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# How would the adoption of French energy technology reduce German and Japanese $CO_2$ emissions?

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**Abstract**
The phasing out of nuclear power in Germany and Japan has been a political topic since the 1980s. This was mainly due to the fear of nuclear power meltdowns, and more generally the risks involved with nuclear power production, driven by the Fukushima nuclear power plant disaster. In stark contrast, France as a nation has wholeheartedly embraced nuclear power. In the discussion of cutting greenhouse gas emissions, it would be a logical move, as nuclear power has no direct greenhouse gas emissions. However, indirect emissions of nuclear power are unclear and, therefore, the nuclear power's greenhouse gas footprint better be determined. We map these footprint reductions and calculate by how much German and Japanese emissions would be reduced following the French example. We find that there would be a 42% total reduction to the German footprint and a 45% reduction to the Japanese footprint, if French energy technology were adopted. We provide a decomposition analysis of footprint changes in emission and technology effects. We find that the technology effects dominate.

**Keywords** Footprints · Nuclear energy · Germany · Japan

**JEL Classification** C67 · O52 · O53 · Q56

## Introduction

The demand for sustainable supply chains is ever growing as the effects of climate change cause further damage every year. We investigate the effects of the greenhouse gas (GHG) footprints, $CO_2$ and its equivalents, in relation to the phasing out of nuclear energy in Germany and France. The phasing out has been prioritized since the Fukushima nuclear disaster in 2011.

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We use input–output modeling to find the GHG footprints for the German and Japanese economies. We make a comparison of a hypothetical energy industry scenario, where France's predominantly nuclear energy industry technology and emissions are inserted into the German and Japanese production structures. The scenario models hypothetical German and Japanese energy industries that mimic France's dominant use of nuclear power, rather than the phasing-out which dominates the policy agenda. We thus map the emission damage that is the flip side of nuclear restraint.

In 2011, the German Parliament (Bundestag) voted for a resolution which paved the way for all nuclear power plants to be decommissioned by 2023. The final three German nuclear power plants were decommissioned a year prior on April 15, 2023. As of the initial phase-out decision, there has been much discussion on the effects on the GHG emissions of such a drastic measure. Germany until March 2011 obtained one-quarter of its electricity from nuclear energy, using 17 reactors (World Nuclear Association, 2025a). The phasing out of nuclear power has been a political topic since the 1980 s due to the German Green Party. The phase-out was popularized mainly due to the fear of nuclear power meltdowns and, more generally, the risks involved with nuclear power production. Yet in the end, the German Green Party was not the one to push for this legislation, but rather the conservative Christian Democratic Party (CDU). This was due to the large politicization of the Fukushima nuclear power plant disaster into German politics, where phasing out nuclear power became the popular opinion at the time. Although it is speculation, some believe that the reason the CDU made this legislation was to "steal" votes from the German Green Party (Gensing 2019).

In stark contrast, France as a nation has wholeheartedly embraced nuclear power, and as of 2022 roughly 70% of all power produced is from nuclear sources (World Nuclear Association, 2025b). This is opposite to the German approach, but in the discussion of cutting GHG emissions, it would be a logical move, as nuclear power has no direct GHG emissions. However, indirect emissions of nuclear power are more unclear and, therefore, the nuclear power's GHG footprint better be determined, unlike many studies, e.g., AlFarra and Abu-Hijleh (2012). France is not the main focus of this paper but used as an alternative economy, that has embraced nuclear power advantages, rather than pushed away the technology due to politics and risk.

Most prior research into emissions and sustainability concerns have either focused on the comparisons between electric, gas, and hybrid cars in the automotive industry or the relationship of footprints and income. Most studies calculate footprints to utilize as a variable in a multivariate regression. Paravantis et al. (2021) focused on the urbanization aspect of human populations and utilized footprints to see the effects of urban agglomeration and income on emissions. However, we focus on the total footprint of German and Japanese industries to have a more general understanding of trends.

Research into nuclear power and impacts onto GHG emissions has been done in the past. However, these results have been inconclusive as there is not a standardized method to compare or measure these two concepts. A study from Bandyopadhyay et al. (2022), using a quantile-on-quantile regression, found that the nuclear power's relationship with GHG footprints is unclear. This is due to positive and negative links being found between GHG footprints and nuclear power depending on the upper or lower quantiles. Murshed et al. (2022) found that when creating a multivariate regression which focused on renewables, nuclear and carbon footprints, nuclear power was shown to reduce environmental externalities. In other words, this study found that increased nuclear power usage resulted in lower $CO_2$ footprints. We look into the effects in a hypothetical scenario analysis of Germany and Japan using nuclear power.

Heinrichs and Markewitz (2017) did a scenario-based analysis to show the impact of the coal industry on emissions, segregating the energy industry into the different production methods, and concluding that coal has severe impacts. They found that an early coal phase out would allow Germany to complete its emission goals for 2020 but would have a negative impact on the economy. We expand upon this scenario-based analysis and create an analysis to mimic a Germany and a Japan with almost no coal and sizable nuclear power production.

Basically, we just replace the technical coefficients and emission coefficients for energy production in the German and the Japanese input–output tables by the French coefficients, before calculating new industry-level footprints. This illustrates the fact that German and Japanese decisions to phase out nuclear power have a significant impact on their GHG emissions, that these two large economies would have much lower emissions with an energy mix relying more on nuclear power, as in France. The limitation of our methodology is that it does not take into account the nuclear risk of the French policy. Moreover, a refinement of our model would be to decompose the contribution of coal, gas, oil, nuclear, and renewable energies in the current energy mixes of Germany and Japan, and to use disaggregated emission coefficients and to change the shares. Aggregation is a limitation associated with input–output analysis. We use the OECD input–output database. Here, the energy industry includes not only electricity, but also gas, steam, and air conditioning supply. However, the electricity supply subsector dominates in almost all indicators for which data is available: number of enterprises (93.2%), employee benefits expense (81.5%), and turnover (82.9%) (Eurostat 2024). We expect the emission/employee benefits expense ratio and the emission/turnover ratio to be the greatest in the electricity supply subsector or at least of the same order; hence, it is safe to assume that electricity generation accounts for the lion share of $CO_2$ emissions in this industry. We admit that it is a simplification to assume that German and Japanese resourcing to nuclear power would yield the French energy production mix. However, there is some independence. Many circumstances, especially prices, determine the mix of techniques, but the footprints depend only on the consequent input–output and emission coefficients, as we will see in the next section.

The remainder of the paper is structured as follows. Section 2 presents the basic methodology, describes the data, and explains our models. Sections 3 and 4 analyze the potential on emission reductions in the German and the Japanese economies, respectively, as implied by the adoption of the French energy production. Since the French energy adoption involves changes of the German and the Japanese energy input coefficients and of their energy emission coefficients, we may decompose the $CO_2$ benefits in emission effects and technology effects. Section 5 derives the decomposition formula and its application to the German and Japanese economies. Section 6 concludes.

## Methodology

Nian et al. (2014) distinguish broadly two approaches in conducting life cycle analysis exercises, the top-down and the bottom-up approaches. In the top-down approach, the input–output method has emerged as the most popular method. It is a robust method in evaluating energy systems at the macroeconomic level. However, it is lacking in granularity at the engineering process level. The bottom-up approach enables high granularity, but there is a lack of standardized methodology. Since we analyze national economies, we stick to the input–output method.

Data was collected from the OECD (2002) input–output database and the OECD (2024) emissions database, for Germany, Japan, and France in 2018 (the data were updated in 2021). For each economy, the data consist of the 44 by 44 industries *input–output table* $X$, the 44 industries *final demand* column vector $y$, and the 44 industries *emissions* row vector $M$. The OECD aggregates the energy industry into "Electricity, gas, steam and air conditioning supply." We exclude industry 45, "Activities of households as employers," of which the data are all zero.

Letting $e$ be the summation vector, with all entries equal to one, define total output $x$ as the sum of intermediate demand and final demand:

$$x = Xe + y \tag{1}$$

Let ^ transform a vector to a diagonal matrix, then Eq. (1) can be rewritten as

$$x = Ax + y \tag{2}$$

with

$$A = X\hat{x}^{-1} \tag{3}$$

the input–output coefficients matrix (45 by 45 industries). Likewise, the emission coefficients are defined by row vector

$$m = M\hat{x}^{-1} \tag{4}$$

The emission coefficients measure the emissions per unit of output, without taking into account the emissions generated in the production of the intermediate inputs. Footprints, however, measure the emissions per unit of final demand, taking into account the emissions generated in the supply chain. Footprints are determined by decomposing total emissions, $Me$, by final demand components. This we do as follows. By Eq. (4) and substituting the solution to Eq. (2), we obtain

$$Me = mx = m(I - A)^{-1}y \tag{5}$$

Equation (5) shows that the total emissions $Me$ are proportional to the components of final demand $y$ with weights

$$m(I - A)^{-1} \tag{6}$$

Equation (6) is the row vector that defines the product footprints, or *relative footprints*, as they are per unit of final demand components. We see that product footprints are emission coefficients inflated by the Leontief inverse $(I-A)^{-1}$ to account for the emissions of intermediate production. Separating out the terms on the right-hand side of Eq. (5) we have the footprints of the different components of final demand, or total footprints,

$$m(I-A)^{-1}\hat{y} \tag{7}$$

Table 1 shows the emissions and footprints of the German economy. (The Japanese and French counterparts have the same format and can be found in the Appendix.) The first column in Table 1 displays the German emissions by industry, as given by data vector *M*. The second column shows the product footprints, calculated according to Eq. (6). The product footprints are multiplied by the quantities of the products delivered to final demand according to Eq. (7). The emissions (column 1) are pollution by the industries of supply. The footprints (column 3) are pollution by the products of final demand. Emissions and footprints are alternative decompositions of total pollution according to Eq. (5) and this is confirmed by the bottom row of Table 1.

Emissions are accounted by production units (industries) and footprints by consumption units (households, net exports, investment, and public demand). However, this distinction is different than the one made between production-based and consumption-based emissions (Danish et al. 2022). Consumption-based emissions are generated by household and foreign production, which we miss.

The *units* are as follows. Outputs, gross or net, are in million dollars (*m$*). Emissions and footprints are in million metric tons (*m tons*). Coefficients of emissions and footprints are in metric tons per m$. In Table 1, representing the German economy, the middle row, 23, shows the figures for the electricity, gas, steam, and air conditioning supply. The industry emits 259.00 m tons $CO_2$. The relative footprint is 1888.80 ton per m$. The OECD database shows that the final demand for the produce is 68,997.30 m$. Multiplying the last two figures, we obtain the total footprint of this industry: 1888.80 ton/m$*68,997.30 m$ = 130,322,100.24 ton = 130.32 m ton. The last figure is rounded and found in the last column of Table 1. Mind that overwhelming imports may turn final demand components negative. For this reason, the second through fifth footprints in the last column of Table 1 are negative.

To make a scenario comparison between nuclear and non-nuclear power in energy industries, technology and emission coefficients gathered for the French energy sector are utilized and replaced into the German economy. As column 23 is the energy sector, the German economy using French energy technology is shown in Eq. (8), where $a^F_{i,23}$ are the French elements of their $A$ matrix,

$$\widetilde{A} = \begin{pmatrix} a_{1,1} & \cdots & a_{1,22} & a^F_{1,23} & a_{1,24} & \cdots & a_{1,45} \\ \vdots & & \vdots & \vdots & \vdots & & \vdots \\ a_{45,1} & \cdots & a_{45,22} & a^F_{45,23} & a_{45,24} & \cdots & a_{45,45} \end{pmatrix} \tag{8}$$

Simultaneously, the emission coefficient for the French energy sector must be incorporated into the model. The emission coefficients $\widetilde{m}$ for the German economy using French energy technology are defined in Eq. (9) as

**Table 1** German emissions, product footprints and final demand footprints

| Industry | Emissions, $CO_2$ m tons | Footprints, tons per m$ spent | Footprints, $CO_2$ m tons |
|---|---|---|---|
| Agriculture, hunting, forestry | 9.31 | 288.00 | 3.81 |
| Fishing and aquaculture | 0.09 | 265.63 | − 0.06 |
| Mining and quarrying, energy producing products | 4.44 | 804.38 | − 42.41 |
| Mining and quarrying, non-energy producing products | 0.68 | 260.20 | − 1.03 |
| Mining support service activities | 0.03 | 224.87 | − 0.09 |
| Food products, beverages and tobacco | 8.61 | 198.90 | 31.00 |
| Textiles, textile products, leather and footwear | 0.72 | 166.14 | 3.30 |
| Wood and products of wood and cork | 0.53 | 191.17 | 1.51 |
| Paper products and printing | 6.47 | 288.69 | 5.61 |
| Coke and refined petroleum products | 19.30 | 741.79 | 16.72 |
| Chemical and chemical products | 15.66 | 283.27 | 20.53 |
| Pharmaceuticals, medicinal chemical, botanical products | 5.52 | 178.00 | 8.75 |
| Rubber and plastics products | 1.44 | 173.58 | 5.15 |
| Other non-metallic mineral products | 18.60 | 530.97 | 8.65 |
| Basic metals | 56.51 | 936.39 | 5.68 |
| Fabricated metal products | 1.49 | 209.70 | 11.36 |
| Computer, electronic and optical equipment | 1.04 | 113.75 | 6.83 |
| Electrical equipment | 1.23 | 145.53 | 9.97 |
| Machinery and equipment, nec | 2.78 | 145.06 | 31.19 |
| Motor vehicles, trailers and semi-trailers | 3.26 | 135.32 | 43.15 |
| Other transport equipment | 0.38 | 138.68 | 5.09 |
| Manufacturing nec; repair and installation of machinery | 1.61 | 141.26 | 10.28 |
| Electricity, gas, steam and air conditioning supply | 259.00 | 1,888.80 | 130.32 |
| Water supply; sewerage, waste management | 1.90 | 122.79 | 3.08 |
| Construction | 10.72 | 145.86 | 37.25 |
| Wholesale and retail trade; repair of motor vehicles | 14.78 | 107.43 | 35.59 |
| Land transport and transport via pipelines | 11.41 | 219.06 | 8.96 |
| Water transport | 16.94 | 653.86 | 16.36 |
| Air transport | 33.53 | 1,294.90 | 21.60 |
| Warehousing and support activities for transportation | 9.06 | 169.41 | 3.67 |
| Postal and courier activities | 2.17 | 158.86 | 0.17 |
| Accommodation and food service activities | 1.25 | 120.79 | 10.44 |
| Publishing, audiovisual and broadcasting activities | 0.99 | 79.62 | 3.37 |
| Telecommunications | 0.86 | 87.27 | 2.52 |
| IT and other information services | 1.77 | 39.95 | 0.48 |
| Financial and insurance activities | 2.72 | 56.79 | 6.16 |
| Real estate activities | 4.38 | 40.65 | 13.03 |
| Professional, scientific and technical activities | 5.16 | 60.74 | 8.39 |
| Administrative and support services | 4.51 | 83.76 | 6.51 |
| Public administration and defence | 5.31 | 71.65 | 20.22 |
| Education | 2.12 | 37.99 | 6.59 |

**Table 1** (continued)

| Industry | Emissions, $CO_2$ m tons | Footprints, tons per m$ spent | Footprints, $CO_2$ m tons |
|---|---|---|---|
| Human health and social work activities | 4.21 | 67.81 | 25.74 |
| Arts, entertainment and recreation | 1.06 | 70.68 | 3.54 |
| Other service activities | 1.36 | 66.37 | 5.92 |
| Total | 554.92 | | 554.92 |

$$\widetilde{m} = (m_1 \cdots m_{22} m_{23}^F m_{24} \cdots m_{45}) \tag{9}$$

We determine how the German footprints would change if Germany had embraced nuclear power technology rather than phased out the technology as follows. According to expression (6), the product footprints become $\widetilde{m}(I - \widetilde{A})^{-1}$. The product footprint reductions are $m(I - A)^{-1} - \widetilde{m}(I - \widetilde{A})^{-1}$. This vector is displayed in column 2 of Table 2. Remarkably, all product footprints are reduced.

Multiplying the new product footprints by the final demand components, we obtain $\widetilde{m}(I - \widetilde{A})^{-1}\hat{y}$. This vector is displayed in column 3 of Table 2, also in the form of reductions, i.e., $m(I - A)^{-1}\hat{y} - \widetilde{m}(I - \widetilde{A})^{-1}\hat{y}$. Some reductions are negative, because the French energy technology has different input requirements and, therefore, prompts reallocations, including some output increases. The first column in Table 3 does not contain emission data but the emissions that would be generated if the German economy were to adopt French energy technology. The emission reductions have to be calculated. Final demand is observed, vector $y$. The industry outputs that would sustain delivery of final demand is obtained by premultiplying $y$ by the Leontief inverse of the new technology, Eq. (8), yielding industry output $(I - \widetilde{A})^{-1}y$. The emissions, industry by industry, are obtained by premultiplying each output component by the respective emission coefficient, without summing. This is done by premultiplying industry output by the diagonal matrix of the new emission coefficients, Eq. (9). Hence, the emissions would be $\hat{\widetilde{m}}(I - \widetilde{A})^{-1}y$. Subtracting this vector from column 1 of Table 1, we obtain the vector of reductions, displayed in column 1 of Table 2.

Equations (8) and (9) will also be applied to the Japanese economy to analyze the reductions of emissions and footprints that would be feasible in Japan should the economy go nuclear, or at least adopt the French energy mix. Of course, Japan has quite a different economic and environmental structure than Germany, and, therefore, the impacts of nuclear energy adoption may prove different as well. However, we will show there is surprising similarity between the Japanese and German economies in terms of the environmental benefits of adopting French energy production.

The Appendix contains the pair of tables for the Japanese economy similar to Tables 1 and 2 for the German economy, namely Table 3 with the actual emissions and footprints, and Table 4 with the emission and footprint reductions, should Japan go nuclear. The Appendix also contains Table 5, of which we use

**Table 2** Germany with French energy technology: Reductions in emissions, product footprints, and final demand footprints

| Industry | Emissions, $CO_2$ m tons | Footprints, tons per m$ spent | Footprints, $CO_2$ m tons |
|---|---|---|---|
| Agriculture, hunting, forestry | 3.05 | 55.28 | 0.73 |
| Fishing and aquaculture | 0.02 | 43.07 | − 0.01 |
| Mining and quarrying, energy producing products | 2.80 | 47.06 | − 2.49 |
| Mining and quarrying, non-energy producing products | 0.09 | 35.98 | − 0.14 |
| Mining support service activities | 0.00 | 29.89 | − 0.01 |
| Food products, beverages and tobacco | 0.11 | 51.77 | 8.07 |
| Textiles, textile products, leather and footwear | − 0.38 | 56.29 | 1.12 |
| Wood and products of wood and cork | − 0.65 | 59.49 | 0.47 |
| Paper products and printing | 1.86 | 84.11 | 1.63 |
| Coke and refined petroleum products | 16.34 | 72.67 | 1.64 |
| Chemical and chemical products | 5.46 | 66.24 | 4.80 |
| Pharmaceuticals, medicinal chemical, botanical products | 1.00 | 31.66 | 1.56 |
| Rubber and plastics products | − 2.74 | 63.96 | 1.89 |
| Other non-metallic mineral products | 8.50 | 79.80 | 1.30 |
| Basic metals | 33.72 | 103.37 | 0.63 |
| Fabricated metal products | − 9.81 | 51.10 | 2.76 |
| Computer, electronic and optical equipment | − 3.35 | 31.70 | 1.91 |
| Electrical equipment | − 4.89 | 36.57 | 2.50 |
| Machinery and equipment, nec | − 11.33 | 37.00 | 7.96 |
| Motor vehicles, trailers and semi-trailers | − 13.67 | 35.93 | 11.19 |
| Other transport equipment | − 1.52 | 35.74 | 1.31 |
| Manufacturing nec; repair and installation of machinery | − 3.64 | 35.68 | 2.59 |
| Electricity, gas, steam and air conditioning supply | 239.88 | 1,594.41 | 110.01 |
| Water supply; sewerage, waste management | − 1.20 | 49.93 | 1.25 |
| Construction | − 9.88 | 32.50 | 8.30 |
| Wholesale and retail trade; repair of motor vehicles | − 11.41 | 38.19 | 12.65 |
| Land transport and transport via pipelines | 3.29 | 62.91 | 2.55 |
| Water transport | 11.28 | 28.40 | 0.71 |
| Air transport | 22.61 | 27.96 | 0.47 |
| Warehousing and support activities for transportation | 0.53 | 35.45 | 0.77 |
| Postal and courier activities | − 0.24 | 39.71 | 0.04 |
| Accommodation and food service activities | − 2.88 | 54.18 | 4.78 |
| Publishing, audiovisual and broadcasting activities | − 1.03 | 27.86 | 1.18 |
| Telecommunications | − 0.84 | 37.25 | 1.07 |
| IT and other information services | − 1.33 | 11.45 | 0.14 |
| Financial and insurance activities | − 2.35 | 22.21 | 2.41 |
| Real estate activities | − 6.00 | 14.67 | 4.70 |
| Professional, scientific and technical activities | − 4.28 | 22.15 | 3.06 |
| Administrative and support services | − 7.46 | 22.10 | 1.72 |
| Public administration and defence | − 5.56 | 24.95 | 7.04 |

**Table 2** (continued)

| Industry | Emissions, $CO_2$ m tons | Footprints, tons per m$ spent | Footprints, $CO_2$ m tons |
|---|---|---|---|
| Education | 1.94 | 14.55 | 2.53 |
| Human health and social work activities | − 7.49 | 28.24 | 10.72 |
| Arts, entertainment and recreation | − 1.03 | 30.78 | 1.54 |
| Other service activities | − 1.87 | 28.62 | 2.56 |
| Total | 231.82 | | 231.82 |

the French emissions and technology data, particularly of the energy, and Table 6, the decomposition of the $CO_2$ benefits in emission effects and technology effects.

## Application to Germany

Tables 1 (all German) and 2 (with adoption of French energy technology) display the total emissions, $M$, the relative footprints $m(I-A)^{-1}$, and the total footprint per industry, $m(I-A)^{-1}\hat{y}$, respectively. As noted at the presentation of Table 2, all German relative footprints decrease in magnitude with the adoption of French energy technology. The relative footprint of the electricity, gas, steam, and air conditioning supply industry would decrease by 84% for the energy industry. The total footprint of the electricity, gas, steam, and air conditioning supply industry would also decrease by 84%. Practically all other total footprints would reduce as well.

Our results show a clear decrease in the relative and total $CO_2$ footprints in Germany when French energy technology would be adopted. As nuclear power is the largest portion of the French energy mix (roughly 70% of electrical production) and nuclear powers direct $CO_2$ output is negligible, it is fair to say that the phase out of nuclear power in Germany has caused a greater $CO_2$ footprint.

Germany has already decommissioned all of their nuclear power plants. Since 2012, Germany has been investing into more renewable energy production methods but had to increase usage of coal power plants in order to keep up with domestic energy demand (Fraunhofer IEE 2018). This has led to an energy mix where around 35% of power produced comes from coal plants (including both lignite and hard coal) and around 35% renewable energy as of 2018. The renewable energy is not just wind, hydro, and solar power but includes biomass and house waste generators. Biomass power production is facilitated by burning collected waste from mainly the farming industry, while house waste power similarly burns collected waste from individual households. While these methods are renewable due to waste being a byproduct of normal activities, they do not help to reduce GHG emissions. Results from the model support the idea that while renewables may be the future of electrical production, they do not all help with reducing the $CO_2$ footprint or emissions. Nuclear power on the other hand, seems to show a noticeable reduction with $CO_2$ emissions and with the $CO_2$ footprints as well.

The coal industry in Germany is the main culprit into why there is such a vast difference between the total German $CO_2$ footprint before and after adopting French technology. Indeed, Kharecha and Sato (2019) found that coal energy production increased after the events of Fukushima in 2011, which consequently increased preventable emissions. Moving on, the total German energy industry's $CO_2$ footprints are more than nine times as much as the French energy industry $CO_2$ emissions. Despite the fact that Germany and France consume similar amounts of electricity, in 2018, they consumed 536 and 480 TwH, respectively (Statista 2022). Germany consumes only 11% more electricity, but its $CO_2$ footprint is more than 150% higher, as the totals of Table 1 (Germany) and Table 5 show (France).

The total German $CO_2$ footprint would decrease by a whopping 42% when adopting French energy technology.

### Application to Japan

Table 3 (all Japanese) displays the total emissions ($M$), the relative footprints, and the total footprint per industry ($m(I-A)^{-1}\hat{y}$), respectively. Table 4 (with adoption of French energy technology) displays the reductions. All Japanese relative footprints decrease with the adoption of French energy technology, by 86% for the energy industry. The total footprint of the electricity, gas, steam, and air conditioning supply industry would even decrease by 94%. The latter reduction is even more dramatic than for Germany.

An interesting trend is the subtle decreases across other industries when Japan adopts French energy technology. For instance, the food, beverage, and tobacco industry shows a 28% decrease under this new energy scenario. The relative footprint sees a similar trend.

Two of the largest per industry reductions other than the energy sector relative footprints were the accommodation and food service industry, and the arts, entertainment, and recreation industry. The accommodation and food service industry saw a relative footprint decrease of 51%. Similarly, the arts, entertainment, and recreation sector saw decrease 50%.

This effect is seen at a lower level for other industries, but it is most visible when viewing those with larger footprints, as we found for the German economy. This means that as most industries have decreases in their total and relative $CO_2$ footprint, the Japanese economy would have lower relative $CO_2$ emissions if nuclear power technology were utilized similarly to France. In fact, comparison of the totals in Tables 3 and 4 reveals that the Japanese emissions would be reduced by a whopping 45% when adopting French energy technology, even slightly more than we found for Germany.

### Decomposition of footprint changes in emission and technology effects

The changes in the footprints (6) to $\widetilde{m}(I-\widetilde{A})^{-1}$ are due to emission changes, from the German or Japanese coefficients row vectors $m$ to $\widetilde{m}$—featuring the emission coefficient of the French energy—and to technical changes, from the German and Japanese coefficients $A$ to $\widetilde{A}$—featuring the input coefficients of the French energy industry. The change in footprints is given by Eq. (10), where $0 \le \vartheta \le 1$ parametrizes alternative decompositions:

$$\widetilde{m}\left(I-\widetilde{A}\right)^{-1} - m(I-A)^{-1} = (\widetilde{m}-m)[(1-\vartheta)(I-A)^{-1} + \vartheta\left(I-\widetilde{A}\right)^{-1}] + [\vartheta m + (1-\vartheta)\widetilde{m}]\left[\left(I-\widetilde{A}\right)^{-1} - (I-A)^{-1}\right] \tag{10}$$

Decomposition formula (10) consists of two row vectors: the change in $m$, weighted by the average Leontief inverse, and the change in the Leontief inverse, weighted by the average emission coefficients. The two row vectors have to be post-multiplied by final demand. The consequent inner product shows term by term, i.e., industry by industry, the change in the total emissions.

Since the changes in the emission coefficients row vector is limited to the energy industry component, see Eq. (9), the change in the first factor on the right side of Eq. (10) simplifies to $\widetilde{m} - m = (0 \cdots 0 m_{23}^{F} - m_{23} 0 \cdots 0)$. Hence the first term on the right side of Eq. (10) reduces to $m_{23}^{F} - m_{23}$ times the 23rd row of the average Leontief inverse $(1-\vartheta)(I-A)^{-1} + \vartheta\left(I-\widetilde{A}\right)^{-1}$ (before and after the adoption of the French energy technology). This product row vector is the share of the footprint change row vector on the left side, ascribable to the emission coefficients change in the energy industry.

The problem is which weight $\vartheta$ to use. If the changes in the emission and input–output coefficients are infinitesimal, it does not make the difference and the product rule of differentiation decomposes the changes in the footprints as shown now.

Denoting the Leontief inverse by $B = (I-A)^{-1}$ and differentiating $(I-A)B = I$, the product rule yields $-(dA)B + (I-A)dB$. Premultiplying by the Leontief inverse, $dB = B(dA)B$. Hence the row vector of footprints changes by $d(mB) = (dm)B + mdB = (dm)B + mB(dA)B$. The first term is the change in emission coefficients, inflated by the Leontief inverse. The second term is the footprint of the Leontief inflated input coefficients change. The change in input coefficients, $dA$, is inflated twice, namely the post-multiplication by Leontief inverse $B$, and, by taking the footprint, the pre-multiplication by $mB$. Hence, we expect the technology effect to be stronger than the emission effect.

One might integrate the infinitesimal changes from the incumbent (German or Japanese) coefficients to the ones with the French energy coefficients inserted, but the decomposition depends on the path of integration. This dependence manifests itself in the different results when alternative values of $\vartheta$ are chosen. If $\vartheta = 1$, the right side of Eq. (10) reduces to $(\widetilde{m}-m)\left(I-\widetilde{A}\right)^{-1} + m[\left(I-\widetilde{A}\right)^{-1} - (I-A)^{-1}]$, but if $\vartheta = 0$, the right side of Eq. (10) reduces to $(\widetilde{m}-m)(I-A)^{-1} + \widetilde{m}[\left(I-\widetilde{A}\right)^{-1} - (I-A)^{-1}]$.

Mathematically, the problem is that the field of footprints is not conservative, footprints have no potential function. As a compromise we select $\vartheta = ½$ in Eq. (10) but warn the reader that the consequent decomposition is arbitrary in the discrete context of inserting French energy technology in the German and Japanese economies.

Post-multiplication of Eq. (10) (with $\vartheta = ½$) by final demand $y$ decomposes the change in the total emissions (5) into a term with the change in the energy emission coefficients, $m_{23}^F - m_{23}$, weighted by the average Leontief inverse $½(I-A)^{-1} + ½\left(I-\widetilde{A}\right)^{-1}$, and a term $(I-\widetilde{A})^{-1} - (I-A)^{-1}$ due to technical changes, from the German and Japanese coefficients $A$ to $\widetilde{A}$—featuring the input coefficients of the French energy industry, weighted by the average emission coefficients, $½m + ½\widetilde{m}$.

We report these shares of footprint changes for the economy (taking final demand as weights) in Table 6 for Germany and Japan. We find that technical change drives the emission reduction, confirming our theoretical prediction.

## Concluding remarks

Germany and Japan limit nuclear power production not so much for economic or environmental incentives but for political reasons. Although it cannot be determined in all certainty that this is the only reason, it is hard to assess any large benefit from phasing out nuclear for the environment utilizing our model. One of the reasons is, of course, that we have not quantified the downsides of nuclear power, accident, and long-run radiation risks.

The political aspect of nuclear power plays a massive role on why and how Germany decided to phase out the technology (Gensing 2019). This decision was politically motivated, and the model supports this, as no tangible environmental benefit can be seen from phasing out nuclear power when looking at $CO_2$ emissions and footprints. The political debate in Japan also flares up. Additionally, France has been investing in nuclear power since the 1970 s, and it would be impossible for Germany and Japan to reasonably invest that much into any type of infrastructure overnight.

Research looking to expand upon these findings or methods should consider mainly how to simulate the gradual changes that one usually sees with energy mix data. As changes to the energy mix are usually only visible from at least five years or even decades depending on the country. Attempting to somehow show this transition scenario would likely be the best way to approach this problem of immediate transitioning that the model currently has.

This paper shows that the German and Japanese $CO_2$ footprints would shrink at similar rates when the predominantly nuclear French energy technology is adopted. Decomposing the emission reductions in a technology effect and an emission effect, we find that the first effect dominates. The fruitfulness of nuclear power has been shown in the context of greenhouse gas footprints.

## Appendix

**Table 3** Japanese emissions, product footprints and final demand footprints

| Industry | Emissions, $CO_2$ m tons | Footprints, tons per m$ spent | Footprints, $CO_2$ m tons |
|---|---|---|---|
| Agriculture, hunting, forestry | 8.64 | 241.35 | 5.84 |
| Fishing and aquaculture | 4.16 | 454.72 | 1.34 |
| Mining and quarrying, energy producing products | 2.62 | 2,310.25 | − 5.26 |
| Mining and quarrying, non-energy producing products | 0.71 | 403.45 | − 50.92 |
| Mining support service activities | 0.18 | 312.20 | 0.00 |
| Food products, beverages and tobacco | 9.81 | 188.57 | 38.37 |
| Textiles, textile products, leather and footwear | 1.43 | 204.81 | 1.85 |
| Wood and products of wood and cork | 0.50 | 195.52 | − 1.15 |
| Paper products and printing | 12.99 | 355.55 | 2.06 |
| Coke and refined petroleum products | 39.58 | 743.61 | 30.32 |
| Chemical and chemical products | 35.59 | 495.85 | 23.11 |
| Pharmaceuticals, medicinal chemical, botanical products | 14.63 | 369.28 | 9.34 |
| Rubber and plastics products | 1.36 | 241.67 | 9.94 |
| Other non-metallic mineral products | 25.95 | 675.53 | 2.42 |
| Basic metals | 139.58 | 831.17 | 21.56 |
| Fabricated metal products | 1.13 | 349.55 | 1.81 |
| Computer, electronic and optical equipment | 1.58 | 177.51 | 27.11 |
| Electrical equipment | 1.38 | 225.76 | 12.23 |
| Machinery and equipment, nec | 2.80 | 200.09 | 30.81 |
| Motor vehicles, trailers and semi-trailers | 2.67 | 227.28 | 49.81 |
| Other transport equipment | 0.45 | 297.24 | 11.51 |
| Manufacturing nec; repair and installation of machinery | 5.24 | 188.08 | 7.29 |
| Electricity, gas, steam and air conditioning supply | 480.69 | 2,702.13 | 270.77 |
| Water supply; sewerage, waste management | 1.61 | 91.58 | 4.52 |
| Construction | 11.33 | 204.76 | 111.62 |
| Wholesale and retail trade; repair of motor vehicles | 25.90 | 133.52 | 63.45 |
| Land transport and transport via pipelines | 14.17 | 172.00 | 17.47 |
| Water transport | 58.72 | 1,976.18 | 32.33 |
| Air transport | 28.70 | 1,236.84 | 21.49 |
| Warehousing and support activities for transportation | 1.76 | 110.80 | 4.29 |
| Postal and courier activities | 0.55 | 126.39 | 0.33 |
| Accommodation and food service activities | 4.27 | 187.14 | 40.06 |
| Publishing, audiovisual and broadcasting activities | 1.68 | 122.39 | 3.96 |
| Telecommunications | 2.86 | 104.79 | 14.19 |
| IT and other information services | 2.94 | 81.75 | 6.54 |
| Financial and insurance activities | 4.77 | 77.78 | 12.54 |
| Real estate activities | 9.01 | 37.81 | 21.40 |

**Table 3** (continued)

| Industry | Emissions, $CO_2$ m tons | Footprints, tons per m$ spent | Footprints, $CO_2$ m tons |
|---|---|---|---|
| Professional, scientific and technical activities | 6.14 | 101.06 | 10.07 |
| Administrative and support services | 5.79 | 95.12 | 4.31 |
| Public administration and defence | 8.55 | 103.96 | 35.03 |
| Education | 3.07 | 78.46 | 14.38 |
| Human health and social work activities | 8.22 | 108.82 | 58.28 |
| Arts, entertainment and recreation | 2.20 | 181.29 | 11.33 |
| Other service activities | 1.90 | 134.52 | 10.07 |
| Total | 997.82 | | 997.82 |

**Table 4** Japan with French energy technology: Reductions in emissions, product footprints, and final demand footprints

| Industry | Emissions, $CO_2$ m tons | Footprints, tons per m$ spent | Footprints, $CO_2$ m tons |
|---|---|---|---|
| Agriculture, hunting, forestry | 0.54 | 53.02 | 1.28 |
| Fishing and aquaculture | 1.44 | 45.17 | 0.13 |
| Mining and quarrying, energy producing products | 0.67 | 82.67 | − 0.18 |
| Mining and quarrying, non-energy producing products | 0.18 | 113.72 | − 14.35 |
| Mining support service activities | 0.04 | 66.65 | 0.00 |
| Food products, beverages and tobacco | − 4.20 | 53.31 | 10.85 |
| Textiles, textile products, leather and footwear | − 0.29 | 74.61 | 0.68 |
| Wood and products of wood and cork | − 0.54 | 70.43 | − 0.42 |
| Paper products and printing | 2.99 | 114.24 | 0.67 |
| Coke and refined petroleum products | 28.12 | 187.15 | 7.63 |
| Chemical and chemical products | 12.49 | 117.38 | 5.47 |
| Pharmaceuticals, medicinal chemical, botanical products | 3.06 | 61.36 | 1.55 |
| Rubber and plastics products | − 5.44 | 100.46 | 4.13 |
| Other non-metallic mineral products | 9.86 | 69.95 | 0.26 |
| Basic metals | 84.32 | 84.45 | 2.19 |
| Fabricated metal products | − 12.74 | 62.08 | 0.32 |
| Computer, electronic and optical equipment | − 7.60 | 40.93 | 6.25 |
| Electrical equipment | − 7.80 | 56.06 | 3.04 |
| Machinery and equipment, nec | − 21.36 | 37.84 | 5.83 |
| Motor vehicles, trailers and semi-trailers | − 21.49 | 48.50 | 10.63 |
| Other transport equipment | − 3.75 | 65.48 | 2.53 |
| Manufacturing nec; repair and installation of machinery | − 4.97 | 39.19 | 1.52 |
| Electricity, gas, steam and air conditioning supply | 465.15 | 2,335.74 | 253.73 |
| Water supply; sewerage, waste management | − 1.57 | 48.34 | 2.39 |
| Construction | − 31.18 | 38.12 | 20.78 |
| Wholesale and retail trade; repair of motor vehicles | − 26.79 | 48.83 | 23.21 |
| Land transport and transport via pipelines | − 4.22 | 56.27 | 5.71 |
| Water transport | 38.09 | 63.27 | 1.03 |
| Air transport | 20.84 | 80.78 | 1.25 |
| Warehousing and support activities for transportation | − 2.63 | 44.07 | 1.70 |
| Postal and courier activities | − 0.44 | 28.25 | 0.08 |
| Accommodation and food service activities | − 6.76 | 95.36 | 20.41 |
| Publishing, audiovisual and broadcasting activities | − 1.87 | 38.44 | 1.24 |
| Telecommunications | − 2.78 | 37.42 | 5.07 |
| IT and other information services | − 3.57 | 20.39 | 1.63 |
| Financial and insurance activities | − 5.58 | 24.45 | 3.96 |
| Real estate activities | − 5.34 | 12.04 | 6.81 |
| Professional, scientific and technical activities | − 7.68 | 37.28 | 3.71 |
| Administrative and support services | − 4.90 | 31.23 | 1.42 |
| Public administration and defence | − 7.04 | 37.49 | 12.63 |

**Table 4** (continued)

| Industry | Emissions, $CO_2$ m tons | Footprints, tons per m$ spent | Footprints, $CO_2$ m tons |
|---|---|---|---|
| Education | − 3.86 | 36.06 | 6.61 |
| Human health and social work activities | − 17.81 | 37.51 | 20.09 |
| Arts, entertainment and recreation | − 1.75 | 91.42 | 5.71 |
| Other service activities | − 2.73 | 58.19 | 4.36 |
| Total | 453.50 | | 435.51 |

**Table 5** French emissions, product footprints and final demand footprints

| Industry | Emissions, $CO_2$ m tons | Footprints, tons per m$ spent | Footprints, $CO_2$ m tons |
|---|---|---|---|
| Agriculture, hunting, forestry | 11.29 | 279.58 | 12.35 |
| Fishing and aquaculture | 1.03 | 555.44 | 0.37 |
| Mining and quarrying, energy producing products | 1.35 | 5254.24 | − 200.90 |
| Mining and quarrying, non-energy producing products | 0.88 | 375.72 | − 0.28 |
| Mining support service activities | 0.02 | 191.37 | − 0.27 |
| Food products, beverages and tobacco | 8.74 | 213.11 | 25.07 |
| Textiles, textile products, leather and footwear | 0.53 | 153.26 | 1.28 |
| Wood and products of wood and cork | 0.37 | 178.54 | − 0.01 |
| Paper products and printing | 2.26 | 242.31 | 0.71 |
| Coke and refined petroleum products | 6.57 | 3053.91 | 56.07 |
| Chemical and chemical products | 8.29 | 456.22 | 15.69 |
| Pharmaceuticals, medicinal chemical, botanical products | 2.85 | 202.20 | 4.81 |
| Rubber and plastics products | 1.01 | 205.13 | 0.79 |
| Other non-metallic mineral products | 9.48 | 561.76 | 0.26 |
| Basic metals | 25.81 | 1205.14 | 0.04 |
| Fabricated metal products | 0.95 | 269.79 | 1.55 |
| Computer, electronic and optical equipment | 0.48 | 131.82 | 1.04 |
| Electrical equipment | 0.33 | 212.88 | 1.30 |
| Machinery and equipment, nec | 0.70 | 200.57 | 2.41 |
| Motor vehicles, trailers and semi-trailers | 0.64 | 198.48 | 10.93 |
| Other transport equipment | 0.56 | 133.33 | 7.12 |
| Manufacturing nec; repair and installation of machinery | 1.25 | 160.62 | 7.07 |
| Electricity, gas, steam and air conditioning supply | 27.19 | 1098.87 | 51.12 |
| Water supply; sewerage, waste management | 0.86 | 155.56 | 2.07 |
| Construction | 5.97 | 149.27 | 40.39 |
| Wholesale and retail trade; repair of motor vehicles | 11.36 | 106.27 | 27.76 |
| Land transport and transport via pipelines | 14.68 | 340.16 | 15.78 |
| Water transport | 16.51 | 1101.46 | 19.49 |
| Air transport | 23.99 | 1404.33 | 23.42 |
| Warehousing and support activities for transportation | 1.61 | 105.55 | 0.88 |
| Postal and courier activities | 0.23 | 58.01 | 0.09 |
| Accommodation and food service activities | 1.09 | 96.99 | 10.61 |
| Publishing, audiovisual and broadcasting activities | 0.99 | 126.90 | 4.75 |
| Telecommunications | 0.89 | 90.97 | 2.30 |
| IT and other information services | 1.39 | 51.02 | 3.43 |
| Financial and insurance activities | 2.38 | 61.04 | 4.23 |
| Real estate activities | 2.81 | 23.70 | 7.26 |
| Professional, scientific and technical activities | 5.10 | 69.34 | 8.91 |
| Administrative and support services | 3.44 | 65.81 | 2.13 |
| Public administration and defence | 3.44 | 62.30 | 15.25 |
| Education | 1.52 | 45.21 | 6.16 |

**Table 5** (continued)

| Industry | Emissions, $CO_2$ m tons | Footprints, tons per m$ spent | Footprints, $CO_2$ m tons |
|---|---|---|---|
| Human health and social work activities | 2.47 | 44.94 | 12.87 |
| Arts, entertainment and recreation | 1.20 | 110.90 | 5.89 |
| Other service activities | 0.59 | 74.07 | 2.94 |
| Total | 215.08 | | 215.08 |

**Table 6** Decomposition of the German and Japanese footprints changes due to the adoption of French energy emissions and technology

| | Germany | Japan |
|---|---|---|
| Observed | 0.922 | 0.738 |
| Hypothetical | 0.666 | 0.534 |
| Change | – 0.256 | – 0.204 |
| Emission Coefficient Component | 0.003 | 0.099 |
| Input coefficient component | – 0.260 | – 0.303 |

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