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Indirect CO_2 Emission Implications of Energy System Pathways: Linking IO and TIMES Models for the UK

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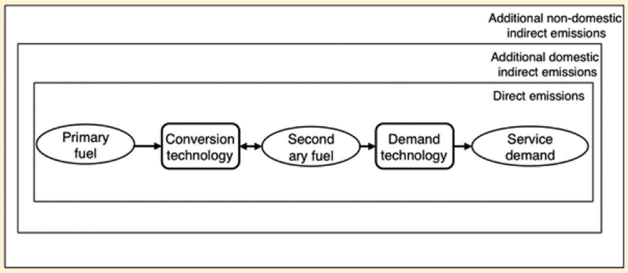
Supporting Information



ABSTRACT: Radical changes to current national energy systems—including energy efficiency and the decarbonization of electricity—will be required in order to meet challenging carbon emission reduction commitments. Technology explicit energy system optimization models (ESOMs) are widely used to define and assess such low-carbon pathways, but these models only account for the emissions associated with energy combustion and either do not account for or do not correctly allocate emissions arising from infrastructure, manufacturing, construction and transport associated with energy technologies and fuels. This paper addresses this shortcoming, through a hybrid approach that estimates the upstream CO_2 emissions across current and future energy technologies for the UK using a multiregional environmentally extended input−output model, and explicitly models the direct and indirect CO_2 emissions of energy supply and infrastructure technologies within a national ESOM (the UK TIMES model). Results indicate the large significance of nondomestic indirect emissions, particularly coming from fossil fuel imports, and finds that the marginal abatement cost of mitigating all emissions associated with UK energy supply is roughly double that of mitigating only direct emissions in 2050.

1. INTRODUCTION

1.1. Background. Global and national climate policies rely on accounting systems that measure carbon dioxide (CO_2) and other greenhouse gas (GHG) emissions at the point of production. For the energy system, emissions are accounted for in the sector or country where fuel is burned, and the lifecycle emissions of goods are not considered. However, up to a quarter of global CO_2 emissions are from the production of exported goods. In the UK, around 50% of consumption-based CO_2 was emitted overseas in 2009, and the gap between production- and consumption-based GHG emissions is rising.[1] This increasing quantity of emissions embedded in traded goods from developing to developed countries is offsetting territorial emissions reductions achieved by countries with commitments to reducing GHG emissions.[2] Developing countries, in particular China and other manufacturing intensive and export dependent economies, are resisting national climate targets based on production emissions.[3]

Well-designed environmental policies should as far as possible internalize all externalities, otherwise a polluter's impact on other actors is not accounted for. The concept of externalities can be applied to globally traded emissions. Net emission importing economies drive more emissions outside their territory than they regulate for. Therefore, in the absence of a global cap on emissions and with large variations between national mitigation ambitions, climate change policy can be undermined.[4,5]

This point is increasingly being recognized in policy and the academic literature: In the UK, the Department of Environment, Food and Rural Affairs (DEFRA) and the Committee on Climate Change (CCC) acknowledge imported and indirect emissions and provide complementary information on the UK's global impact. Looking across the opportunities for emission reduction strategies, imported emissions have been gaining stature in UK climate policy.[1,6,7]

Consumption-based accounting of emissions has not typically focused on energy but materials and trade. Decarbonizing the supply of energy is a necessary step in achieving ambitious climate targets, but energy systems analyses generally focus on direct emissions. All technologies, even those that produce carbon-free energy, have energy and emissions embedded in the production process and material.[8−11] These indirect emissions are relatively modest compared with the impact of combustion in fossil fuel-based systems but will become dominant in very low-carbon scenarios.

The tools to measure indirect emissions are mature. Consumption-based accounting, which attributes GHG emissions to the final end user of a product, rather than at the point at which it is produced, has effectively been used to calculate the global impact of national trade and consumption but has

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not yet been used to look at the indirect impacts of the energy system.[12,13]

This paper addresses this issue and for the first time includes the indirect CO_2 emissions of energy supply in a full energy system analysis. We define indirect emissions as the emissions generated along the energy supply chain up to the point of operation (direct energy combustion emissions are excluded), often referred to as embedded emissions. Our approach soft-links two models, the UK TIMES model (UKTM), a bottom-up energy system optimization model (ESOM) of the UK energy system,[14] and an environmentally extended multiregion input−output (EE-MRIO) model, which calculates the global environmental impact associated with UK economic activity. The approach is applied to a UK case study, which has set out an ambitious target of an 80% reduction in territorial GHG emissions by 2050, based on 1990 levels. By developing a hybrid approach it combines the greater detail of the energy system while capturing the energy system dependencies on the global economy. Using this novel approach, the following five questions are addressed, the first two focusing on inclusion of domestic indirect CO_2 emissions, and the latter three also including nondomestic indirect emissions:

1. What proportion of the UK's 2050 carbon budget is needed to build and maintain an energy system to deliver an 80% reduction on 1990 emissions and to what extent are emissions transferred from the UK industrial sector to the energy supply sector?
2. Should domestic indirect emissions be a determining factor in energy system decarbonization pathways?
3. Which energy supply vectors and technologies are most responsible for (both direct and indirect) indirect emissions?
4. What are the carbon leakage implications of cost-optimal energy system pathways which do not take all indirect emissions into account?
5. Can the UK meet a 2050 target which includes all indirect emissions related to UK energy consumption?

1.2. Literature Review. Bottom-up ESOMs have a long track record of underpinning the analysis of long-term decarbonization policies and targets.[15−18] The TIMES/MARKAL family of ESOMs has been used extensively in research and policy analysis, at country, regional, and global scales.[19−21] An established link between ESOMs and the macroeconomy exists, for example with the MARKAL-MACRO framework.[22−24] A weakness of the approach to date, however, has been a focus on direct impacts of the energy system: In general only emissions from fuel combustion are accounted for, and the impact of an energy system is only considered on the basis of emissions at the point of production, neglecting the global element, which can be termed as externalities in the context of international climate mitigation.

Indirect impacts have been included in systems models to an extent, mainly by assigning a cost to external impacts, for example by adding the external costs of environmental burdens into the ESOM objective function. Several studies use the results of life cycle analysis (LCA) to derive external costs and apply these costs to energy models.[25−29]

Beyond LCA, input−output (IO) analysis, described in the Supporting Information, has also been used to calculate indirect impacts in energy-economy models. Weinzettel et al.[30] created an indicator using electricity trade data from input−output analysis to allocate external costs of electricity production to electricity consumption. While the link between direct emissions and energy-economic models is well-established, the application of indirect emissions to energy technologies and imported fuels to bottom-up energy system optimization analysis has been very limited. Klaassen et al.[37] link an IO model with a MARKAL model, the only other study the authors know of which takes this approach. However, the rationale for doing so is to introduce economic realism to the MARKAL model, rather than representing indirect or lifecycle impacts. A second report, Kypreos et al.,[38] describes a project aiming to integrate lifecycle emissions and external cost data of energy technologies from an LCA database with the Pan-European TIMES model; however, it does not go beyond a theoretical framework for the approach. Vögele et al.[39] uses an IO model to project energy service demands, particularly in the industry and services sectors for a MARKAL model.

The methodologies described above largely use technology-detailed bottom-up energy-economy models. Top-down models have also to a limited extent quantified and internalized indirect impacts.[31]

A further set of LCAs studies,[10,32−36] on the other hand, typically measure the indirect emissions of a process or product, not looking at energy system or economy-wide emissions, with a few exceptions where the wider electricity system is considered.

Applied approaches have mixed bottom-up and top-down models to account for upstream and indirect emissions associated with energy technologies: Wiedmann et al. developed an integrated hybrid model combining bottom-up technology detail with top-down MRIO data to estimate the supply chain impacts of renewable wind energy.[40] This study, however, is the first to apply domestic and international indirect emissions separately to all energy supply and infrastructure technologies in an energy system model.

2. METHODOLOGY

2.1. Overview. To understand how cost-optimal pathways for the UK energy system would change when indirect emissions are internalized, this paper develops a soft link between two UK models: the UK TIMES model (UKTM) and a UK environmentally extended input−output (EE-MRIO) model. Each model and corresponding methodology is described in the Supporting Information.[41−46] The following summarizes the steps followed to achieve a soft link. The rest of this section details these steps.

1. Energy system technologies and fuel inputs in UKTM are associated with an economic sector in the EE-MRIO;
2. The EE-MRIO model generates indirect emission factors (IEFs) associated with the economic output of 224 economic sectors in 2008 for domestic and directly imported sectors separately, distinguishing within those supply chain emissions that occur inside the UK (domestic) and outside the UK and double counting is removed from emission factors where upstream emissions are already accounted for in UKTM;
3. Domestic and RoW (rest-of-world) IEFs for 2010 are calculated for energy system technologies and traded fuels, from tCO_2/m£ to tCO_2/GW on the basis of installed capacity or fuel flow;
4. CO_2 emissions are reduced in the industrial sector to balance the energy system emissions assumed generated (i.e., emissions generated in UK industry to manufacture UK energy system components are transferred from the industry sector to the energy system);
5. Scenarios on the future emissions intensities for domestic and RoW economic activity and the import dependency of the

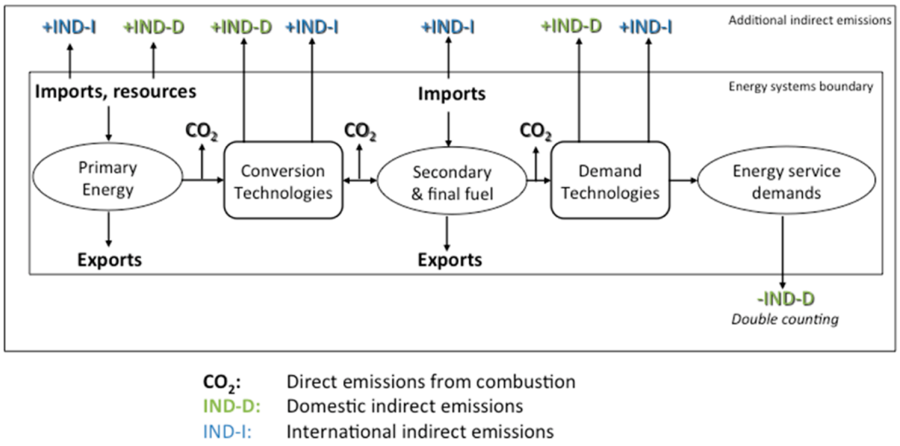

Figure 1. Simplified UKTM energy system with addition (+) and removal (−) of indirect emissions (domestic and international).

UK economy are developed and run through scenarios in UKTM.

Figure 1 describes UKTM's simplified reference energy system and the points at which domestic and nondomestic indirect emissions are added and removed from the system.

2.2. Modeling Scope. Ideally, indirect emissions would be applied to each energy system technology, including end-use, supply, and conversion technologies. This study applies indirect emissions to energy supply and infrastructure and not to end-use technologies (i.e., technologies in the transport, industrial, services, or residential sectors). This is because the economic sectors in the EE-MRIO model do not distinguish in detail between different potential mitigation technologies (e.g., between different car types), and therefore the difference in indirect emissions between such competing technologies is due to the difference in investment costs. Further, because the technology investment cost per energy used in end-use sectors tends to be higher than in supply sectors, including indirect emissions from the demand side dominates overall indirect emissions. The uncertainty in this assumption is therefore considered to be too high to include in the analysis. This leads to an imbalanced portrayal of indirect emissions, giving energy supply technologies a larger mitigation cost: It is therefore not possible to draw conclusions about the consequences of indirect emissions on the optimum level of mitigation from the demand side versus the supply side, and results must be interpreted in this light.

2.3. Model Harmonization. Products in EE-MRIO models are defined by the economic sector which produces them, according to the 2003 Standard Industrial Classification (SIC). The SIC defines 123 sectors, which Wiedmann et al.[40] disaggregated into 224 sectors, including a disaggregation of the electricity sector. 224 sectors are available for both the UK and an average "Rest of World" (RoW) region (giving 448 sectors in total). Considering the millions of different products produced, their aggregation into 448 sectors results in relatively homogeneous sectors and does lead to modeling uncertainty (discussed in section 4.2). However, the method presents a complete system in which full supply chain impacts are captured, and such integration of technology-rich bottom-up data with input−output factors applied to model the background economy has been shown to be desirable over selecting one method or the other.[47,48]

IEFs need to be assigned to each stage of the energy supply chain defined in UKTM. Therefore, we need to align economic sectors (SIC) to the energy system categories: two disparate classifications. UKTM specifies fuels that are directly imported which are assigned a RoW IEF; otherwise the energy system component is aligned to a domestic sector. For each subsystem in UKTM, we selected the SIC sector thought to be most representative (which is subject to interpretation). The detailed allocation of classifications is described in the Supporting Information. Some sectors will not directly correspond to UKTM categories. For example, Natural Gas-fired Combined Cycle CHP plants in UKTM will include the construction, machinery, and equipment in the plant, whereas these are separate categories in the SIC system. While the indirect emission multipliers are not dissimilar within these sectors, we selected a single sector and ensured consistency in the policy for alignment.[49]

Models must be further aligned to remove double counting, which can arise when the IEF for a sector encompasses the entire supply chain of that sector, and UKTM accounts for the upstream emissions separately. The process of removing double counting and an illustration is described in the Supporting Information.

2.4. Calculating IEFs. *Calculating IEFs from EE-MRIO Analysis.* This study employs a two region global input−output model[40] updated to 2008 (the latest data year available at project commencement) to generate indirect emission factors (IEFs). A linear production function relates direct inputs used to produce 1 unit of industries' product output, which when inverted using the Leontief inverse shows the direct and indirect requirements of one unit of industries' output − the total input coefficient. By attaching a direct emission intensity to industry sectors and propagating it through the trade transactions in the MRIO model, the method generates direct and indirect emission factors (IEFs, also referred to as multipliers, coefficients, and factors) measured in terms of emissions per unit of economic output (CO_2/£). These account for the full supply chain emissions embodied in a sector's product (defined by its economic output). An illustration of how IEFs are calculated using the IO model is included in the SI.

Calculating Capacity-Based IEFs for UKTM. The EE-MRIO model calculates emission factors on the basis of economic activity (gCO_2/£) for each economic sector. We convert this for UKTM using the capital cost of technologies in m£ per unit of capacity (MW) divided by the technology lifetime, so that

$$\varepsilon_t = em_{s(t)} \times C_t \div L_t$$

where ε_t is the IEF in $MtCO_2$/MW of technology t, $em_{s(t)}$ is the IEF of the EE-MRIO sector s associated with technology t in $MtCO_2$/m£, and C_t and L_t are the capital cost in m£/MW and the lifetime of technology t (years). The IEF projected forward is also based on the assumed future cost of a technology, so that technologies assumed to decrease in cost over time are also assumed to have lower associated indirect emissions. This implies that indirect emissions from technology capacity are annualized over the lifetime and not applied at the year of installation. Existing technologies are also represented in this way. This approach has some limitations, as most indirect emissions are embedded at the construction phase of building. This approach does however capture the embedded emissions of the existing UK energy system which is modeled.

Fuel Mining and Trading IEFs. Fuel mining and export and import processes in UKTM are modeled on the basis of annual energy flows as opposed to technology capacities, as is the rest of the energy system. IEFs representing annual emissions per unit (£) of output for the equivalent mining or traded sector are multiplied by the cost flow. It is not determined by capacity but is solely based on the cost of the trade flow.

Negative RoW indirect emissions should be applied when running consumption-based emissions accounting scenarios to compensate for the indirect emissions added to UKTM for the manufacturing of exported fuels, which should be counted in the country of consumption. However, no RoW IEFs are applied to the model at the optimization stage, because the indirect emissions associated with exported fuels are dependent on the mixture of inputs to their production and the type of process used to produce each fuel. For example, petrol could be produced from one of three types of refinery, with different associated indirect emissions, and from either imported or domestically mined oil. Similarly, the IEF associated with electricity exports are dependent on the generation mixture, which are an outcome of the model solution. Therefore, it is impossible to calculate the IEF for exported fuels without iterating model results. In order to circumvent this, RoW indirect emissions are calculated posthoc.

2.5. Balancing Domestic Indirect Emissions.

UKTM accounts for all energy related CO_2 emissions and is calibrated to the national emissions inventory for 2010. As our approach adds indirect emissions related to energy system technologies and infrastructure, some of which are emitted from UK industries, a further stage in removing double counting and balancing emissions correctly in UKTM requires the removal of an equivalent level of energy system emissions from the model's industry accounts. In order to calculate the level of direct emissions in UKTM that need to be removed for balancing the model, we calculate base-year domestic indirect emissions and project this amount forward using the average carbon intensity of the industrial sector. This profile varies according to the assumed level of decarbonization of the entire energy system. This is based on the assumption that energy system related emissions are accounted for implicitly in UKTM and are mainly accounted for in the industrial sector.

2.6. Future IEF Trajectories.

The domestic (D) IEF $\varepsilon^D_{s(t)}$ of a technology t in year y in $ktCO_2$/capacity is calculated by the following

$$\varepsilon^D_{t,y} = \phi^D_{s(t)} \times C_{t,y} \times 1/L_t \times \pi^D_{s(t),y} \times i^D_{s(t),y}$$

where

- $s(t)$ is the EEIO model sector applied to technology t;
- $\phi^D_{s(t)}$ is the domestic emission intensity of sector $s(t)$ (the EEIO model sector applied to technology t, adjusted for double counting) in 2010;
- $C_{t,y}$ is the capital cost of technology t in year y;
- L_t is the lifetime of technology t in years;
- $\pi^D_{s(t),y}$ is the proportionate change in the proportion of domestically sourced emissions in sector $s(t)$ compared with the base year;
- $i^D_{s(t),y}$ is the proportionate change in the emissions intensity of sector $s(t)$ compared with the base year. We assume that the intensity change of each MRIO sector is the same for each scenario.

Nondomestic RoW IEFs ($\varepsilon^R_{t,y}$) are generated in a similar way.

IEFs in $ktCO_2$ per capacity unit are applied to all technologies in UKTM's resource, processing, and electricity sectors. A list of technologies, corresponding EEIO model sectors and calculated IEFs, is contained in the Supporting Information.

Projecting Domestic Indirect Intensities. Static input−output coefficients describing technological change can be projected using past trends or expert judgment,[50] with the latter being suggested as more realistic. Domestic indirect emissions in the real world are a function of the emissions intensity of the economy as a whole, with the industrial sector being the most important component. Our approach estimates the future emissions intensity of the UK economy as an output of a UKTM run, depending on scenario assumptions, and therefore to fully endogenize domestic IEFs in UKTM requires either a nonlinear feedback mechanism in the model or an iteration step to ensure that projected domestic IEFs are consistent with the scenario run for UKTM. We take the latter step and project future domestic emissions intensity, $\phi^D_{s(t)}$, based on the industrial sector emissions trajectory of UKTM depending on the scenario in question. Hence, this considers both expert knowledge in-built into UKTM[24] and has a temporal link with the energy system.

Projecting Nondomestic Indirect Intensities. For projecting the future emissions intensity of nondomestic IEFs, we assume a single scenario for the carbon intensity of UK imports, an annual decarbonization rate of 1%, which assumes production efficiencies in the rest of the world progress at the global average of 1% per year. This is within the range referenced in the literature e.g. see ref 51.

Import/Export Split. The share of UK imports is changing constantly. In order to project the changing proportion of imports and exports in each sector, $\pi^D_{s(t),y}$, we project the percentage of each product which will be sourced domestically up to 2050 using recent trends from available annual MRIO tables, available from 2004 to 2008. The exponential growth function is applied to the share of a sector's direct expenditure on domestic compared to imported products to produce its output.

3. RESULTS

This section presents the overall direct and indirect emissions of the energy system under different scenarios and describes the impact of including indirect emissions on the achievement of a scenario which decarbonizes the 2050 UK energy system by 80% on 1990 levels by 2050. Figure 1 in the Supporting Information summarizes the values obtained for indirect emissions by technology and fuel.

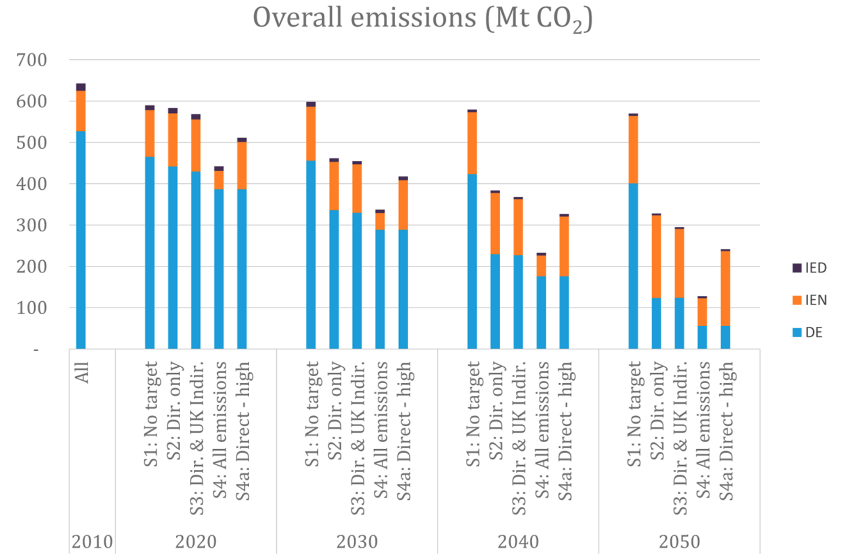

Figure 2. Overall direct emissions (DE), indirect emissions—domestic (IED), and indirect emissions—nondomestic (IEN) between 2010 and 2050 in five scenarios.

Table 1. Marginal Abatement Cost of CO$_2$

	scenario	2020	2025	2030	2035	2040	2045	2050
carbon shadow price (£/tCO$_2$)	*S2*: direct only	131	115	224	207	186	178	173
	S3: direct and domestic indirect	42	60	92	193	194	186	242
	S4: all emissions	298	182	303	221	195	268	566
	S4a: direct only - higher target	338	164	256	230	215	227	555

3.1. Scenario Descriptions. The purpose of modeling indirect emissions within UKTM is to illustrate the consequences of not counting, and of counting, indirect emissions when designing low-carbon energy system trajectories.

To that end, this paper details results for the following scenarios:

S1. No Target: The UK energy system is optimized on the basis of cost, with no emissions constraint. This scenario illustrates the indirect emission consequences of the energy trajectory undertaken in the absence of mitigation policies.

S2. Target—direct only: The UK energy system is optimized on the basis of cost, with total direct CO$_2$ emissions between 2020 and 2050 constrained to meet an 80% reduction target on 1990 by 2050. This is a standard UKTM run to examine mitigation pathways to reaching the 2050 target.

S3. Target — Direct and UK emissions: As above, with domestic indirect emissions included in the target. The purpose of this scenario is to illustrate the difference in mitigation cost and source of emissions when domestic indirect emissions are reallocated from the end-use sectors to the energy sector.

S4. Target — All emissions: As above, with nondomestic indirect emissions also included in the target. This scenario illustrates a consumption-based accounting approach to setting the 2050 mitigation target, with all global emissions associated with the UK energy consumption counted.

S4a. Target—direct only; consumption accounting: The previous scenario includes nondomestic indirect emissions and therefore both extends the boundary of what is counted for the target and changes the composition of the target. This analysis wishes to distinguish between the effects of increasing the burden of the target and of including a different element into the target (indirect emissions). This scenario distinguishes these two effects by imposing a target on direct emissions only, at the level obtained in *S4*, and does not constrain indirect emissions.

Table 3 of the Supporting Information describes the CO$_2$ constraint applied to each scenario.

For each scenario we report the level and source of direct, domestic indirect, and nondomestic indirect emissions and the marginal abatement cost of meeting the 2050 target in *S2*–*S4a*.

3.2. Overall Emissions. Figure 2 displays all emissions resulting from the UK energy system from UKTM run under these scenarios. Domestic indirect emissions (IED) in 2010 are calculated to be 2.7% of overall emissions (17 MtCO$_2$),and fall in the future across all scenarios, both absolutely and as a share of overall emissions. In 2050, with no target in place (*S1*), they account for 0.9% of overall emissions (5.4 Mt). With a target in place this share increases to 1.3%. When accounted for in the target, (*S3*) the level of IED reduces from 4.2 Mt when not accounted for (*S2*) to 3.9 Mt.

Nondomestic indirect emissions (IEN) play a much more significant role: In 2010, 98 Mt of IEN is emitted (15% of overall emissions). With no target in place (*S1*) this rises to 163 Mt (29% of overall emissions) in 2050. With a target in place and not constraining IEN (*S2, S3, S4a*), this level increases to 167–200 Mt, and the share of emissions increases to between 57% and 75% of overall emissions. The scenario with the largest level of IEN is *S2*.

The effect of including indirect emissions in the target is clearly a reduction in their level, as the model seeks to mitigate their impact. Compared with a scenario where only DE are accounted for in the 2050 target (*S2*), including all indirect emissions (*S4*) lowers overall emissions by 61% in 2050. This reduction comes from DE (68 Mt) and IEN (133 Mt), whereas IED rise slightly. The share of indirect emissions is lower when they are accounted for (57% in *S4* compared with 62% in *S2*),

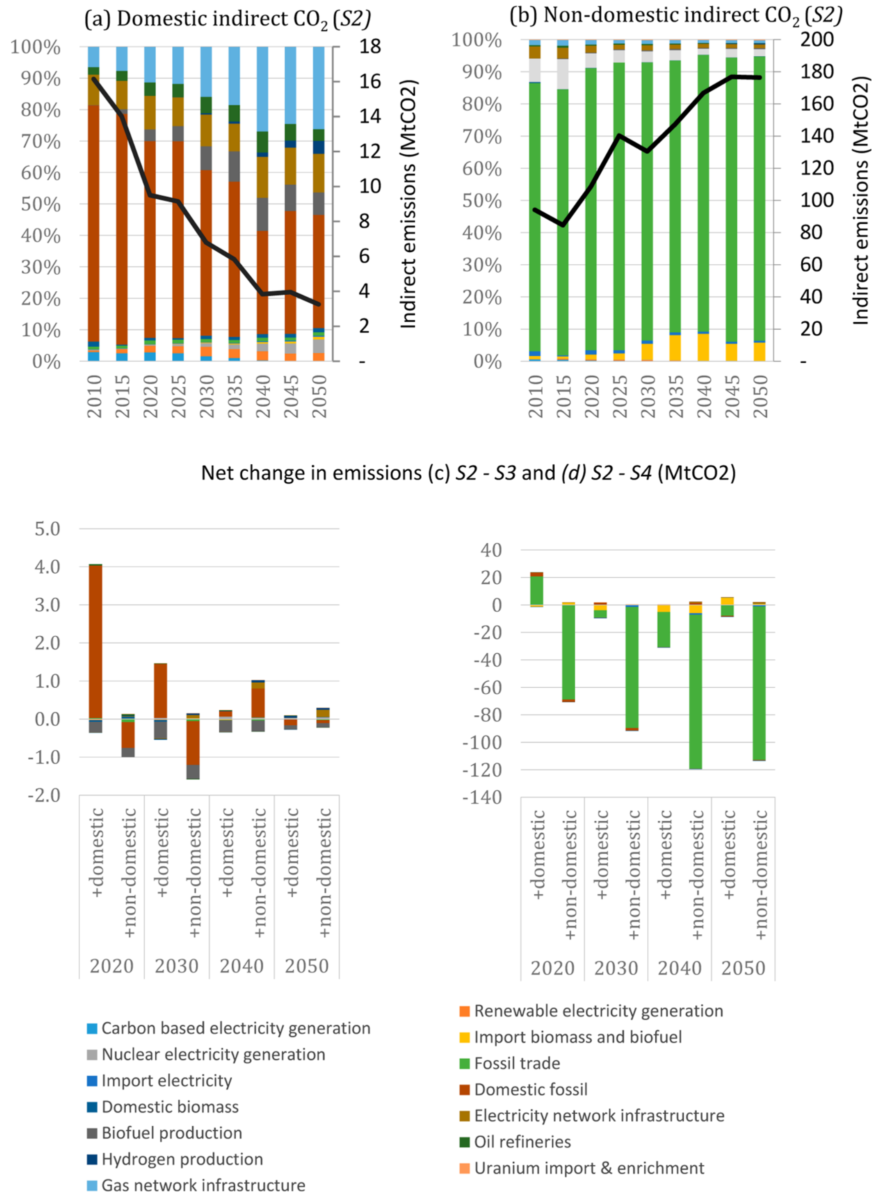

Figure 3. Total domestic and nondomestic indirect emissions (Mt) and share according to source in *S2* and net changes in IEDs and IENs when mitigating for domestic and nondomestic emissions, in *S3* and *S4*, respectively.

suggesting that there are better mitigation options for nondomestic indirect emissions than for direct emissions at that level of abatement.

Scenario *4a* tests what are the additional cost of including nondomestic indirect emissions to the target separately by fixing the target for direct emissions at the level attained in *S4* and optimizing the energy system with no constraint on indirect emissions. Indirect emissions are 2.7 times greater in *S4a* that in *S4*.

3.3. Marginal Abatement Cost. Table 1 shows the shadow price of CO_2, representing the marginal abatement cost (MAC) for each scenario. The MAC rises to 173 £/tCO_2 in 2050 in *S2*, and including the abatement of domestic indirect emissions (*S3*) increases this cost to 242 £/tCO_2; however, it is lower than the cost in *S2* for much of the period up to 2040. Including all indirect emissions in the target (*S3*) increases the abatement significantly to 566 £/tCO_2.

3.4. Sectoral Indirect Emissions. In this subsection we analyze the trend and source of indirect emissions from the energy system when indirect emissions are not taken into account in the 2050 target. We examine which sectors of the energy system account for domestic and nondomestic indirect emissions and how this changes over time across the scenarios.

Figure 3 (a) and (b) show the trend and source of domestic and nondomestic indirect emissions over time, in a scenario where only direct emissions are taken into account in the optimization solution (*S2*). Domestic indirect emissions represent a small share of overall emissions and therefore do not change significantly from one scenario to the next and do not influence the overall level of emissions greatly. Total domestic indirect emissions in this scenario fall by 80% over the period 2010 to 2050, a decrease which is driven by a reduction in indirect emissions from domestic fossil fuel production, which fall by 90% over the period. Gas and electricity network infrastructure together account for 3.1 MtCO_2 in 2010 and 1.74 MtCO_2 in 2050, growing relatively in significance compared with fossil production. The relative significance of imported electricity (which causes domestic indirect emissions mainly via interconnection infrastructure) and biofuel production also grows, but biofuel import, production, and processing are the only categories that grow absolutely over the period.

Figure 3 (b) shows the trend and shares for IEN, which is also dominated by fossil fuels, in this case the indirect emissions from domestic production abroad and imported to the UK. Significantly, nondomestic indirect emissions grow substantially in this scenario, from 94 $MtCO_2$ in 2010 to 176 $MtCO_2$ in 2050. This is caused primarily by an increase in the impact of fossil imports and also the impact of imported biomass and biofuels, which cause 10 $MtCO_2$ to be produced abroad in 2050 for UK consumption.

3.5. Impact of Including Indirect Emissions in Abatement Target. Figure 3 (c) and (d) show the impact on indirect emissions (domestic and nondomestic, respectively) of including them to the target (comparing *S3* and *S4* with *S2*). Including domestic indirect emissions, representing approximately 1% of overall emissions, does not create a large difference in emissions but does cause a reduction in emissions from biofuel production and fossil imports and production. Nondomestic indirect emissions account for a far greater proportion of overall emissions, up to 75% with a 2050 target, when they are not taken into account. The impact of including nondomestic emissions to the target is large, leading to a reduction in nondomestic emissions by 96 $MtCO_2$ in 2050 compared with not abating them. This impact is largely due to a reduction in domestic fossil imports − this is compensated somewhat by increases in domestic fossil imports.

4. DISCUSSION

ESOMs have played an important role in visioning and planning energy system pathways within policy analysis, and indeed UKTM has been undertaken by the UK government for critical carbon budget analysis in 2016,[52] putting it at the forefront of policy-relevant whole-systems tools in the UK. However, ESOMs to date have only minimally addressed the issue of embedded carbon in the energy system, which is sourced both from domestic industry and other end-use sectors and from abroad. Lifecycle emissions analyses show that national carbon footprints vary dramatically depending on the boundary of the analysis, and consumption-based accounting approaches have shown that the UK's apparent success in reducing carbon emissions can be called into question, when counting all emissions associated with UK consumption.

4.1. Research Questions. In concluding, we refer to the research questions posed in the Introduction:

What Proportion of the UK's 2050 Carbon Budget Is Needed To Build and Maintain the Energy System and to What Extent Are Emissions Transferred from the UK Industrial Sector to the Energy Supply Sector? According to the modeling results, domestic indirect emissions are not significant to the UK meeting its 2050 carbon budget, accounting for 1.3% of 2050 CO_2 emissions in a scenario where the UK meets its commitment to reaching 80% GHG reductions on 1990 levels by 2050. Redistributing these emissions from the end-use sectors to the relevant energy technologies and fuels does not significantly alter the cost or level of carbon abatement. The reduction in domestic indirect emissions is due in part to the assumed decarbonization of the industrial sector, and therefore domestic indirect emissions, in the base case. Results suggest that the optimal energy system pathway with no target in place becomes less carbon intensive, particularly when looking at direct and domestic emissions alone.

Should Domestic Indirect Emissions Be a Determining Factor in Energy System Decarbonization Pathways? The model indicates that mitigating domestic indirect emissions is marginal yet chosen by the model as a mitigation option when it is given the option. The average marginal abatement cost of CO_2 reduces when this option is allowed.

Which Energy Supply Vectors and Technologies Are Most Responsible for (Both Domestic and Nondomestic) Indirect Emissions? Despite the decarbonization of the UK energy system in these scenarios, fossil fuels still are predominantly responsible for indirect emissions. While indirect emissions from infrastructure and electricity generation still play a role, the modeling suggests that reducing fossil fuel domestic production and imports are the key potential mechanisms for reducing indirect emissions.

What Are the Carbon Leakage Implications of Cost-Optimal Energy System Pathways Which Do Not Take Indirect Emissions into Account? The cost-optimal pathway resulting from our model runs lead to substantial carbon-leakage. Nondomestic indirect emissions represent a major share of overall emissions, 15% (98 $MtCO_2$) in 2010, which increases in share and magnitude to 61% (200 $MtCO_2$) in 2050, when not abated. The most substantial impact on indirect emissions is in fossil trade and fossil mining.

Can the UK Meet a 2050 Target Which Includes All Indirect Emissions Related to UK Energy Consumption? The UK can meet a 2050 target which includes all indirect emissions related to energy supply are counted. However, the marginal cost of abating all emissions is roughly twice that of only counting domestic emissions.

This paper shows that indirect emissions play an important role in decarbonization pathways, showing strongly the caution that is needed when formulating policies targeting domestic emissions only − global impacts can be highly significant, diluting the impact of a national target. For countries interested in extending the boundaries of emission targets to include those emitted in other countries to serve consumption domestically, these results indicate the scale of the challenge to achieving this target.

4.2. Uncertainties and Sensitivities. This study is the first to combine a technology-rich energy system model and a multiregional IO model to study the indirect emissions associated with future energy system transitions. The methodology is novel and has produced new interesting insights, especially on the implications of taking nondomestic indirect emissions into account in developing national mitigation targets.

The methodological focus of this paper on model soft-linking and harmonization gives four main areas for sensitivity analysis to fully explore the robustness of the findings. First, in balancing the technology-rich detail of the energy system with the aggregated but global coverage of the input−output model − we employed a UK-centric two-region model with the greatest economic sector disaggregation (448 sectors), particularly for energy, available at the time of study. An extension would have a disaggregated RoW region with different country characteristics. This would make a significant difference to the results only if key energy related indirect emissions came predominately from different regions and if these regions still had different emissions characteristics through the model horizon.

Second, sectoral aggregation is a significant source of uncertainty, as sectors with very different carbon intensities inevitably end up being grouped together, which potentially can poorly represent the emissions profile of some sectors. The input−output model employed had disaggregated its economic sectors as much as possible based on Lenzen's[53] recommendation that the disaggregation of economic sectors was preferential to an aggregation to fit with the available environmental data. An uncertainty analysis on further sectoral disaggregation would only make a significant difference to the results if particular energy system components are significantly more impacted by indirect emissions to change the structure of the future energy system itself.[54]

Third: As the EE-MRIO model is static and its outputs are restricted to 2009, we projected forward indirect emission factors based on an assumption that global emissions intensity will decrease by 1% annually, following historical patterns. The future trade balance of UK imports also critically determines the share of domestic and nondomestic indirect emissions, which is projected in this analysis according to historical trends. A sensitivity analysis on this assumption would require an clear underpinning logic − for example, some analysis suggests that the potential for efficiency gains has peaked and overall emissions reductions will need to come from demand-side management.[55] An alternate uncertainty analysis would examine the variation in the indirect emissions of different fuels produced abroad, and an improvement on this approach would be to include biofuels from different sources at different costs and indirect emissions.

Fourthly and last, a further important area for future research is the effect of energy demand. IEFs in this analysis are only applied to energy supply and infrastructure; end-use technologies are omitted, although captured in UKTM. On average one-half of UK consumption emissions are produced abroad, and with manufactured technologies up to 80% is emitted abroad. A sensitivity analysis that included the indirect emissions from energy consuming technologies, such as vehicles and household appliances, will likely strengthen the main conclusion of this paper, that − if they are not mitigated − nondomestic indirect imported emissions play a key role in the costs and characteristics of future national decarbonization pathways.

■ ASSOCIATED CONTENT

Ⓢ Supporting Information

S1 − Modeling context; S2 − Illustration of generation of IEFs and removing double counting; S3 − Domestic IEF emissions intensity trajectories; S4 − CO_2 constraint imposed on each scenario; S5 − Indirect emissions of different technologies and energy vectors; S6 − Calculated IEFs for UKTM technologies (attached spreadsheet); S7 − Detailed allocation of UKTM technologies to SIC classifications (attached spreadsheet). The Supporting Information is available free of charge on the ACS Publications website at DOI: 10.1021/acs.est.5b01020.

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Notes

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