Growth of what? An exploration of pathways for global economic demand with low fossil fuel use and high employment

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Abstract

This paper presents a system dynamics input-output energy-economy model which calculates the energy and labor requirements of various pathways for global final demand. The model is used to create two scenarios, one which projects historic trends, and one which targets different levels of sectoral growth (or degrowth), based on the energy and labor needs of each sector. This "Targeted Growth" scenario is able to achieve substantial reductions in energy use from fossil fuels with a comparably small reduction in labor use compared to the historic projection. These results imply the usefulness of further investigation into the role of the composition of final demand in decarbonization. Looking forward to future research, the paper presents four key feedbacks which should be considered in future scenario and modeling work.

1 Introduction:

In 2015, the countries of the world agreed to dramatically limit their greenhouse gas emissions such that global temperatures would not exceed two degrees, or if possible 1.5 degrees, over pre-industrial averages by the end of the century. The limits set in the Paris Agreement imply a highly ambitious pathway of decarbonization that will require changes to the world's technological, economic and social systems. Unfortunately, up until now, this pathways has not been followed, as the world remains firmly on track to violate the limits it set for itself (IPCC, 2022b, p. 15; UNEP, 2022, p. 35). In order to meet the challenge of the Paris Agreement, a greater scale of action is needed, as existing efforts must be substantially scaled up. Deeper changes will also likely be needed however, with the UN Environment Program calling for a "rapid transformation of societies" and the IPCC invoking "System Transformations" in order to meet the climate crisis (IPCC, 2022b, p. 17; UNEP, 2022).

One of the most critical systems which could be transformed in service of decarbonization is the global economy, as our structures of production and consumption account for virtually all global greenhouse gas emissions. There is currently an active debate about how changing, and specifically reducing, the

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overall size of advanced economies could aid an ecological transition (Hickel and Kallis, 2020). A less widely discussed topic is the role changes in the structure of the economy could play in facilitating decarbonization. The composition of growth is crucial to understanding the actual social and environmental effects of growth, as different sectors and activities have very different impacts. In short, to know what a 2 percent economic growth rate means for the environment or society, one must know which 2 percent is growing.

This paper will investigate the degree to which targeted shifts in the composition of final demand could be useful in easing the environmental and social pressures associated with decarbonization and the ecological transition. It will do so by introducing a system dynamics model which uses input-output analysis to project the energy and labor requirements of various pathways of sectoral final demand. The paper will present initial results of two such pathways: a "Historic Growth" scenario and a "Targeted Growth" scenario designed to reduce energy use from fossil fuels while maintaining sufficiently high levels of employment. The paper will then discuss how the model can be used in the future to further explore economic pathways which are simultaneously environmentally and socially sustainable.

2 Final Demand in Climate-Economy Modeling

2.1 Economic structure in climate-economy modeling

Climate-economy models are one of the primary tools used to analyze decarbonization pathways. These models, also known as integrated assessment models (IAMs), combine a number of modules representing various systems—such as climate, energy, technology, and economy—to create a larger, interconnected, picture of how decarbonization could plausibly unfold. IAMs come in a wide variety of sizes and are built using a number of different core modeling techniques (Hafner et al., 2020; Nikas et al., 2019). The most common modeling methodologies are Computable General Equilibrium (CGE) models, in which the growth path of the entire economy is optimized, and Partial Equilibrium models in which a single sector or set of sectors are optimized (IPCC, 2022a, p. 1845; Matsumoto and Fujimori, 2019). Other methodologies, like macroeconometric modeling, system dynamics modeling, input-output analysis, stock flow consistent modeling, and agent-based modeling are also used in constructing IAMs (Hafner et al., 2020; Hardt and O'Neill, 2017).

The topic of structural economic change can be treated *endogenously* within equilibrium models by projecting changes in the relative size of sectors in response to growth in average incomes (IPCC, 2022a, p. 1845). For example, this can allow equilibrium models to account for a shift in a country's share of agriculture, manufacturing and service sectors as its national income grows (Herrendorf et al., 2014). What these models are less apt for is assessing the impact of *exogenous* changes to the sectoral composition of the economy resulting from directed industrial policy. Equilibrium implies that in the absence of policy the economy will operate at full capacity over the long run, with interventions necessarily shifting the economy off of its optimized growth path to a less productive track (Köberle et al., 2021). In this context, some form of carbon pricing typically presents itself as a first-best solution, leaving little room for other policy interventions such as targeted sectoral growth rates. Other modeling frameworks not based on optimization however are much better suited for analyzing the social and environmental implications of changes in the structure of the economy.

2.2 Economic composition with Input-Output: MEDEAS World Model

One such model is the MEDEAS World integrated assessment model. MEDEAS is a large-scale system dynamics model which combines a demand-led economic system with a representation of the bio-physical limits to growth in the shape of an energy availability feedback which constrains economic activity to the amount of energy produced within the model's energy module. A key result of published scenarios created with MEDEAS is that "business as usual" and "green growth" pathways face serious challenges in supplying enough energy to maintain economic growth, and that "post-growth" pathways are more readily suited for respecting climate limits (de Blas et al., 2020; Capellán-Pérez et al., 2020; Nieto et al., 2020b).

At the core of the MEDEAS economic system is a 35-sector input-output framework, adapted from the World Input Output Database, with global data running from 1995 to 2009. In scenarios created using the model, Nieto et al. (2020) explore the importance of changes to composition of the production by proposing various evolutions of technical structure of the economy. In doing so, they found that the ultimate level of production and energy use was significantly responsive to changes in the technical structure of the economy, with changes in the amount of inputs needed for production leading directly to different evolutions of the sectoral composition of production (ibid.).

They do not, however, directly model scenarios in which final demand is targeted as the lever with which to change sectoral composition. This paper picks up with this task, conceptualizing the rates of sectoral final demand growth as an exogenous policy variable and analyzing the possible efficacy of such a tool in reducing fossil fuel use.

3 Methodology

This section will begin with a presentation of the system dynamics, input-output model used in this paper (3.1). A graphic overview of the model can also be found in Figure 10 in the Appendix. It will then discuss the calculation of the sensitivity of energy and labor to changes in sectoral final demand within the model (3.2). These *final demand sensitivities* will form the basis for the initial design of a "Targeted Growth" scenario (3.3), the results of which will be presented in Section 4.

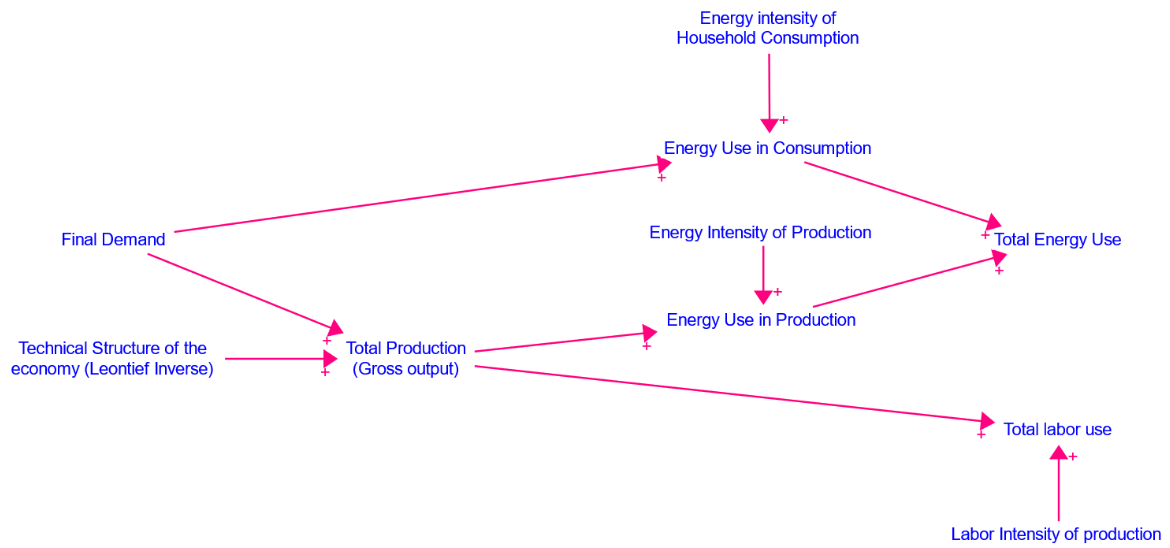
3.1 Model construction and data

The model presented in this paper is an input-output model built using the system dynamics software Stella. The core of the model is a 35-sector global input-output matrix, with data from satellite accounts providing information about the energy use and labor requirements associated with various levels of production. Economic and energy data in the model are taken from the World Input-Output Database (WIOD), and have been adapted for use in energy-economy modeling in the open-source MEDEAS-World model. (Dietzenbacher et al., 2013; Timmer et al., 2015; Capellán-Pérez et al., 2020). The economic data run from 1995 to 2009 and are drawn from 40 countries, with imputations calculated for a "Rest of the World" region to create a global input-output table. Data for the labor intensities are adapted directly from WIOD for this paper, as described below. Data for the energy intensity of household consumption are taken from MEDEAS based on calculations from International Energy Agency data (de Blas et al., 2019). The model itself runs from 1995 to 2030.

3.1.1 Static model

The static model calculates the energy and labor requirements associated with various levels of sectoral final demand, given various levels of energy and labor intensities and the technical structure of the economy. Figure 1 provides an influence diagram showing the relation between the variables in the model. The remainder of the section will describe the equations and data used to calculate energy and labor use.

Figure 1: Influence diagram of the core calculations of the model



Firstly, final demand is calculated for each of the 35 sectors, according to equation (1),

$$\mathbf{fd} = \mathbf{c} + \mathbf{gfcf} + \mathbf{ge} + \Delta\,\mathbf{invent} \quad (1)$$

with fd representing the 35 x 1 vector of final demand with the following components: c for household consumption, gfcf for gross fixed capital formation, ge for government expenditures, Δ invent for the annual change in inventories. Final demand is expressed in fixed 1995 dollars.

Sectoral final demand is used to calculate the total level of production, or gross output, in equation (2),

$$\mathbf{x} = (\mathbf{I}-\mathbf{A})^{-1} \cdot \mathbf{fd} \quad (2)$$

with x as the 35 x 1 vector of sectoral gross production and $(I-A)^{-1}$ as the 35 x 35 matrix of the technical structure of the economy in the form of the Leontief Inverse. This procedure of calculating production was initially designed by Wassily Leontief and is described in detail in Miller and Blair, (2022).

Gross output is then multiplied by energy and labor intensities calculated from the environmental and socio-economic satellite accounts of the WIOD to calculate both sectoral energy and labor requirements (Erumban et al., 2012; Genty et al., 2012). The calculation of energy required in production is given in equation (3) and the calculation of required labor in equation (4):

$$\mathrm{ep} = \mathbf{x} \cdot \mathrm{ei} \quad (3)$$

$$\mathrm{lh} = \mathbf{x} \cdot \mathrm{li} \quad (4)$$

with ep for energy used in production, ei for the energy intensity of production, lh for labor hours required for production and li for the labor intensity of production. Energy use is calculated for five different classification of energy carriers represented in the data—electricity, heat, liquid fuels, solid fuels, and gases. Energy intensities are expressed in units of exajoule (EJ) per 1995 fixed dollar, and energy use is expressed in exajoule.

The labor intensities were calculated directly from the WIOD socio-economic accounts, which cover between 85 to 88 percent of global demand between 1995 and 2009. An adjustment was made to account for missing countries by projecting the annual average labor intensity to fill the gap in final demand. Labor intensities are expressed in units of hour worked per 1995 fixed dollar.

In addition to the energy used in production, the model also calculates the energy used by households in the process of consumption. As an example of the distinction, while the energy associated with producing a car would be captured above by the energy intensities of production, the energy used to drive the car would be captured by household consumption (unless of course it was being driven in the production process of another sector). Household energy use is calculated according to equation (5),

$$eh = c \cdot ehi \tag{5}$$

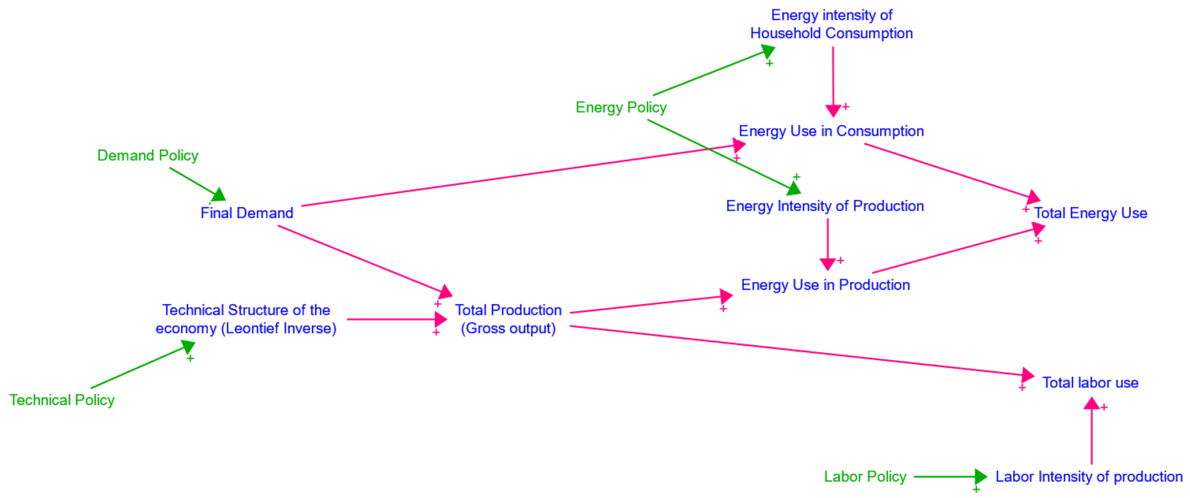
where energy use by consumption of households (eh) is received by multiplying total sector-wide consumption (c) with the intensity of energy use by households (ehi). These energy calculations are again made for each of the five energy carriers referenced above. Finally, total energy use (e) is obtained by adding the energy used in production to the energy used in consumption in equation 6.

$$e = ep + eh \tag{6}$$

3.1.2 Dynamic development: projection and policy

The previous section described how production, energy and labor use are calculated in each period. This section outlines how each variable evolves over time within the model. There are a number of options built into the model for how each variable will evolve, with the user picking the desired option using a built-in policy switch. In general, each variable contains at least one policy pathway and one pathway representing a historic projection. By alternating the various switches, different overall scenarios can be created in the model. Figure 2 locates the four policy switches within the influence diagram of the static model. The remainder of the section will describe the options available in each policy module.

Figure 2: Influence diagram of the model with exogenous policy variables



Demand Policy

The model has two options for demand policy: 1) Historic projection and 2) Ad hoc policy.

The historic projection is created using the observed geometric growth rates of consumption (c), gross fixed capital formation (gfcf) and government expenditure (ge) for each of the 35 sectors between 1995 and 2009. Changes in inventories are not linearly projected, but are rather set to gradually decline to zero between 1995 and 2009, as a majority of sectors had very low or negative inventories in 2009. Inventories then stay at zero for all sectors for the remainder of the model run, as theoretically inventories would be expected to oscillate around zero over the business cycle rather than perpetually grow like the other components of demand.

One major limitation of the historic projection is that it takes the fairly limited period of 1995 to 2009 as representation of the future development of each sector. While this may be an acceptable assumption for most sectors, for others it is less neutral, as for example the telecommunications sector grew at over 7% annually during this period which coincided with an explosion in telecommunications technology.

It was also investigated whether 2009, the ending point of the dataset, was a problematic end point due to the Global Financial Crisis which occurred in that year. While final demand levels do notably drop in 2009, it was found that the resulting global growth rates between 1995 and 2009 more closely resemble the rates observed in the years afterwards than the higher growth rates calculated between 1995 and 2008.

Future work to improve the historical projection using a longer historical reference is planned.

The second option within the model is to have final demand develop along the lines of exogenously set growth rates determined in the creation of scenarios. The current paper will present one such scenario, the "Targeted Growth" scenario, and future work intends to develop more demand pathways.

Technical Policy

The technical structure of the economy, represented in the model by the Leontief Inverse matrix, can evolve in the following way: 1) Linear projection, 2) Convergence to a "Green Growth" scenario, 3) Convergence to a "Post-Growth" scenario, 4) Static projection, and 5) Ad hoc projection.

The linear projection of the Leontief Inverse is calculated in the same way as the final demand historic projection, with geometric growth rates projecting forward the observed changes between 1995 and 2009. As a first approximation, this projection contains fewer notable outliers than the final demand projections, as the technical coefficients are less prone to sudden dramatic changes than final demand, even during large events like the Global Financial Crisis.

Options 2 and 3, Convergence to Green Growth and Post-Growth scenarios respectively, are built from scenarios of two possibilities for the global Leontief Inverse by the year 2050 presented in Nieto et al., (2020b). The Green Growth scenario represents a global convergence to the technical structure of Denmark in 2009, a country chosen as a representative of an advanced "green" country. The Post Growth scenario includes an ad hoc Leontief Inverse designed to represent the economic structure under a post-growth economic regime[2]. The two options available in this model project linear growth rates from the global Leontief Inverse in 1995 towards the two 2050 endpoints identified above, creating a full convergence by 2050 in each case.

In Option 4, the Leontief Inverse is left unchanged for the duration of the model run, while Option 5 allows the user to directly set growth rates to different cells in the Leontief Inverse.

This paper will only present results using Option 1, the linear projection, but future work will focus on the interactions between changes to final demand and the technical structure.

Energy Policy

The energy policy module includes four different options for the evolution of both production and consumption energy intensities: 1) Historic projection through smoothed regression 2) Historic projection through linear growth rate 3) Maximum policy scenario, and 4) Ad hoc policy.

The historic projection through smoothed regression is taken from de Blas et al., (2019) which use the calculation as the stable, historic element in their detailed modeling of the development of energy intensity. The historic projection through linear regression is created in the same way described above, with changes between 1995 and 2009 projected forward. The Maximum policy scenario is created using estimates from de Blas et al., (2019) of the potential annual change in each sector's use of each energy type due to either efficiency gains or substitution with other energy types. The combination of these two reductions creates a maximum possible annual reduction rate for each sector-energy type combination. To approximate the impossibility of unlimited reductions in energy intensity, de Blas et al., (2019) propose that each energy intensity has a floor of 30% of its 2009 value, a convention that is recreated in this model.

[2] Exact details for the construction of the Post-Growth 2050 Leontief Inverse can be found in the Appendix A2 of (Nieto et al., 2020b).

Finally, as above, there is an option for ad hoc growth rates to be applied to each sector-energy type combination. In the future, this ad hoc option can be used to explore scenarios in which the use of one or more energy type decline rapidly.

Labor Policy

The labor intensities in the model can evolve either as 1) Linear projections, calculated in the same way as the linear projections described above, 2) as a Static projection, or 3) as Ad hoc growth rates. Future work will add convergence scenarios, along the lines of the technical structure module. It is also important to note here that reductions in sectoral labor intensity are synonymous with improvements in labor productivity, and significant changes to global labor intensity can be expected under different development scenarios.

3.2 Calculation of final demand sensitivities

The intensities referenced so far in the model indicate the amount of energy or labor needed within each sector to fulfil one unit of output created by this sector. In this sense, the intensities account for all of the energy and labor used by a sector in production. This includes a sector's production needed to fulfil its own final demand, but also production for intermediate inputs used by other sectors in their productive processes. What the intensities do not tell us however, is how much energy and labor use each unit of final demand is ultimately responsible for.

To better understand the relationship between final demand and energy and labor use, our model also calculates *final demand sensitives* which relate each unit of final demand to the amount or energy and labor needed, across all sectors, to fulfil it. These sensitivities are calculated by pre-multiplying the energy (ep) and labor (lh) intensities by the Leontief Inverse ($\mathbf{(I\text{-}A)^{-1}}$) and taking the column sums of the resulting product, in a process described by (Nieto et al., 2020b) in reference to energy sensitivities. The resulting sensitivities indicate which sectors' final demand is, dollar for dollar, responsible for the most energy and labor use.

When multiplying the energy and labor sensitivities by the final demand of each sector, we can obtain a measurement of the amount of energy and labor use which can be attributed to the final demand of each sector, giving us an idea of which sectors drive the most energy and labor use in absolute terms.

The resulting sensitivities are presented below in Figures 3 and 4. For the energy sensitivities, the use of electricity and heat have been removed, leaving only the use of solid fuels, liquid fuels and gases, all of which are overwhelmingly provided by fossil fuels. The sectors are organized on the charts below in order of the indentation numbers, as organized within the WIOD. In the Appendix, the same data is represented as treemaps (Figures 11 and 12) which better show the relative distribution of the larger sectoral sensitivities.

Figure 3: Sensitivity of energy use from fossil fuels to sectoral final demand (in EJ/$)

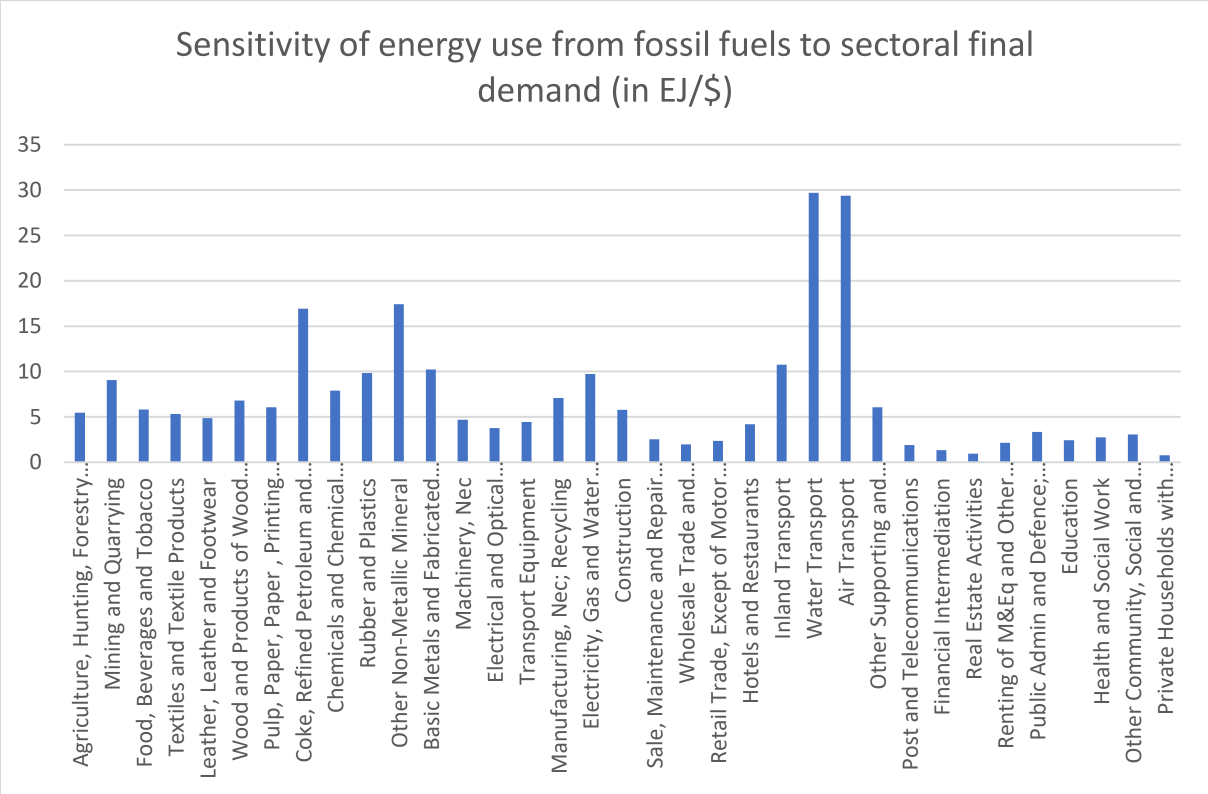
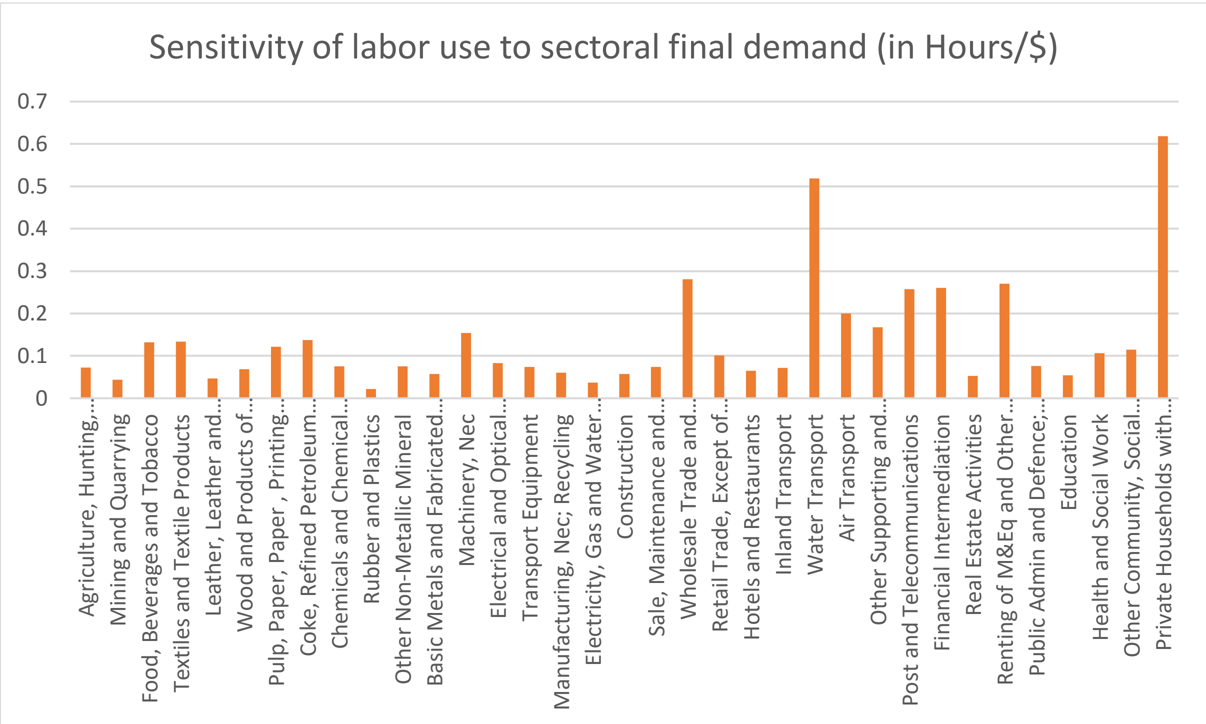


Figure 4: Sensitivity of labor use to sectoral final demand (in Hours/$)



3.3 Initial scenario design

The final demand sensitivities are then used in the creation of a "Targeted Growth" scenario for the evolution of final demand. This scenario attempts to simultaneously prioritize final demand growth in sectors which have high labor sensitivities and target low, or negative growth, in sectors with high fossil fuel sensitivities.

Specifically, the sectors were ranked according to the two sensitivities, with each sector being assigned a target growth rate based on the two rankings. The fifteen most desirable sectors for each ranking were assigned a score of 2, the next ten sectors, a score of 0, the next five, a score of -1, and the final five, a score of -2. The scores for the two rankings were then combined. To more closely align the overall growth rate of the economy with the historical trend, the resulting scores were increased (or decreased for negative scores) by 20 percent, to create the growth rates shown in Figure 5.

This process, while admittedly fairly arbitrary, is intended to show the rough potential of a policy of differentiated demand compared to the historical projection. The resulting scenario built with these ad hoc final demand growth rates, called the "Targeted Growth" scenario, relies on historical projections for the technical structure and energy and labor intensities. The "Historic Growth" scenario meanwhile relies on historic projections for all dynamic variables, including final demand. Future work will allow for a more systematic exploration of final demand scenarios.

Figure 5: Sectoral final demand growth rates in the Targeted Growth scenario

Sector	**Annual percent change in final demand**
Agriculture, Hunting, Forestry and Fishing	0
Mining and Quarrying	-3.6
Food, Beverages and Tobacco	2.4
Textiles and Textile Products	2.4
Leather, Leather and Footwear	-2.4
Wood and Products of Wood and Cork	0
Pulp, Paper, Paper, Printing and Publishing	2.4
Coke, Refined Petroleum and Nuclear Fuel	0
Chemicals and Chemical Products	-1.2
Rubber and Plastics	-3.6
Other Non-Metallic Mineral	-2.4
Basic Metals and Fabricated Metal	-2.4
Machinery, Nec	2.4
Electrical and Optical Equipment	2.4
Transport Equipment	2.4
Manufacturing, Nec; Recycling	-1.2
Electricity, Gas and Water Supply	-3.6
Construction	-1.2

Sale, Maintenance and Repair of Motor Vehicles and Motorcycles; Retail Sale of Fuel	2.4
Wholesale Trade and Commission Trade, Except of Motor Vehicles and Motorcycles	4.8
Retail Trade, Except of Motor Vehicles and Motorcycles; Repair of Household Goods	2.4
Hotels and Restaurants	1.2
Inland Transport	-2.4
Water Transport	0
Air Transport	0
Other Supporting and Auxiliary Transport Activities; Activities of Travel Agencies	2.4
Post and Telecommunications	4.8
Financial Intermediation	4.8
Real Estate Activities	0
Renting of M&Eq and Other Business Activities	4.8
Public Admin and Defence; Compulsory Social Security	2.4
Education	1.2
Health and Social Work	4.8
Other Community, Social and Personal Services	4.8
Private Households with Employed Persons	4.8

4 Initial Results: Targeted Growth vs Historic Projection

The following initial results show the differences between the Historic Growth and Targeted Growth scenarios presented above.

As shown in Figure 6, a primary result is that the Targeted Growth scenario is able to achieve a 30.8% reduction in fossil energy used in production by 2030, with the Historic Growth scenario using 298 EJ of fossil energy in production by 2030 and the Targeted Growth scenario using only 206 EJ. This reduction is achieved while sustaining only a 5.2% reduction in labor use, with Targeted Growth accounting for 7.04 trillion hours of labor and Historic Growth for 7.43 trillion hours in 2030 (Figure 7).

The growth rate of total final demand (shown in Figure 8) remains lower for the Targeted Growth scenario throughout the run of the model, leading to a 14.4% smaller scale of final demand in 2030 compared to Historic Growth. While lower than Historic Growth, Targeted Growth is in no ways a no-growth or low-growth scenario, as it is intended to show to potential impact of a shift in the composition of demand, rather than a significant change in the overall level of demand.

The combination of a substantial fall in fossil energy use with only a moderate drop in associated labor needs between the two scenarios is a proof of concept for the premise that targeted shifts in the composition of final demand could be an interesting factor in decarbonizing the global economic system.

Figure 6: Fossil fuel use in production in both scenarios

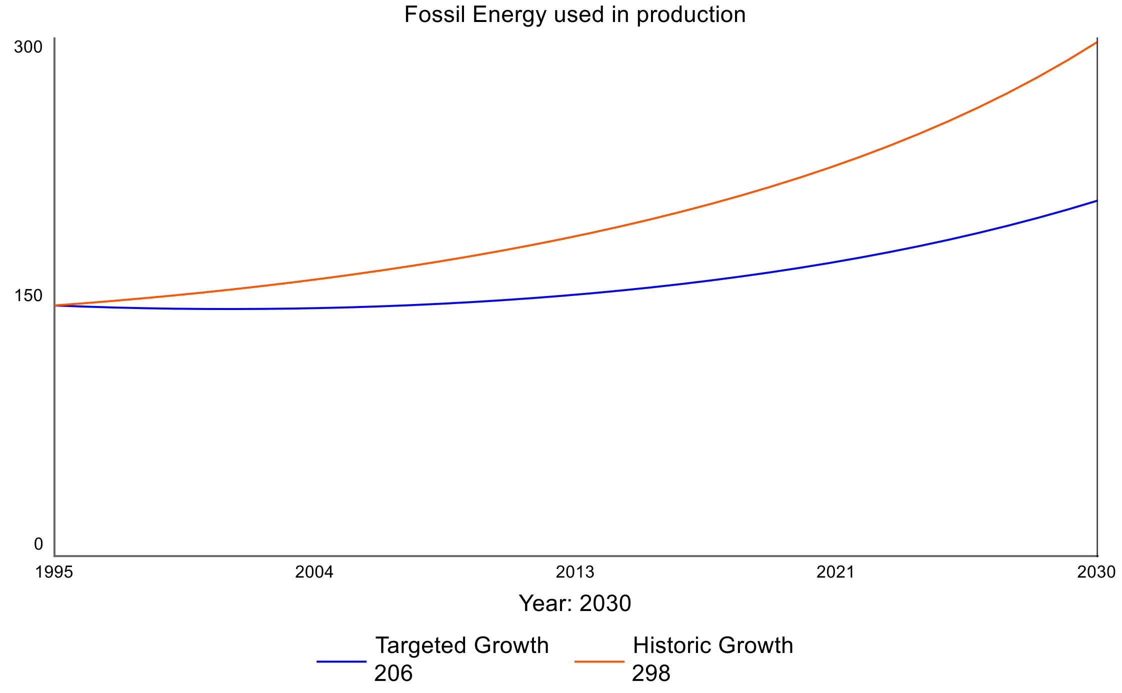
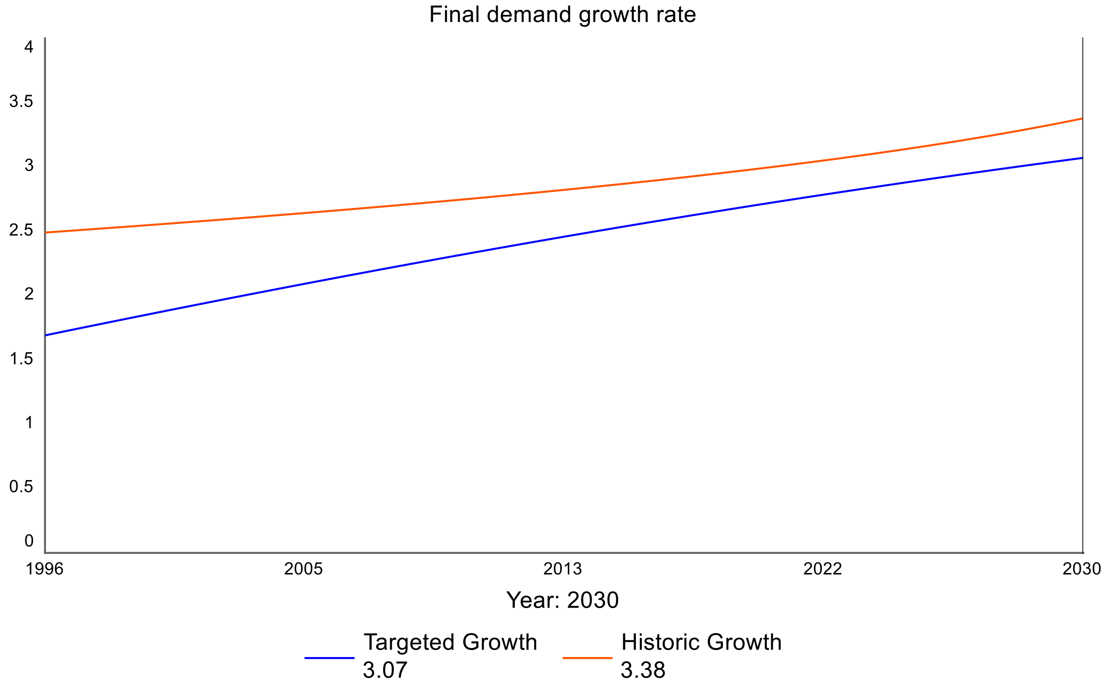


Figure 7: Labor use in both scenarios

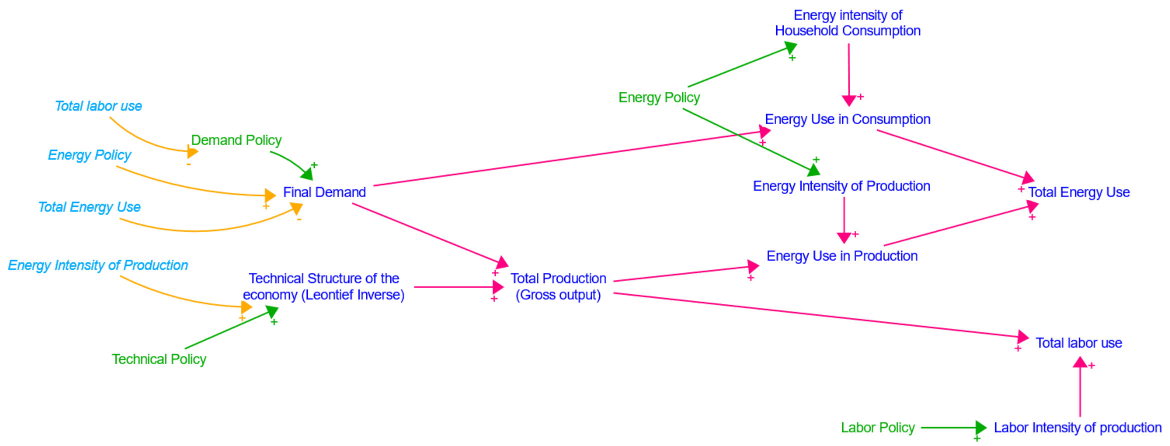
Figure 8: Final demand growth rates in both scenarios



5 Conclusions and further work: additional scenarios and feedbacks

The current results confirm the possibility that targeted shifts in the composition of final demand could alleviate environmental pressures in a way that does not result in a dramatic reduction in employment. Future work envisions the creation of more detailed and extensive scenarios which can capture key feedback loops that are relevant in representing relations between economic, social, energy, and climatic systems. Figure 9 depicts four initial loops which have been identified as important starting points for first informing scenario construction, and eventually for directly integrating into the model structure. The paper will conclude with a short description of each loop and a discussion of how it could be accounted for.

Figure 9: Feedback loops to be simulated off-model through scenario construction[3]



The first feedback is a link between total labor use and demand policy which limits the possibility of negative sectoral growth if economy-wide labor use drops by too much. This loop is intended to provide a celling for sectoral negative growth policies should the shrinkages lead to unacceptably high unemployment. In practice, this feedback would imply rejecting scenarios with employment losses over a certain threshold as socially implausible, although the exact link between hours of labor required and social stability can be further nuanced, for instance through the addition of working time reductions. A future link could build a hard limit into the model itself, partially endogenizing the level of policy ambition to the level of employment.

The second feedback connects changes in the energy policy module with the associated changes that would be expected in final demand. Specifically, in scenarios with aggressive improvements in energy intensity, it is assumed that this occurs due to large investments in energy efficiency technology and an energy transition towards renewables which allows the substitution of fossil energy carriers with electricity and heat. These energy transition activities require well defined inputs, which can be mapped onto the sectors of final demand in our model (Černý et al., 2022). This will ensure that sectors which are critical to the transition are not downsized to the point of not being able to support the energy intensity improvements coming out of the energy policy module.

The third feedback accounts for climate damages, as pathways with higher levels of fossil fuel requirements will incur progressively increasing negative shocks to final demand growth.

The final feedback links the projected changes in energy use coming from the energy intensities with the changes in inputs required from energy producing sectors in the Leontief Inverse. While energy use is tracked directly through the sectoral energy intensities, it also appears indirectly through the

[3] The italic text for variable names is a system dynamics convention indicating the variable is a duplicate, or "ghost", of another variable on the influence diagram.

technical structure of the economy, where some sectors produce and sell energy products to other sectors for use in production. Should the energy intensities significantly change, for instance, to project a large reduction in the need for liquid fuels, this should be matched with a corresponding reduction in the inputs required from the Coke, Refined Petroleum and Nuclear Fuel sector. Nieto et al., (2023) provide estimates of how the technical structure could be endogenized with respect to changes in energy intensity. But for now, it remains a link to be considered when designing consistent scenarios in which both energy intensities and the technical structure evolve in compatible directions.

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Appendix

Figure 10: Overview of the model in Stella software

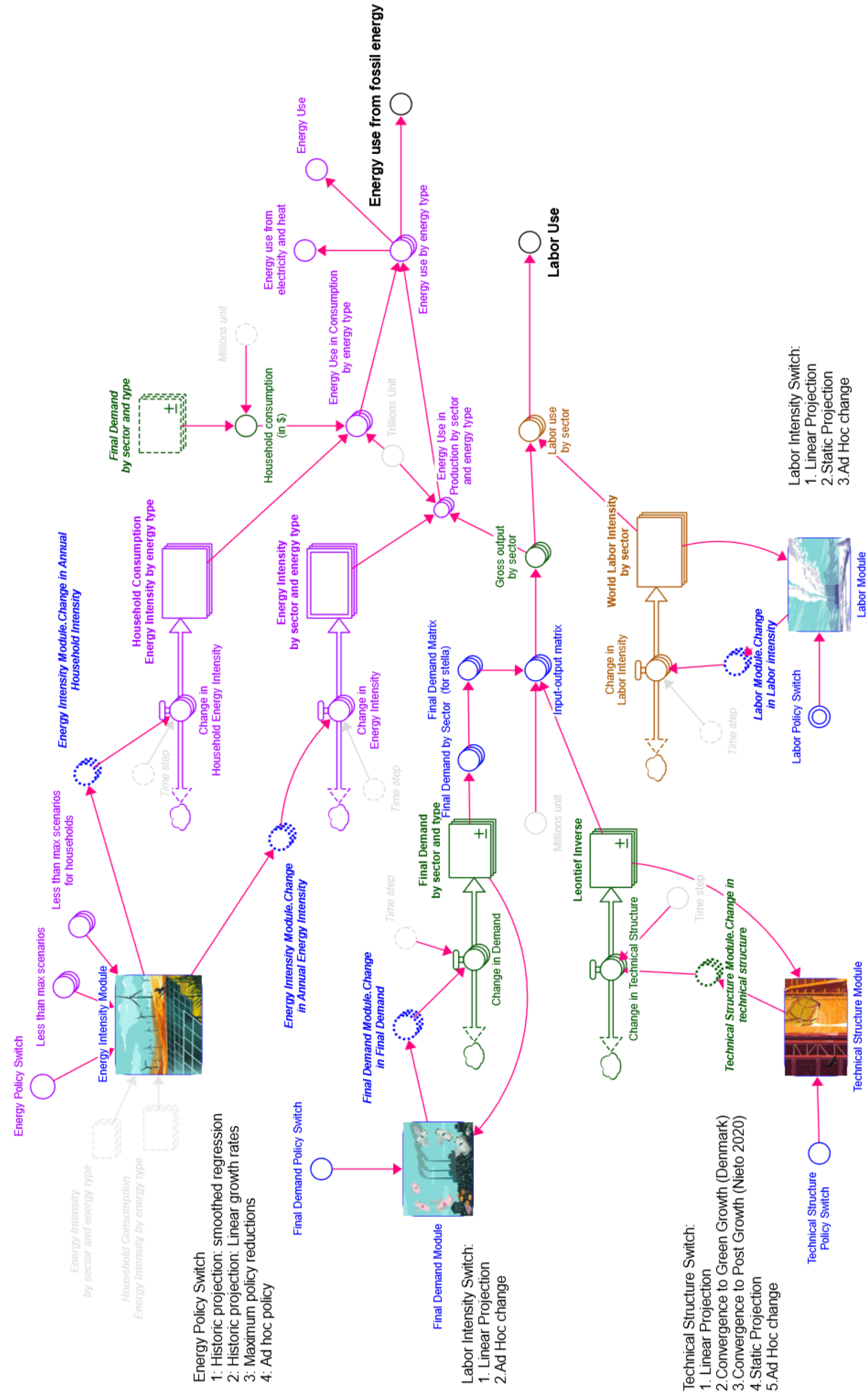

Figure 11: Treemap of sensitivity of energy use from fossil fuels to sectoral final demand

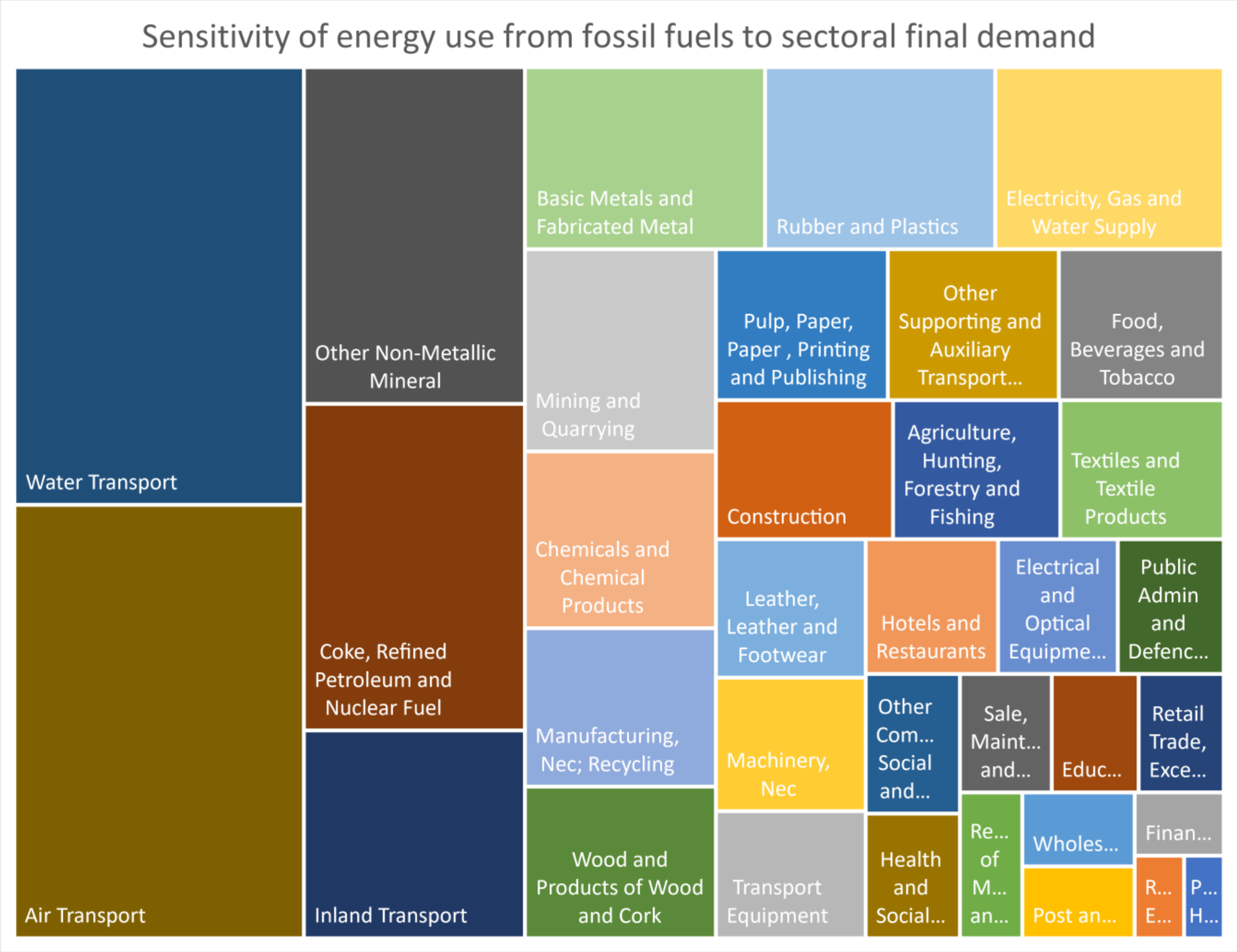

Figure 12: Treemap of sensitivity of labor use to sectoral final demand