

An Economic Analysis of The Circular Economy

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Abstract

In this paper we develop a global computable general equilibrium (CGE) model to evaluate the effects of illustrative circular economy scenarios for Denmark and the European Union using the GTAP 8 dataset. The goal of a circular economy is to minimize the use of virgin resources and the generation of residuals not re-used in production. We simulate four circularity scenarios – two Denmark specific circularity scenarios and two scenarios that affect the European Union. The modeling results show that Denmark’s gross domestic product (GDP) could increase by 0.8% to 1.4% relative to the baseline by 2035. Under similar circular economy assumptions, European Union’s GDP could increase by 1.4% to 2.7% by 2035 relative to the baseline. Our sectoral modeling results show that the construction sector in Denmark contributes more than half of the GDP growth. The rest of the GDP growth comes from other sectors therefore playing an important role in placing the economy on a sustainable growth path. The scenarios assume that there are no upfront economic costs and opportunity costs of achieving the efficiency improvements that define the circular economy.

Keywords: Circular economy, zero waste, recycling, sustainability, energy efficiency, macroeconomic impact

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Introduction

Global population has more than doubled in the last fifty years (3.3 billion in 1965 to about 7.3 billion in 2015 (World Bank)). During the same period global gross domestic production (GDP) increased by more than fourfold. Looking into the future, world population could grow by an additional 2 billion people by 2050 and global GDP could grow to more than three times its current level. As the global economy grows and economies get more affluent, consumption of material and waste from usage will also increase. According to one estimate, during the past century waste from consumption and production increased by more than tenfold and could double again over the next decade (Hoornweg 2013).

Concerns that global resources and capacity to absorb waste are depleting lead to pressure for more efficient use of scarce resources either by consuming less, sharing resources, effectively minimizing waste or transforming waste into useful materials. If the value of non-marketed goods such as waste and product residuals could be increased by transforming them into forms that can be used as substitutes for produced inputs or virgin materials, it might be possible to move toward a circular economy with lesser generation of waste. If the cost of using residuals as inputs to production could be brought below the cost of virgin resources, the result could be both improved economic performance and reduced residual generation.

In this paper we develop a global computable general equilibrium (CGE) model to evaluate the effects of illustrative circular economy scenarios for Denmark and European Union (EU). The paper shows that under a simple formulation to represent a circular economy, economic growth could be increased and resources used in a more sustainable way. The remainder of the paper is organized as follows. Section 2 provides a brief description of how the circular economy can be represented. Section 3 presents our approach to represent circularity within a CGE model. Section 4 describes the scenarios. Section 5 discusses model results. We conclude in section 6.

1. Representing the circular economy in a CGE framework

Proposals for a circular economy purport to maximize the value of products, materials and resources as long as possible, minimize waste generation, and develop a sustainable, efficient, and competitive economy (European Commission 2015). The first requirement for a full

representation of circularity in a CGE framework is to incorporate a table of material flows that is parallel to the input-output table of flows of goods and services (see Ayres, D'Arge and Kneese (1969) and Noll and Trijonis (1971)). The CGE framework can be extended to incorporate concepts of circularity based on the material flows. In this framework, we can introduce a circular activity which involves refurbishing, remanufacturing, recycling or regenerating what would otherwise be residuals. This activity takes waste and residues as inputs. The outputs of this process can then be substituted for virgin materials or other factors of production, for intermediate goods, and for investment or consumption as components of final demand.

Extending a general equilibrium model to account for the full circular flow of all materials is conceptually straightforward, but data requirements and computational complexities are so large that there are only a few examples of data-based models of this type (See Kang 2006).

In absence of such material flows for the economy under study, we can think of circularity as the allocative efficiency improvement achieved by a new technology on the output side that allows wastes to be marketed and a new technology on the input side that provides cost savings due to recycling activities. Efficiency improvements are readily incorporated into production functions used in CGE models. Production functions typically contain parameters that govern the overall efficiency of production or the productivity of specific inputs. Increasing the parameter for overall productivity implies that the same amount of output can be produced with a proportionally smaller utilization of every input. The parameters for each individual input (or virgin material or residual) can be adjusted to represent technology changes that make it possible to produce the same amount of output with less of that specific input, virgin material or residual. Consumer behavior can be represented with essentially similar mathematical constructions to those used to represent residuals generation, substitution and efficiency improvements in production.

This approach involves an offline calculation of the output augmentation and input savings to reparametrize the production function. The modified production function represents the technology that embodies circular activities. Comparing with the baseline, we can find out the contribution of circular activities by sector or as an aggregate to the economy.

It is useful to think of circularity as being based on specific kinds of technology improvements to avoid creating the impression that the move to a more circular economy would be cost free. If such technologies were available today, it would be necessary for us to assume that they are more costly than less “circular” technologies in order to create a baseline in which they are not adopted. In such a case, a model of the competitive market would show that policies mandating the use of such technologies would produce net economic costs unless some specific market imperfections that prevented their use were introduced into the baseline as well.

2. The Global N_{ew}ERA Model

The Global N_{ew}ERA model is a forward-looking, dynamic computable general equilibrium (CGE) model of the world economy. It is built on the GTAP dataset and based on the theoretical concept of an equilibrium in which macro-level outcomes are driven by the decisions of self-interested consumers and producers. The basic structure of CGE models, such as N_{ew}ERA, is built around a circular flow of goods and payments between households, firms, and the government.

The Global N_{ew}ERA model is used extensively in the energy and environmental policy analysis, including studies of the effects of carbon restrictions on trade and economic welfare in different regions of the world. The model includes a disaggregated representation of industries, based on the GTAP 8 dataset, so that differences in energy intensities across countries and differences in the composition of industry can be taken into account. It can represent a wide variety of international emissions trading regimes, define trading blocs composed of any grouping of regions, and place any set of constraints on both purchases and sales of emissions permits. The model computes changes in welfare (calculated as the infinite horizon equivalent variation), national income and its components, terms of trade, output, imports and exports by commodity, carbon emissions, and capital flows. It is fully dynamic, with saving and investment decisions based on full intertemporal optimization. The model is written in GAMS/MPSGE which is a non-algebraic computer language for the formulation of applied general equilibrium models (Rutherford 1998).

Conceptually, the N_{ew}ERA model computes a global equilibrium in which supply and demand are equated simultaneously in all markets. The model assumes full employment and there is no

money. There is a representative agent in each region, and goods are indexed by region and time. The budget constraint in the model implies that there can be no change in any region's net foreign indebtedness over the time horizon of the model. Even though there is no money in the model, changes in the prices of internationally traded goods produce changes in the real terms of trade between regions. All markets clear simultaneously, so that agents correctly anticipate all future changes in terms of trade and take them into account in saving and investment decisions. A technical description is shown in Appendix A.

For this study, we aggregate the world into five regions – Denmark (DNK), China (CHN), Oil exporting countries (OPC), European Union (EUR) excluding Denmark, and Rest of the world (ROW). Each region includes 5 energy and 12 non-energy sectors. For Denmark, we disaggregate the Construction and the Services sectors, to capture sectoral circularity effects in greater detail for Denmark. The model includes 22 production sectors for Denmark. The details of the model regions and sectors are shown in Figure 1 below. The $N_{ew}ERA$ model is based on the GTAP 8 dataset. We construct a global economic dataset consistent with 2011 economic conditions. We first estimate GDP growth rates from 2007 to 2011 for China, Oil exporting countries, European Union, and Rest of the world. We then apply these growth rates to estimate 2011 economic flows (or 2011 Input Output table). We replace Denmark's 2007 GTAP8 flows by Denmark's 2011 Input Output flows. We then rebalance this adjusted dataset to create a globally balanced 2011 dataset.

Figure 1: Model Regions and Sectors

Country/Region		Sector	
DNK	Denmark	GAS	Natural gas works
CHN	China	OIL	Refined oil products
OPC	Oil and Petroleum Exporting Countries	COL	Coal transformation
EUR	European Union	CRU	Crude oil
ROW	Rest of the World	ELE	Electricity
		MEP	Machinery and electronic products
		CNS	All construction
		CNS-N*	Construction - New buildings and infrastructure
		CNS-R*	Construction - Repair and maintenance of buildings
		FBV	Food and beverages
		CHM	Chemical industry, plastics and pharma
		AGR	Agriculture, forestry and fishing
		FAB	Basic metals and fabricated metal products
		MIN	Mining
		AOG	Other manufacturing
		WRH	Wholesale, retail and hospitality
		SRV	All Services
		SER*	Other Services
		RPD*	Services - Repair of machinery and other durables
		RNT*	Services - Renting of buildings
		HSP*	Services - Hospitals
		SOT*	Services - other
		TRN	Transport
		WTR	Sewerage and waste management

* Additional Denmark sectors

3. Circular economy scenarios

We simulate four circularity scenarios – two Denmark specific circularity scenarios and two scenarios that affect the European Union. The two Denmark circularity scenarios (Conservative) and Ambitious) affect five focus sectors (food and beverage, construction and real estate, machinery, plastic packaging and hospitals) that represents about one fourth of the Danish economy and other forward and backward linked sectors. A conservative scenario (Conservative) assumes a relatively mild circularity effect; while an ambitious scenario (Ambitious) assumes an aggregative change. We also analyze the effect of same set of efficiency improvements for the Conservative and Ambitious scenarios for EU as well.

We show below in Figure 2 the assumed efficiency improvements relative to the baseline for years 2020 and 2035. The efficiency improvements are applied to ten sectors: Natural gas (GAS), Machinery and electronic products (MEP), Construction (CNS), Food and beverage (FBV), Chemicals (CHM), Agriculture (AGR), Basic metal and fabricated metal products (FAB),

Mining (MIN), Other manufacturing (AOG), and Sewerage and waste management (WTR). The efficiency assumptions on the sectoral scale are built up from micro level representative project data each of the sectors that would be affected directly and indirectly as circular economy evolves overtime. The representative projects' input and output effects are scaled to the aggregate sectoral level to estimate total effects on the economy as a whole.² The improvements for the intermediate years are linearly interpolated for simplicity. These efficiency parameters values are used to alter the input cost coefficients exogenously to capture the effects of the circular economy in the model.³

Figure 2: Efficiency improvements by sector

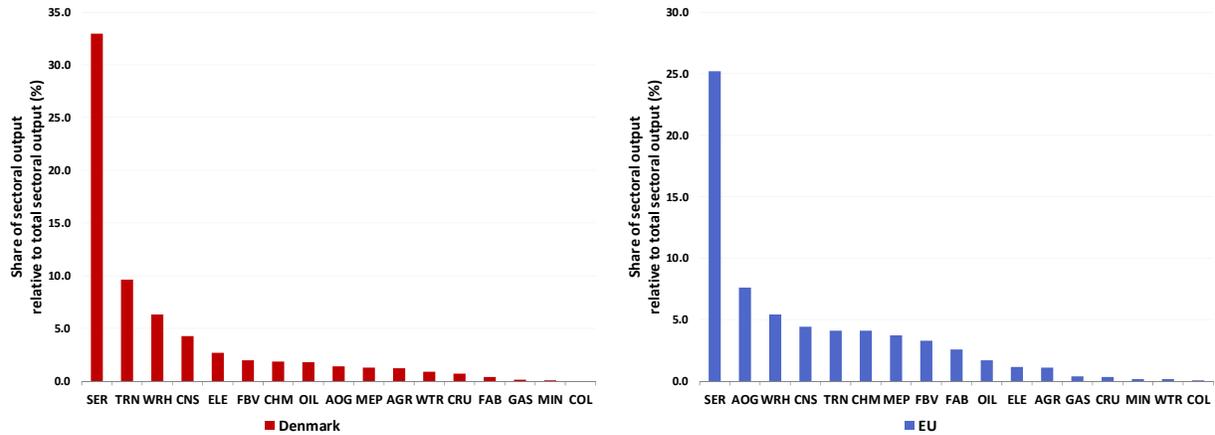
Denmark Circularity Scenario		Sector										
		GAS	MEP	CNSNR	CNSR	FBV	CHM	AGR	FAB	MIN	AOG	WTR
Conservative	2020	0.7%	0.4%	0.3%	0.1%	0.0%	0.1%	0.1%	0.1%	0.1%	0.2%	0.0%
	2035	3.1%	0.9%	2.9%	1.5%	0.3%	1.1%	0.4%	0.3%	0.2%	0.5%	0.0%
Ambitious	2020	0.8%	0.4%	0.5%	0.4%	0.0%	0.1%	0.1%	0.5%	0.6%	0.5%	0.0%
	2035	3.6%	1.0%	5.9%	4.3%	0.3%	1.3%	0.4%	1.2%	1.4%	1.3%	0.0%

The extent of the efficiency improvement implied by sectoral input and output changes depends upon the relative size and intensity of factor improvement that is built up from a bottom-up cost construct. Figure 3 shows relative shares of key sectors for Denmark and EU. The relative sectoral sizes are similar between the two regions. Service, transportation, wholesale, retail and hospitality, construction, electricity, chemicals, refinery, rest of the manufacturing, machinery and electronic products, and agriculture are key sectors in both regions; while EU's industrial sectors (rest of manufacturing, machinery and electronic products, chemicals, and food and beverage) are, percentage-wise, relatively larger than Denmark's corresponding sectors. Hence the effects of circular economy in sectors that is relatively important (large) have higher impacts on the economy.

², see the Ellen MacArthur Foundation 2015 Study (citation) for detailed description of the methodology used to estimate the efficiency improvements for 2020 and 2035.

³ The efficiency improvement envisaged in this exercise is assumed to be free with zero economic opportunity cost. That is, there is no cost for developing, commercializing, and implementing new circular economy technologies which outperform existing technologies. Moreover, the analysis assumes that the circular economy activities are profitable and the sectors would adopt them with no lag or transition costs. This is only a first-order approximation to estimate the effects of circular economy in the absence of explicit representation of circular economy and market failures that prevent movement toward it, as discussed in Section 1.

Figure 3: Share of sectoral output relative to the total industrial output for Denmark and EU (%)



4. Results

The efficiency improvements by which we quantify sector-specific impacts of new circular technologies lead to net value creation through economizing on inputs and producing more valuable outputs or lower cheaper outputs. All sectors of the economy experience savings or costs from using lower cost parts and components in the manufacturing process, materials, labor, services, energy, and capital. In addition, output revenue effects due to incremental profitability/sales are also estimated. The shift in technologies leads to greater output per unit of input in the specified sectors of the Danish economy and therefore increased sectoral profitability. These changes capture two primary effects of the circular economy: (i) reduce economy-wide inputs or resource intensity to reflect waste recycling; and (ii) change production and consumption technologies by changing the goods intensity or the mixture of intermediate demand for goods and services to produce a commodity.

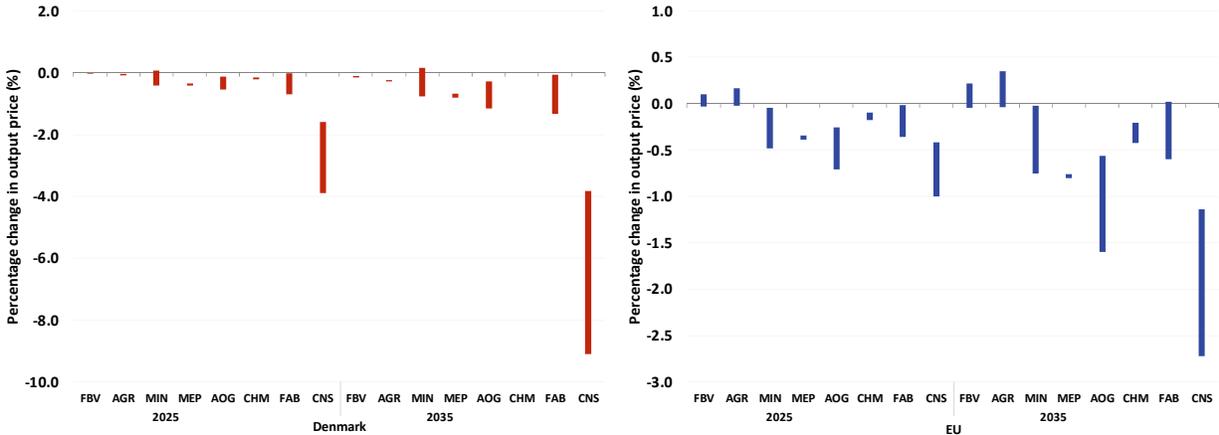
In all scenarios circularity leads to higher levels of economic activity. Higher efficiency, particularly in the focus sectors, means that goods and services can be produced at lower costs hence making these goods more competitive.

4.1 Circular economy leads to lower output prices for key economic sectors

Figure 4 shows impacts on some key industrial sector output prices in Denmark and EU. Output prices of the Construction sector decrease by 2% to 4% in 2025 and 4% to 9% by 2035 for

Denmark. For the EU the reductions in Construction output prices are between 0.5% to 1% in 2025 and 1% to 2.5% by 2035. The relative size of the sector and its efficiency gain are the main reasons that the Construction sector sees the largest drop in output prices in Denmark and in EU. Other sectors that are affected directly by the circular economy also see reductions in output prices, but at a much lower level (less than 2% for Denmark and less that 1.6% for EU).

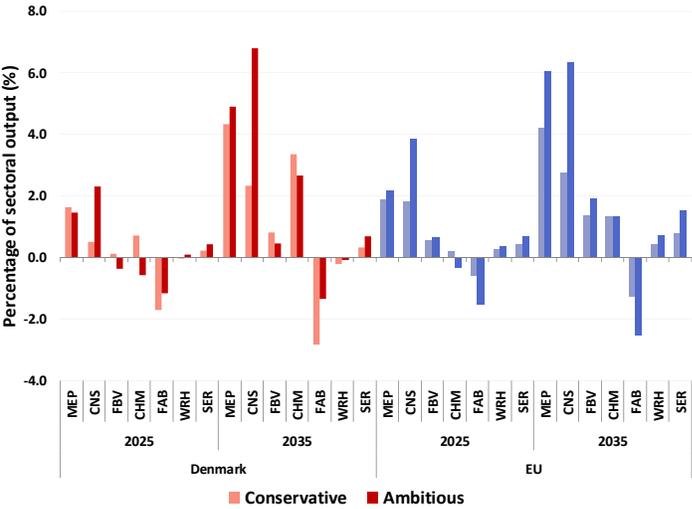
Figure 4: Circular economy reduces output prices for key economic sectors in Denmark and EU



4.2 Circular economy improves competitiveness and output for key economic sectors

Sectors that utilize resources more efficiently lead to lower output prices. More demand for lower priced commodity stimulated more production and in turn lead to more demand for intermediate goods and services in production, fueling positive spillover effect of circular economy.

Figure 5: Percentage change in output relative to the baseline (%)



For sectors such as Construction, Machinery and Electronic products that are highly impacted by circular economy, the output can expand by 6% on average in the long run under the Ambitious scenario. Figure 5 shows the effects on sectoral output for some key sectors in Denmark and the EU for the Conservative and Ambitious circular economy scenarios.

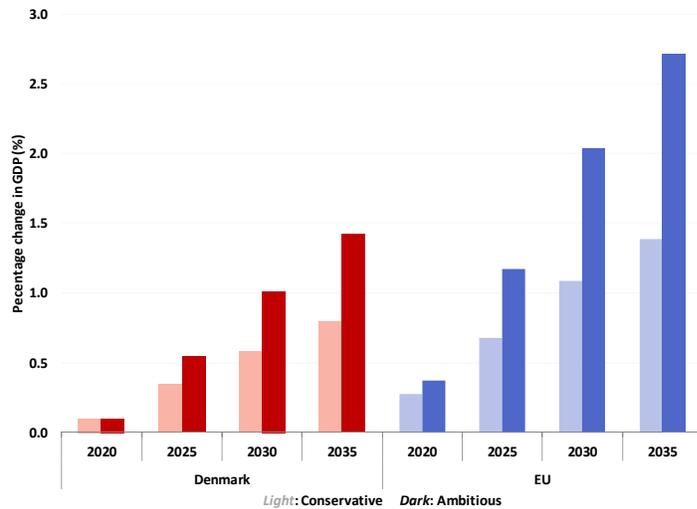
4.3 Higher economic activity leads to higher GDP

To support higher economic activity under a circular economy, investment in Denmark increase by 1% to 2% while investment in EU increase by 4% to 8% in 2035. More economic activity also means that consumers receive more income in the form of higher labor and capital income leading to more spending on goods and services. Aggregate consumption in Denmark increases by 1% to 1.6%; while for EU the aggregate consumption increases by about 0.6% to 1.4% by 2035. Higher aggregate consumption, investment, and improvement in net exports lead to higher GDP. Denmark’s GDP could improve about 0.5% in 2025 and by 0.8% to 1.4% by 2035. As circular economy effects improve over time so does GDP.

If Europe attains the same level of efficiency improvements as that of Denmark, the EU could see significant improvement in its GDP, which increases by about 1.4% to 2.7% relative to a baseline without the circular economy. The technology shift in the EU provides much more opportunity for the EU as a whole than it does to Denmark in the corresponding scenario in

which the circular economy was created within Denmark only. The EU's economy is in general less efficient than Denmark's and hence we see that the same efficiency improvement in the EU as a whole provides more benefit to the EU economy as a whole. Figure 6 below shows the GDP effects for Denmark and the EU in the Conservative and Ambitious scenario over time.

Figure 6: Percentage change in GDP and consumption relative to the baseline (%)

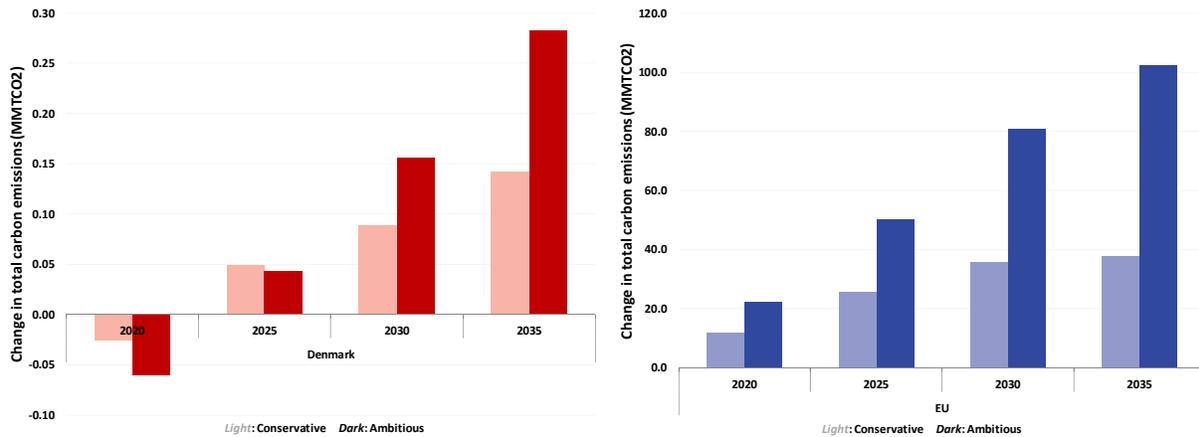


4.4 Circular economy leads to improvement in emissions intensity

The overall increase in economic activity from a circular economy leads to more demand for goods and services including fossil energy.⁴ For the Denmark circular economy scenarios, by 2035 emissions could increase by 0.15 MMTCO₂ (0.4%) to 0.28 MMTCO₂ (0.8%) relative to the baseline. For the EU scenarios, since the impacts of the circular economy is much larger compared to the Denmark scenarios, demand for fossil fuel and hence emissions are also relative larger. EU could see an increase in emissions from fossil fuel use by 30 MMTCO₂ (0.7%) to 100 MMTCO₂ (1.8%) relative to the baseline by 2035.

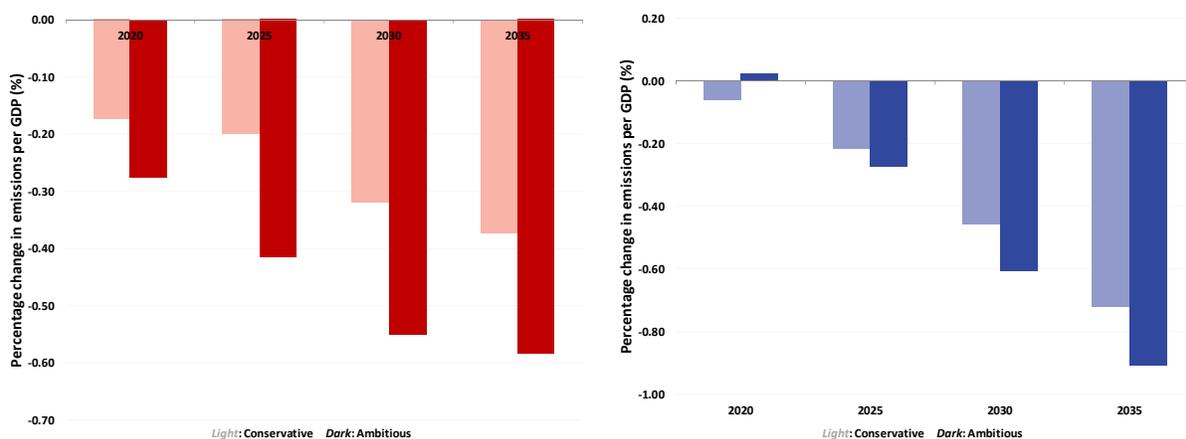
⁴ Since production of fossil fuels becomes more efficient and overall demand for fuels grows with the increase in economic activity, use of fossil fuels and emissions grow. No technologies that would increase the use of zero-carbon fuels were included in the specified scenarios, so that there are no other sources of energy to serve increased levels of economic activity other than fossil fuels.

Figure 7: Change in total carbon emissions (MMTCO₂)



However, even though there is growth in emissions in both economies, emissions growth is less than the regional GDP growth rates. This suggests that both economies are using fossil fuels much more efficiently under the circular economy than in the baseline over time. Figure 8 shows percentage change in carbon intensity (carbon emissions divided by GDP) relative to the baseline. In the Denmark scenarios, carbon intensity decreases by 0.2% in 2020 and 0.5% in 2035. Similarly for the EU scenarios, percentage change in carbon intensity continues to decline to about 0.8% relative to the baseline by 2035.

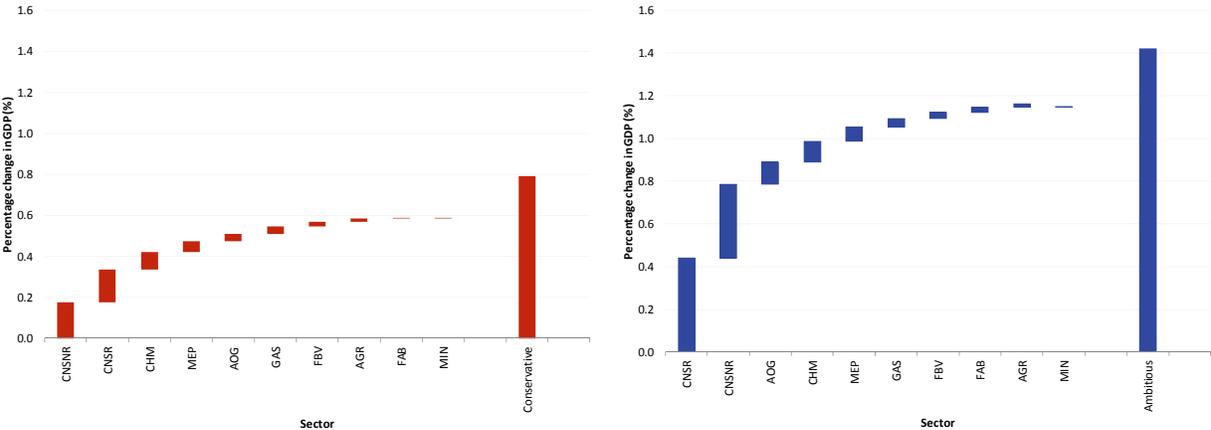
Figure 8: Percentage change in carbon intensity (%)



4.5 Construction sector contributes the largest share of GDP impact

Our results show that impacts are different across sectors. Some sectors have much larger impact than others. From a policy perspective it would be useful to understand the relative sectoral contribution to the GDP growth. We decompose each sector’s effects on GDP by simulating each sector’s circular economy independently for the Conservative and Ambitious scenarios for Denmark. Figure 9 shows the GDP impact if each sector was run independently. It is not surprising to see that in both scenarios the Construction (new buildings and infrastructure and report and maintenance of buildings) sector brings about the largest impact. This is consistent with this sector’s output effect. The Construction sector is a relative important sector and more importantly the efficiency gain in this sector as a result of circular economy is quite large relative to the other sectors. In the Conservative scenario, circular economy in the Construction sector alone contributes to more than 40% of the total GDP impact (0.17% of 0.4% GDP impact) in 2035. The role of the Construction sector is even more pronounced in the Ambitious scenario. Construction sector alone contributes more than 55% of the GDP impact (0.8% of 1.4% of GDP impact) in 2035. In both of the scenarios, Chemicals, machinery and electronic products, and all other manufacturing goods sectors’ contribution to the GDP impact is modest. Just focusing on these sectors can provide modest economic growth.

Figure 9: Decomposition of sectoral GDP impacts for Denmark scenarios



5. Conclusions

We develop a global computable general equilibrium (CGE) model to evaluate the effects of illustrative circular economy scenarios for Denmark and Europe using the GTAP 8 dataset. We simulate four circularity scenarios – two Denmark specific circularity scenarios and two

scenarios that affect the European Union. The scenarios assume that there are no upfront economic costs and no opportunity costs of achieving efficiency improvement that defines the circular economy. The modeling results show that relative to the baseline levels Danish GDP could increase by 0.8% to 1.4% by 2035. Under similar circular economy assumptions, European Union's GDP could rise by 1.4% to 2.7% by 2035. Our sectoral modeling results show that the construction sector contributes more than half of the GDP growth and the rest of the GDP growth comes from other sectors that also play an important role in placing the economy on a sustainable growth path.

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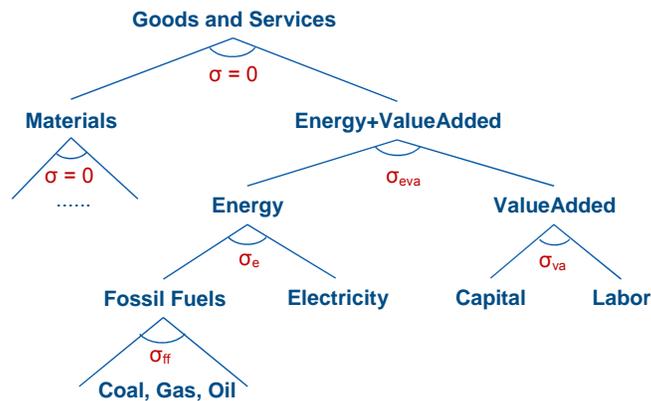
Appendix A: Description of the Global NewERA Model

The model is written in GAMS/MPSGE. The MPSGE syntax adopts a calibrated share form that compared to a conventional coefficient form substitutes a set of parameters calculation with the readily available benchmark values.

A. Production and Trade Structure of Macro Model

We employ a nested constant elasticity of substitution (CES) production function form to specify the elasticity possibility between inputs (capital, labor, energy, materials). In the general production structure (see Figure 10), goods and services are produced in fixed proportion ($\sigma = 0$) with intermediate material inputs and an aggregate of energy and value-added inputs. Energy aggregate trades off against value-added inputs with an elasticity of substitution equal to 0.5. If energy prices rise in response to a policy change, the production function substitutes value-added inputs for energy to a certain extent which depends on the magnitude of the elasticity of substitution.

Figure 10: General Production Structure



The production function in Figure 10 is written as follows:

$$Y_i = \bar{Y}_i \cdot \min \left[\left(\frac{M_{ji}}{M_{jl}} \right), \left(\frac{EVA_i}{EVA_l} \right) \right]$$

$$\frac{EVA_i}{\overline{EVA}_t} = \left[\theta_e \left(\frac{E_i}{\overline{E}_t} \right)^{\frac{(\sigma_{eva}-1)}{\sigma_{eva}}} + (1 - \theta_e) \left(\frac{VA_i}{\overline{VA}_t} \right)^{\frac{(\sigma_{eva}-1)}{\sigma_{eva}}} \right]^{\frac{\sigma_{eva}}{(\sigma_{eva}-1)}}$$

$$\frac{E_i}{\overline{E}_t} = \left[\theta_{ele} \left(\frac{ELE_i}{\overline{ELE}_t} \right)^{\frac{(\sigma_e-1)}{\sigma_e}} + (1 - \theta_{ele}) \left(\frac{FF_i}{\overline{FF}_t} \right)^{\frac{(\sigma_e-1)}{\sigma_e}} \right]^{\frac{\sigma_e}{(\sigma_e-1)}}$$

$$\frac{FF_i}{\overline{FF}_t} = \left[\sum_f \left(\theta_f \left(\frac{F_i}{\overline{F}_t} \right)^{\frac{(\sigma_{ff}-1)}{\sigma_{ff}}} \right) \right]^{\frac{\sigma_{ff}}{(\sigma_{ff}-1)}}$$

$$\frac{VA_i}{\overline{VA}_t} = \left[\theta_k \left(\frac{K_i}{\overline{K}_t} \right)^{\frac{(\sigma_{va}-1)}{\sigma_{va}}} + (1 - \theta_k) \left(\frac{L_i}{\overline{L}_t} \right)^{\frac{(\sigma_{va}-1)}{\sigma_{va}}} \right]^{\frac{\sigma_{va}}{(\sigma_{va}-1)}}$$

The corresponding cost functions are written as follows:

$$PY_i = \overline{PY}_t \cdot \left[\sum_j \theta_j \cdot \frac{P_j}{\overline{P}_j} + \left(1 - \sum_j \theta_j \right) \cdot \frac{P_{EVA}}{\overline{P}_{EVA}} \right] \cdot \frac{Y_i}{\overline{Y}_t}$$

$$\frac{P_{EVA}}{\overline{P}_{EVA}} = \left[\theta_e \left(\frac{P_E}{\overline{P}_E} \right)^{1-\sigma_{eva}} + (1 - \theta_e) \left(\frac{P_{VA}}{\overline{P}_{VA}} \right)^{1-\sigma_{eva}} \right]^{\frac{1}{(1-\sigma_{eva})}} \cdot \frac{EVA_i}{\overline{EVA}_t}$$

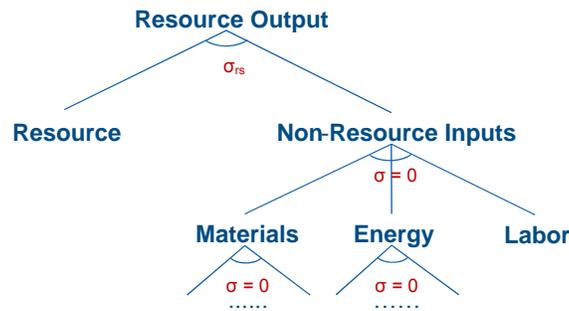
$$\frac{P_E}{\overline{P}_E} = \left[\theta_{ele} \left(\frac{P_{ELE}}{\overline{P}_{ELE}} \right)^{1-\sigma_e} + (1 - \theta_{ele}) \left(\frac{P_{FF}}{\overline{P}_{FF}} \right)^{1-\sigma_e} \right]^{\frac{1}{(1-\sigma_e)}} \cdot \frac{E_i}{\overline{E}_t}$$

$$\frac{P_{FF}}{\overline{P}_{FF}} = \left[\sum_f \left(\theta_f \left(\frac{P_F}{\overline{P}_F} \right)^{1-\sigma_{ff}} \right) \right]^{\frac{1}{(1-\sigma_{ff})}} \cdot \frac{FF_i}{\overline{FF}_t}$$

$$\frac{P_{VA}}{\bar{P}_{VA}} = \left[\theta_k \left(\frac{P_K}{\bar{P}_K} \right)^{1-\sigma_{va}} + (1 - \theta_k) \left(\frac{P_L}{\bar{P}_L} \right)^{1-\sigma_{va}} \right]^{\frac{1}{(1-\sigma_{va})}} \cdot \frac{VA_i}{\bar{VA}_i}$$

In Figure 11, resource sectors (Crude, Coal, and Natural Gas) are characterized with a fixed factor that represents natural resources with which the economy is endowed. Resource prices are calibrated through a process of adjusting the fixed resource endowment so that resource production and prices follow the chosen baseline forecast.

Figure 11: Resource Production Structure



The resource production function is written as follows:

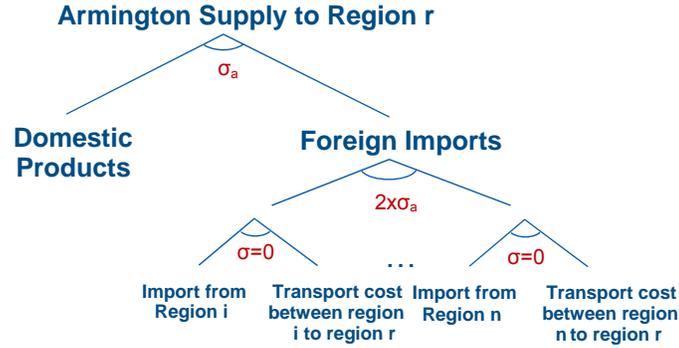
$$\frac{R}{\bar{R}} = \left[\theta_{re} \left(\frac{RE}{\bar{RE}} \right)^{\frac{(\sigma_a-1)}{\sigma_a}} + (1 - \theta_{re}) \left(\frac{NRE}{\bar{NRE}} \right)^{\frac{(\sigma_{re}-1)}{\sigma_{re}}} \right]^{\frac{\sigma_{re}}{(\sigma_{re}-1)}}$$

$$\frac{NRE}{\bar{NRE}} = \min \left[\left(\frac{M_j}{\bar{M}_j} \right), \left(\frac{E}{\bar{E}} \right), \left(\frac{L}{\bar{L}} \right) \right]$$

The model allows for complete bilateral trade in all goods produced by all industries. The Global NewERA model uses an Armington structure (see Figure 12) in its representation of international trade in all goods except crude oil, which is treated as a homogeneous good perfectly substitutable across regions. For all other goods, we assume that domestically produced goods and imports from every other region are differentiated products (i.e., the Armington assumption) by their country of origin. Domestic goods and imports are combined into Armington aggregates, which then function as inputs into production or consumption. This is a key assumption that determines the model's trade behavior. The elasticity of substitution among foreign imports is

usually twice that of the elasticity between domestic and foreign goods, suggesting that it is easier to substitute among imports than substitute between domestic products and imports.

Figure 12: Armington Supply Structure



The Armington supply function is written as follows:

$$\frac{A_i}{\bar{A}_l} = \left[\theta_d \left(\frac{D_i}{\bar{D}_l} \right)^{\frac{(\sigma_a-1)}{\sigma_a}} + (1 - \theta_d) \left(\left[\sum_{s \neq r} \theta_m \left(\frac{TRD_{isr}}{\bar{TRD}_{isr}} \right)^{\frac{(2\sigma_a-1)}{2\sigma_a}} \right]^{\frac{2\sigma_a}{(2\sigma_a-1)}} \right)^{\frac{(\sigma_a-1)}{\sigma_a}} \right]^{\frac{\sigma_a}{(\sigma_a-1)}}$$

The corresponding cost functions are written as follows:

$$\frac{PA_i}{\bar{P}\bar{A}_l} = \left[\theta_d \left(\frac{PY_i}{\bar{P}\bar{Y}_l} \right)^{1-\sigma_a} + (1 - \theta_d) \left(\left[\sum_{s \neq r} \theta_m \left(\frac{PM_i}{\bar{P}\bar{M}_l} \right)^{(1-2\sigma_a)} \right]^{\frac{1}{(1-2\sigma_a)}} \right)^{1-\sigma_a} \right]^{\frac{1}{(1-\sigma_e)}} \cdot \frac{A_i}{\bar{A}_l}$$

The model includes the markets for the three fossil fuels and their products. Refined petroleum products, electricity, and all other non-energy sectors are produced using these fuels, capital, labor, and materials as inputs. Because crude oil is treated as a homogeneous good, it trades internationally under a single world price. Conversely, representing natural gas and coal as Armington goods allows the model to approximate the effects of infrastructure requirements and high transportation costs among some regions. Depletion is assumed to lead to rising fossil fuel prices under constant demand, but the relation between depletion effects on the supply of oil, gas,

and coal and the actual supply of these fuels is ignored. That is, the model does not keep a record of the current stock of each fuel in each time period. World supply and demand determine the world price of fossil fuels. Current taxes and subsidies are included in each country's prices.

Consumers derive utility from consumption of goods and services, including transportation services (commercial and personal transportation), non-energy materials, and energy from electricity and fossil fuels.

Figure 13: Household Consumption Structure

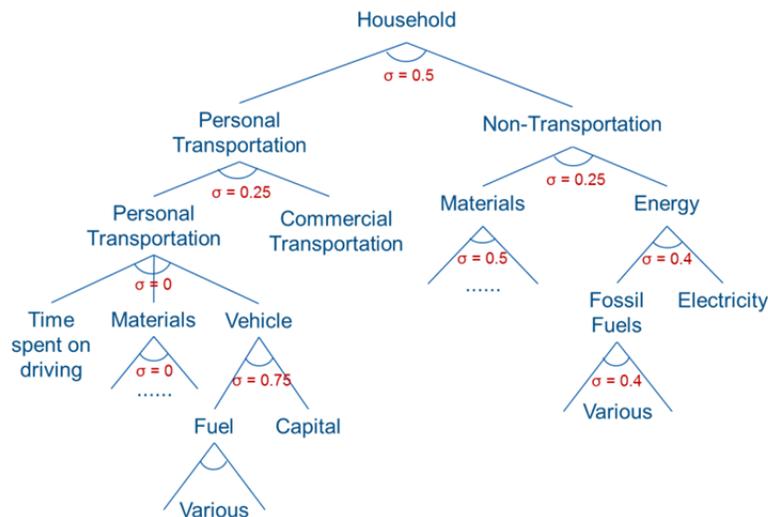


Table A1: Sets

i	sectors
j	alias for sectors
s	region
e	energy goods (coal, natural gas, crude oil, refined oil, electricity)
f	fossil fuels (coal, natural gas, refined oil)

Table A2: Parameters

θ_j	benchmark value share of intermediate material input in production of Y
θ_e	benchmark value share of energy inputs in the energy and value-added composite

θ_{ele}	benchmark value share of electricity in the energy composite
θ_f	benchmark value share of fossil input in the fossil-fuel composite
θ_k	benchmark value share of capital in the value-added composite
θ_{re}	benchmark value share of resource in the resource production
θ_m	benchmark value share of imported goods and services from region s to region r out of all imports
σ_{eva}	compensated elasticity of substitution between the energy and value-added composites
σ_e	compensated elasticity of substitution between electricity and the fossil-fuel composite
σ_{ff}	compensated elasticity of substitution between the fossil fuel inputs in the fossil-fuel composite
σ_{va}	compensated elasticity of substitution between capital and labor in the value-added composite
σ_{re}	compensated elasticity of substitution between resource and non-resource input in the resource production

Table A3: Variables

Market activity

Y	production of non-resource goods and services
R	production of exhaustible resources (coal, gas, crude oil)
M	intermediate material demand
A	Armington goods
D	domestic produced goods and services supplied to the domestic market
TRD	<i>trade of</i> goods and services
EVA	energy and value-added demand
E	energy demand
VA	value-added demand
ELE	electricity demand

FF	fossil-fuel demand
F	fossil fuel demand
K	capital demand
L	labor demand
RE	resource input demand
NRE	non-resource input demand

Market prices

PY	output price of goods and services
P_j	price of intermediate material goods and services
PA	price of Armington goods
PM	price of imported goods
P_{EVA}	price of the energy and value-added composite
P_E	price of the energy composite
P_{VA}	price of the value-added composite
P_{ELE}	price of electricity
P_{FF}	price of fossil-fuel composite
P_F	price of fossil fuel
P_K	rental price of capital
P_L	labor wage rate

The parameter with bar in the production and price formulae represents the benchmark level in the dataset.

B. Crude Oil Market

The model treats all goods as imperfect substitutes except crude oil, which is treated as a homogeneous good. Thus, each region is either an importer or exporter of crude oil as there are no cross flows as there are with the other goods, which are represented as Armington goods. The model region representing OPEC (*i.e.*, OPEC) is assumed to be able to produce crude oil below the market clearing price; hence OPEC enjoys monopoly profits from the sale of crude oil. Because of its situation, OPEC has more flexibility in how it chooses to respond to changes in

market conditions that result in less demand for crude oil. The approach we take to modeling OPEC's response to reduced demand for oil is to construct polar cases. In one case, we maintain the baseline price by cutting OPEC's output. In the other case, we keep output at the baseline level and let the price fall. In the policy scenarios, we assume that the OPEC chooses a middle ground in which it cuts its output by half of the amount required to maintain price at the baseline level.