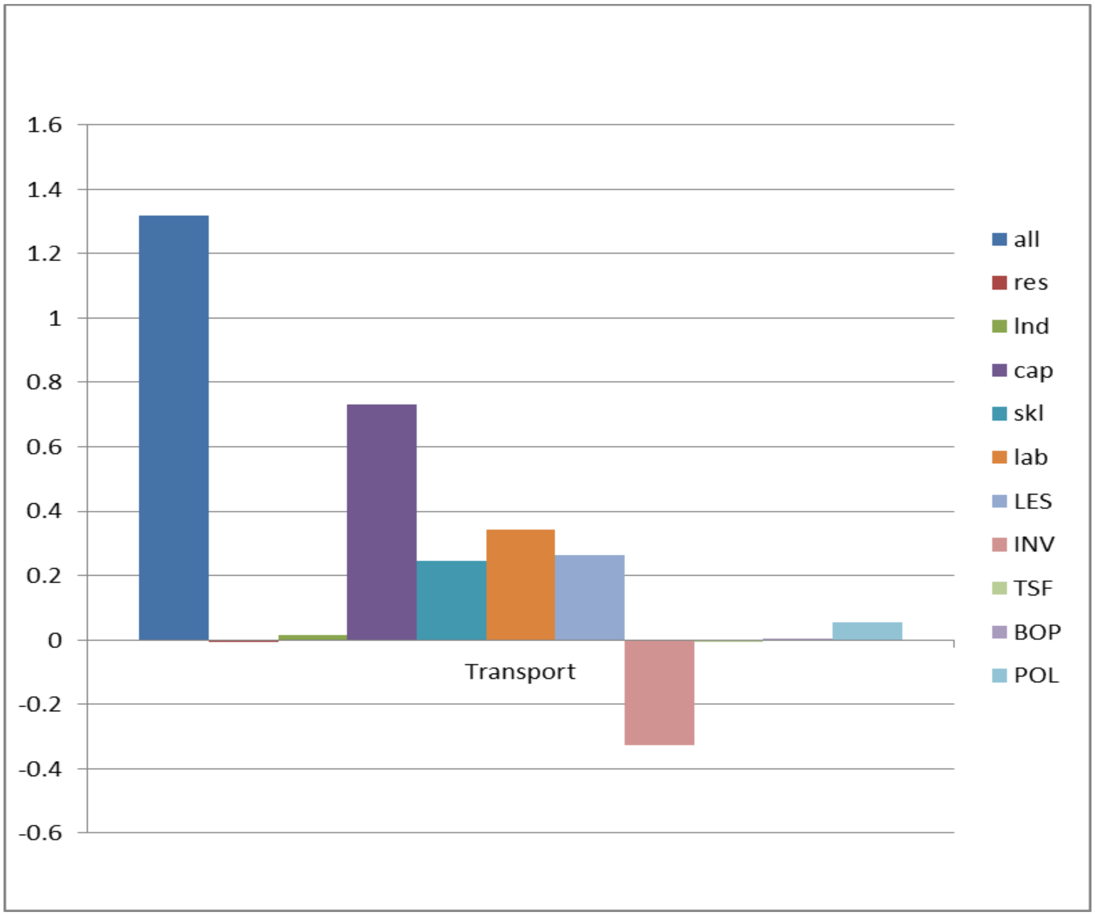

Figure 7: Income decomposition for representative EU household (% points of total income change) under scenario *Transport*

The changes in income components are stated in percentage points of equivalent variation such that the sum over all components (*all*) equals the total welfare change of 1.32% reported in Figure 6 (*ev_ge*). Exogenous productivity changes in the provision of private transportation as postulated in scenario *Transport* (see Table 2) translate primarily into an increase in capital (productivity) remuneration.

Real labor earnings go up as well which is due to the expansion of labor supply that comes along with the postulated reduction in time requirements per unit of private transportation. Likewise, the mandated efficiency improvements with respect to pollution (*POL*) and infrastructure provision (paid by transfers *TSF*) are strong enough to dominate the increase in transportation demand triggered by the exogenous cost savings per unit of private transportation services. Only one component enters visibly with a negative contribution to real income – this is economy-wide investment expenditure which – although fixed at the base-year level in the static model framework – gets more expensive in real terms due to price effects.

General equilibrium adjustments can further be quantified at the sector level. Figure 8 illustrates adjustments in the EU refined oil industry with respect to output (*Y*), exports (*X_X*), imports (*M*), gross value-added (*VA_gross*), and CO_2 emissions. Following reduced demand of refined oil products in private transportation, the domestic price drops which leads to slightly higher exports and a decrease in domestic production and imports. Along with the decline in domestic production, gross value added and CO_2 emissions in the refinery sector decline.

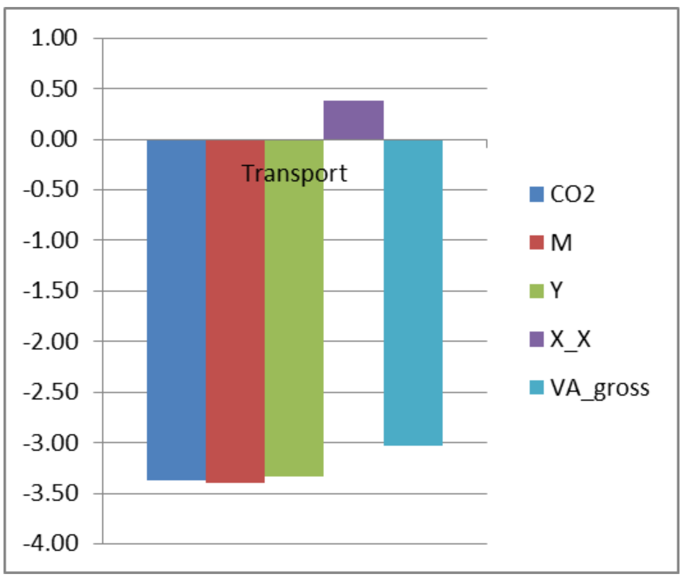

Figure 8: Impacts for the EU refined oil sector (% change from base-year) under scenario *Transport*

Apart from assessing the importance of the rebound effect in technology shift scenarios, the developed model framework can be used to investigate the economic implications of policy regulation in transportation. Economic impacts are then no longer driven by unconditional and potentially arbitrary technology shocks but by tangible changes in public policy such as tax reforms. Figure 9 reports the macroeconomic efficiency implications – in terms of equivalent variation (EV) – for an illustrative regulatory policy scenario with congestion pricing. The simulation results are based on the model variant where private transportation is split into urban and rural transportation (see 3.5.). These two transportation modes combine subject to a constant elasticity of substitution towards the final transportation service demanded by households. The initial situation is characterized by inefficiencies due to congestion externalities caused by urban transportation: People driving in urban areas spend a certain fraction of their traveling time in congestion. Congestion is the source of a market failure which calls for regulatory policies to signal the true cost of urban driving (not only using the driver's own time but causing time losses to others through congestion). A tax on congestion set at the appropriate level of external cost will increase resource efficiency. Figure 9 depicts how real income changes as a function of the level of the congestion tax.

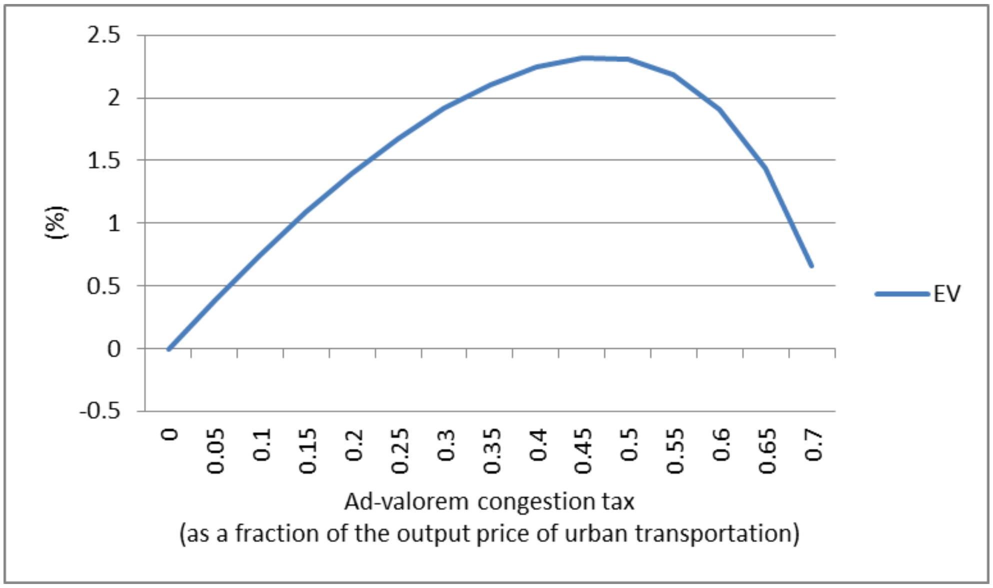

Figure 9: Welfare impacts of congestion pricing (% equivalent variation in income)

The maximum of the inversely U-shaped curve indicates the optimal tax level where the marginal benefit of the tax equates the marginal cost of taxation – for the reference case parameterization this yields a welfare increase for the average household of around 2.3%. As the tax exceeds the optimal level, welfare decreases and eventually may even drop below the initial situation without congestion pricing. The welfare numbers in Figure 9 already take into account the effects of revenue recycling. Since there are initial distortionary taxes to finance a fixed level of public good provision, congestion pricing is not only a means to internalize the congestion externality but provides further scope for efficiency gains through a revenue-neutral tax reform. In this vein, additional revenues are used to reduce initial distortionary labor taxes yielding a double dividend – real income goes up and unemployment declines ((in the specific simulation by around 0.2 percentage points) along with an increase in real wages.

6. Concluding remarks

The primary idea behind a (more) circular economy is to increase the allocative efficiency of scarce resources. This report has laid out the development and illustrative application of a static multi-sector multi-region computable general equilibrium (CGE) model to investigate the economic implications of technological shifts and regulatory policies in the context of a circular economy vision. Impact assessment of regulatory policies is the pre-dominant field of CGE applications where price-responsive supply and demand decisions of economic agents are evaluated on rigorous microeconomic (welfare) grounds for given technologies and preferences. Re-allocation of resource use may not only be triggered by changes in regulation but also by technological change. The drivers and mechanisms of (endogenous) technological change are subject to intense economic research with ambivalent and diverse theoretical as well as empirical findings. Given the complexity of theoretical approaches to explain the endogeneity of technological change and the challenges of its empirical foundations, most CGE models – as the one developed for this project –abstain from the explicit representation of endogenous technological change. Instead technological change is imposed exogenously as "manna from heaven". Consequently, technological change is not captured as the outcome of economic choices; important economic trade-offs inherent to these choices – such as foregoing consumption for investment or picking among alternative R&D options – are omitted in the analytical framework. Technology shifts are then unconditional in the sense that they postulate resource savings on the one hand without accounting for resource demands on the other hand. To put it differently: Exogenous productivity gains in technology shift scenarios towards a circular economy are not traded off against the resource inputs to facilitate the specific technological change nor the opportunity cost of choosing a different "technological future". With this strong caveat, the present CGE analysis of technological shocks still provides valuable insights into the magnitude and composition of economy-wide rebound effects.

Appendix A: Algebraic Summary of the Generic Computable General Equilibrium Model

The computable general equilibrium model is formulated as a system of nonlinear inequalities. The inequalities correspond to the two classes of conditions associated with a general equilibrium: (i) exhaustion of product (zero profit) conditions for producers with constant returns to scale; and (ii) market clearance for all goods and factors. The former class determines activity levels, and the latter determines price levels. In equilibrium, each variable is linked to one inequality condition: an activity level to an exhaustion of product constraint and a commodity price to a market clearance condition.

In our algebraic exposition, the notation Π_{ir}^{z} is used to denote the unit profit function (calculated as the difference between unit revenue and unit cost) for production with constant returns to scale of sector *i* in region *r*, where *z* is the name assigned to the associated production activity. Differentiating the unit profit function with respect to input and output prices provides compensated demand and supply coefficients (Hotelling's lemma), which appear subsequently in the market clearance conditions. We use *g* as an index comprising all sectors/commodities *i* (*g*=*i*), the final consumption composite (*g*=*C*), the public good composite (*g*=*G*), and investment composite (*g*=*I*). The index *r* (aliased with *s*) denotes regions. The index *EG* represents the subset of energy goods coal, oil, gas, electricity, and the label *FF* denotes the subset of fossil fuels coal, oil, and gas. Tables A1.–A5. explain the notations for variables and parameters employed within our algebraic exposition. Numerically, the model is implemented in GAMS (Brooke et al. 1996)[9] and solved using PATH (Dirkse and Ferris 1995)[10].

A.1 Zero Profit Conditions:

1. Production of goods except fossil fuels ($g \notin FF$):

$$\Pi_{gr}^{Y} = p_{gr} - \left[\theta_{gr}^{M} p_{gr}^{M(1-\sigma_{gr}^{KLEM})} + \left(1-\theta_{gr}^{M}\right) \left[\theta_{gr}^{E} p_{gr}^{E\,(1-\sigma_{gr}^{KLE})} + \left(1-\theta_{gr}^{E}\right) p_{gr}^{KL(1-\sigma_{gr}^{KLE})} \right]^{(1-\sigma_{gr}^{KLEM})/(1-\sigma_{gr}^{KLE})} \right]^{1/(1-\sigma_{gr}^{KLEM})} \leq 0.$$

2. Sector-specific material aggregate:

$$\Pi_{gr}^{M} = p_{gr}^{M} - \left[\sum_{i \notin EG} \theta_{igr}^{MN} p_{igr}^{A\;1-\sigma_{gr}^{M}} \right]^{1/(1-\sigma_{gr}^{M})} \leq 0.$$

[9] Brooke, A., D. Kendrick, and A. Meeraus. 1996. GAMS: A User's Guide. Washington, DC: GAMS Development Corporation.
[10] Dirkse, S., and M. Ferris. 1995. The PATH Solver: A Non-monotone Stabilization Scheme for Mixed Complementarity Problems. Optimization Methods & Software 5: 123–56.

3. Sector-specific energy aggregate:

$$\prod_{gr}^{E} = p_{gr}^{E} - \left[\sum_{i \in EG} \theta_{igr}^{EN} \left(p_{igr}^{A} + p_{r}^{CO_2} a_{igr}^{CO_2} \right)^{1-\sigma_{gr}^{E}} \right]^{1/(1-\sigma_{gr}^{E})} \leq 0.$$

4. Sector-specific value-added aggregate:

$$\Pi_{gr}^{KL} = p_{gr}^{KL} - \left[\theta_{gr}^{K} v^{(1-\sigma_{gr}^{KL})} + \left(1-\theta_{gr}^{K}\right) w^{(1-\sigma_{gr}^{KL})} \right]^{1/(1-\sigma_{gr}^{KL})} \leq 0.$$

5. Production of fossil fuels ($g \in FF$):

$$\prod_{gr}^{Y} = p_{gr} - \left[\theta_{gr}^{Q} q_{gr}^{1-\sigma_{gr}^{Q}} + (1-\theta_{gr}^{Q}) \left(\theta_{gr}^{L} w_{r} + \theta_{gr}^{K} v_{r} + \sum_{i \notin FF} \theta_{igr}^{FF} p_{igr}^{A} \right)^{1-\sigma_{gr}^{Q}} \right]^{1/(1-\sigma_{gr}^{Q})} \leq 0.$$

6. Armington aggregate:

$$\prod_{igr}^{A} = p_{igr}^{A} - \left(\theta_{igr}^{A} p_{ir}^{1-\sigma_{ir}^{A}} + (1-\theta_{igr}^{A}) p_{ir}^{IM^{1-\sigma_{ir}^{A}}} \right)^{1/(1-\sigma_{ir}^{A})} \leq 0.$$

7. Aggregate imports across import regions:

$$\prod_{ir}^{IM} = p_{ir}^{IM} - \left[\sum_{s} \theta_{isr}^{IM} \left(p_{is} \right)^{1-\sigma_{ir}^{IM}} \right]^{1/(1-\sigma_{ir}^{IM})} \leq 0.$$

<u>A.2 Market Clearance Conditions:</u>

8. Labor:

$$\bar{L}_{r} \geq \sum_{g} Y_{gr}^{KL} \frac{\partial \Pi_{gr}^{KL}}{\partial w_{r}}.$$

9. Capital:

$$\bar{K}_{gr} \geq Y_{gr}^{KL} \frac{\partial \Pi_{gr}^{KL}}{\partial v_{gr}}.$$

10. Fossil-fuel resources ($g \in FF$):

$$\bar{Q}_{gr} \geq Y_{gr} \frac{\partial \Pi_{gr}^{Y}}{\partial q_{gr}}.$$

11. Material composite:

$$M_{gr} \geq Y_{gr} \frac{\partial \Pi_{gr}^{Y}}{\partial p_{gr}^{M}}.$$

12. Energy composite:

$$E_{gr} \geq Y_{gr} \frac{\partial \Pi_{gr}^{Y}}{\partial p_{gr}^{E}}.$$

13. Value-added composite:

$$KL_{gr} \geq Y_{gr} \frac{\partial \Pi_{gr}^{Y}}{\partial p_{gr}^{KL}} .$$

14. Import composite:

$$IM_{ir} \geq \sum_{g} A_{igr} \frac{\partial \Pi_{igr}^{A}}{\partial p_{ir}^{IM}} .$$

15. Armington aggregate:

$$A_{igr} = Y_{gr} \frac{\partial \Pi_{gr}^{Y}}{\partial p_{igr}^{A}} .$$

16. Commodities (*g=i*):

$$Y_{ir} \geq \sum_{g} A_{igr} \frac{\partial \Pi_{igr}^{A}}{\partial p_{ir}} + \sum_{s \neq r} IM_{is} \frac{\partial \Pi_{is}^{IM}}{\partial p_{ir}} .$$

17. Private consumption composite (*g=C*):

$$Y_{Cr} p_{Cr} \geq w_r \bar{L}_r + \sum_{g} v_{gr} \bar{K}_{gr} + \sum_{i \in FF} q_{ir} \bar{Q}_{ir} + p_r^{CO_2} \overline{CO}_{2r} + \bar{B}_r .$$

18. Public consumption composite (*g=G*):

$$Y_{Gr} \geq \bar{G}_r .$$

19. Investment composite (*g=I*):

$$Y_{Ir} \geq \bar{I}_r .$$

20. Carbon emissions:

$$\overline{CO}_{2r} \geq \sum_{g} \sum_{i \in FF} E_{gr} \frac{\partial \Pi_{gr}^{E}}{\partial \left(p_{igr}^{A} + p_r^{CO_2} a_{igr}^{CO_2} \right)} a_{igr}^{CO_2} .$$

Table A1. Indices (sets)

G	Sectors and commodities (*g=i*), final consumption composite (*g=C*), public good composite (*g=G*), investment composite (*g=I*)
I	Sectors and commodities
r (alias *s*)	Regions
EG	Energy goods: coal, crude oil, refined oil, gas, and electricity
FF	Fossil fuels: coal, crude oil, and gas

Table A2. Activity Variables

Y_{gr}	Production of item *g* in region *r*
M_{gr}	Material composite for item *g* in region *r*
E_{gr}	Energy composite for item *g* in region *r*
KL_{gr}	Value-added composite for item *g* in region *r*
A_{igr}	Armington aggregate of commodity *i* for demand category (item) *g* in region *r*
IM_{ir}	Aggregate imports of commodity *i* and region *r*

Table A3. Price Variables

p_{gr}	Price of item *g* in region *r*
p^{M}_{gr}	Price of material composite for item *g* in region *r*
p^{E}_{gr}	Price of energy composite for item *g* in region *r*
p^{KL}_{gr}	Price of value-added composite for item *g* in region *r*
p^{A}_{igr}	Price of Armington good *i* for demand category (item) *g* in region *r*
p^{IM}_{ir}	Price of import composite for good *i* in region *r*
w_r	Price of labor (wage rate) in region *r*
v_{ir}	Price of capital services (rental rate) in sector *i* and region *r*
q_{ir}	Rent to fossil-fuel resources in region *r* ($i\in$ FF)
$p^{CO_2}_{r}$	Carbon value in region *r*

Table A4. Endowments and Emissions Coefficients

$\overline{L}_r$	Aggregate labor endowment for region *r*
$\overline{K}_{ir}$	Capital endowment of sector *i* in region *r*
$\overline{Q}_{ir}$	Endowment of fossil-fuel resource *i* for region *r* ($i\in$FF)
$\overline{B}_r$	Initial balance of payment deficit or surplus in region *r* (note: $\sum_r \overline{B}_r = 0$)
$\overline{CO_2}_r$	Endowment of carbon emissions rights in region *r*
$a^{CO_2}_{igr}$	Carbon emissions coefficient for fossil fuel *i* in demand category *g* of region *r* ($i \in FF$)

Table A5. Cost Shares

θ^{M}_{gr}	Cost share of the material composite in production of item *g* in region *r*
θ^{E}_{gr}	Cost share of the energy composite in the aggregate of energy and value-added of item *g* in region *r*
θ^{MN}_{igr}	Cost share of the material input *i* in the material composite of item *g* in region *r*
θ^{EN}_{igr}	Cost share of the energy input *i* in the energy composite of item *g* in region *r*
θ^{K}_{gr}	Cost share of capital within the value-added of item *g* in region *r*
θ^{Q}_{gr}	Cost share of fossil-fuel resource in fossil-fuel production ($g \in FF$) of region *r*
θ^{L}_{gr}	Cost share of labor in non-resource inputs to fossil-fuel production ($g \in FF$) of region *r*
θ^{K}_{gr}	Cost share of capital in non-resource inputs to fossil-fuel production ($g \in FF$) of region *r*
θ^{FF}_{igr}	Cost share of good *i* in non-resource inputs to fossil-fuel production ($g \in FF$) of region *r*
θ^{A}_{igr}	Cost share of domestic output *i* within the Armington item *g* of region *r*
θ^{M}_{isr}	Cost share of exports of good *i* from region *s* in the import composite of good *i* in region *r*

Table A6. Elasticities

σ^{KLEM}_{gr}	Substitution between the material composite and the energy value–added aggregate in the production of item *g* in region *r*
σ^{KLE}_{gr}	Substitution between energy and the value-added nest of production of item *g* in region *r* *
σ^{M}_{gr}	Substitution between material inputs within the energy composite in the production of item *g* in region *r*
σ^{KL}_{gr}	Substitution between capital and labor within the value-added composite in the production of item *g* in region *r* **
σ^{E}_{gr}	Substitution between energy inputs within the energy composite in the production of item *g* in region *r* (by default: 0.5)
σ^{Q}_{gr}	Substitution between natural resource input and the composite of other inputs in fossil-fuel production ($g \in$ FF) of region *r* (calibrated consistently to exogenous supply elasticities)
σ^{A}_{ir}	Substitution between the import composite and the domestic input to Armington production of good *i* in region *r* **
σ^{IM}_{ir}	Substitution between imports from different regions within the import composite for good *i* in region *r* **

**See Narayanan, G.B., Aguiar, A., McDougall, R. (2012): Global Trade, Assistance, and Production: The GTAP 8 Data Base, Center for Global Trade Analysis, Purdue University.

Appendix B: An Own-Price and Income Flexible Nested CES Demand System

B1. Data und Parameters

Benchmark data (calibration inputs)

θ_i benchmark value share (and reference demand) for the *i*th good, measured in

Harberger units with benchmark prices of all goods are unity,

η_i income elasticity of demand for good *i*

$$\eta_i \equiv \frac{\partial x_i}{\partial Y}\frac{1}{x_i}\bigg|_{p_i=1,Y=1}$$

ϵ_i own-price elasticity of demand for good *I*

$$\epsilon_i \equiv \frac{\partial x_i}{\partial p_i}\frac{1}{x_i}\bigg|_{p_i=1,Y=1}$$

Income and prices

p_i price of the *i*th market good, $\bar{p}_i$=1

Y consumer income (benchmark value unity).

Endogenous (calibrated) parameters

s_i subsistence demand for good *i*

a_i necessary (price inelastic) demand for good *i*

b_i marginal (price elastic) demand for good *i*

At the benchmark with $p_i = 1$ and $b_i = \bar{b}_i$:

$$\theta_i = a_i + \bar{b}_i + s_i$$

Benchmark shares (computed parameters)

$\bar{M}_i$ non-subsistence expenditure, $= 1 - \sum_i s_i = \sum_i (a_i + b_i)$

α_i value share of necessary input $= a_i/\bar{M}$

β value share of the marginal inputs $= (\sum_i b_i)/\bar{M}$, hence

$$\sum_i \alpha_i + \beta = 1$$

γ_i value share of the *i*th marginal input $= b_i/(\beta\bar{M})$, and

$$\sum_i \gamma_i = 1$$

Free parameters

The elasticity structure for marginal demand is given exogenously. For local calibration, this elasticity is "free", but it's value could be estimated if the function were based on econometric methods .The unit cost function $(c(p))$ only needs to be linearly homogeneous in prices, and it thus provides a means of controlling cross-price elasticities if a more elaborate demand system were desired.

σ elasticity of substitution among marginal goods

Shadow prices

The cost function for supernumerary consumption (c) is calibrated to unity in the benchmark

$$c = \sum_i \alpha_i \, p_i + \beta\pi(p)$$

where

$$\pi(p) = \left(\sum_i \gamma_i p_i^{1-\sigma}\right)^{1/(1-\sigma)}$$

An index of supernumerary expenditure is given by:

$$\phi = \frac{Y - \sum_i p_i s_i}{\bar{M} c}$$

<u>B2. The Demand Function</u>

The demand for commodity *i* is:

$$x_i(p, Y) = s_i + \left[a_i + b_i \left(\frac{\pi(p)}{p_i}\right)^{\sigma}\right] \phi$$

Note that the function is non-separable, as the price of good *i* enters in both the Leontief and CES nests. The unit cost function is portrayed graphically in Figure B1.

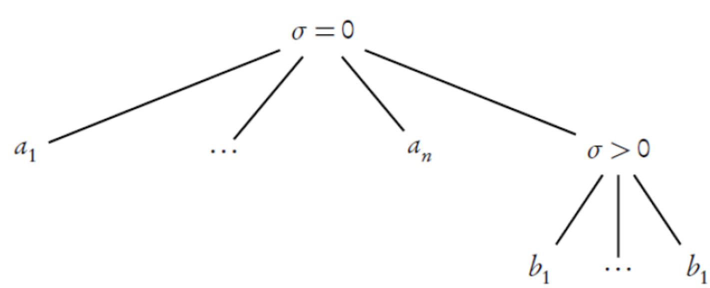

Figure B1.: Substitution structure in supernumerary demand

B3. Price Elasticities

$$\epsilon_i = \frac{\partial x_i}{\partial p_i}\frac{1}{x_i}\bigg|_{p_i=1,Y=1}$$

Hence:

$$\frac{\partial x_i}{\partial p_i} = (a_i + b_i)\frac{\partial \phi}{\partial p_i} + \sigma b_i\left(\frac{\partial \pi(p)}{\partial p_i} - 1\right)$$

Doing some calculus, we find:

$$\frac{\partial \phi}{\partial p_i} = \frac{-s_i}{\bar{M}} - \frac{\partial c}{\partial p_i},$$

$$\frac{\partial c}{\partial p_i} = \alpha_i + \beta\gamma_i,$$

$$\frac{\partial \pi(p)}{\partial p_i} = \gamma_i,$$

and

$$\frac{\partial x_i}{\partial p_i} = -(a_i + b_i)\frac{s_i}{\bar{M}} - (a_i + b_i)(\alpha_i + \beta\gamma_i) + b_i\sigma(\gamma_i - 1)$$

$$= b_i\sigma(\gamma_i - 1) - s_i(\alpha_i + \beta\gamma_i) - (a_i + b_i)(\alpha_i + \beta\gamma_i)$$

$$= -b_i\sigma(\gamma_i - 1)b_i - (\alpha_i + \beta\gamma_i)(s_i + a_i + b_i)$$

$$= b_i\sigma(\gamma_i - 1) - \theta_i(\alpha_i + \beta\gamma_i)$$

Hence:

$$\epsilon_i = \frac{b_i\sigma(\gamma_i - 1) - \theta_i(\alpha_i + \beta\gamma_i)}{\theta_i} \qquad (1)$$

B4. Income Effects

So far as income effects, we have:

$$\eta_i = \frac{dx_i}{dY}\frac{Y}{x_i}$$

$$= (a_i + b_i)\frac{d\phi}{dY}\frac{1}{\theta_i}$$

Hence:

$$\eta_i = \frac{a_i + b_i}{\bar{M}\theta_i} = \frac{\theta_i - s_i}{\bar{M}\theta_i} \qquad (2)$$

B5. Calibration

Given $\bar{M}$, we can solve for subsistence demand from equation (2):

$$s_i = \theta_i(1 - \bar{M}\eta_i).$$

Choosing $\bar{M}$ such that $s_i \geq 0 \quad \forall i$ we have:

$$\bar{M} = \frac{1}{max_i \eta_i}.$$

We then solve the following system of equations to determine β and γ_i:

$$\min_{\beta,\gamma_i} \sigma$$

$$\theta_i(\epsilon_i + \eta_i\theta_i) = \sigma\beta\bar{m}\gamma_i(\gamma_i - 1) \quad \forall i$$

$$\sum_i \gamma_i = 1$$

$$\gamma_i\beta\bar{m} \leq \theta_i \quad \forall i$$

$$0 \leq \sigma$$

$$0 \leq \beta \leq 1$$

$$0 \leq \gamma_i \leq 1 \quad \forall i$$

Appendix C: Assumptions of Central Case Technology Shift Scenarios in GROWTH WITHIN A CIRCULAR ECONOMY

The report GROWTH WITHIN A CIRCULAR ECONOMY: VISION FOR A COMPETITIVE EUROPE – published jointly by the Ellen MacArthur Foundation, the Stiftungsfonds für Umweltökonomie und Nachhaltigkeit (SUN), and the McKinsey Center for Business and Environment – refers on pages 32-33 to economic outcomes of technology shift scenarios in private transportation, housing and food as follows: "The circular economy scenario could increase the disposable income of an average European household through reduced cost of products and services and a conversion of unproductive to productive time (e.g. reduction in congestion cost). This could result in increased consumption and thereby higher GDP growth. Economic modelling across the three study sectors suggests that today's disposable income of an average European household could increase as much as 18 percent by 2030 and 44 percent by 2050 in a circular scenario, compared with 7 and 24 percent in the current development scenario. European GDP could increase as much as 11 percent by 2030 and 27 percent by 2050 in a circular scenario, compared with 4 percent and 15 percent in the current development scenario, driven by increased consumption due largely to correcting market and regulatory lock-ins that prevent many inherently profitable circular opportunities from materialising. Thus, in a circular scenario, GDP could grow with 7 percentage points more by 2030 than the current development path and could increase the difference to 12 percentage points by 2050."

The scenario assumptions and simulation results are listed in Tables C. and C2. below.

Table C1.: Parametrization of technology shift scenarios in CIRCULAR ECONOMY report

N.B.: BMK data are given in % of total private consumption. Scenario cost assumptions are given as an index of the respective BMK cost (==> BAU index = 1).

	Total private cost											
	Direct cash out cost - transport				*Private transport time cost*	*Direct cash out cost - housing*				*Direct cash out cost - food*		
Scenario	VehicleCost	OilUse	Electricity	Maintenance (incl. parking, insurance)	PrivateTime	RentCost	ElectricityCost	GasCost	WaterCost	Food	Beverage Tobacco	***Private cost index***
	veh_cost	toil_cost	tele_cost	tmaint_cost	ptime_cost	rent_cost	hele_cost	hgas_cost	hwtr_cost	foo_cost	b_t_cost	pc_index
BMK	4.716	2.976	0.010	3.603	9.260	20.274	1.925	0.456	0.357	9.652	3.099	
BAU	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000
LINEAR TRAJECTORY 2030	0.760	0.568	7.710	0.807	0.852	0.982	0.763	0.763	0.763	0.997	0.700	0.887
LINEAR TRAJECTORY 2050	0.482	0.154	17.779	0.556	0.414	0.916	0.341	0.341	0.341	1.026	0.500	0.705
CIRCULAR TRAJECTORY 203	0.577	0.404	18.362	0.734	0.593	0.962	0.639	0.639	0.639	0.753	0.500	0.751
CIRCULAR TRAJECTORY 205	0.221	0.046	16.275	0.377	0.242	0.820	0.257	0.257	0.257	0.572	0.250	0.507

	Total external cost				*Income and price elasticities*							
	External cost				*Transport*		*Housing*		*Food*		*BeverageTobacco*	
Scenario	Infrastructure and governance cost	Accidents, pollution and noise costs	External time (congestion)	***Total cost index***	Own price elasticity	Income elasticity	Own price elasticity	Income elasticity	Own price elasticity	Income elasticity	Own price elasticity	Income elasticity
	infra_cost	poll_cost	etime_cost	tc_index	pelas_trn	ielas_trn	pelas_hou	ielas_hou	pelas_foo	ielas_foo	pelas_b_t	ielas_b_t
BMK	6.101	2.227	3.969		-0.3	0.5	-0.84	1.06	-0.58	0.77	-0.68	0.88
BAU	1.000	1.000	1.000	1.000	-0.3	0.5	-0.84	1.06	-0.58	0.77	-0.68	0.88
LINEAR TRAJECTORY 2030	0.869	0.737	0.852	0.878	-0.3	0.5	-0.84	1.06	-0.58	0.77	-0.68	0.88
LINEAR TRAJECTORY 2050	0.641	0.147	0.414	0.664	-0.3	0.5	-0.84	1.06	-0.58	0.77	-0.68	0.88
CIRCULAR TRAJECTORY 203	0.753	0.560	0.593	0.736	-0.3	0.5	-0.84	1.06	-0.58	0.77	-0.68	0.88
CIRCULAR TRAJECTORY 205	0.385	0.050	0.242	0.466	-0.3	0.5	-0.84	1.06	-0.58	0.77	-0.68	0.88

Table C2.: Macroeconomic results quoted in CIRCULAR ECONOMY report

	ev_pe1	*ev_pe2*	*ev_ge*	*GDP_ev*
LINEAR TRAJECTORY 2030	5.84	7.65	7.13	4.30
CIRCULAR TRAJECTORY 2030	12.82	16.57	18.08	10.91
LINEAR TRAJECTORY 2050	15.22	21.09	24.43	14.74
CIRCULAR TRAJECTORY 2050	25.42	33.54	44.14	26.63

Key: *ev_pe1* – private cost savings (% of base-year consumption expenditure); *ev_pe2* – total cost savings including changes in external cost (% of base-year consumption expenditure) as a fraction of total consumption expenditure in the base-year; *ev_ge* –Hicksian equivalent variation in income (%); *GDP_ev* – real income loss (*ev_ge*) as a fraction of base-year GDP.