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General equilibrium impact evaluation of food top-up induced by households' renewable power self-supply in 141 regions

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HIGHLIGHTS

- Outputs of electricity and fossil fuel mining sectors decrease in all countries.
- Positive impacts on agriculture and food production occurs in all countries.
- Land prices increase significantly in land-scarce countries.
- Real GDP reduces in countries with less dependence on agriculture.
- GHG emission levels marginally reduce in various countries.

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ABSTRACT

This article employs a global computable general equilibrium economic model (GTAP-E-PowerS) to examine the impact on the world economy if households in every country self-supply power to meet 30–100% of residential demand, with subsequent monetary savings diverted to consuming more food. Results show the power generation sector reduces output levels by 14%–42% across various countries if households 100% self-supply. Coal mining sectors are adversely affected in numerous countries with contractions of 9%–28% ($6,086-$18,935 million) in the United States and 4%–13% ($2,505–$8,143 million) in Australia. Improved outcomes for the world environment are found with reductions of CO_2e emission levels of 2.24%–7.38% (or 924–3,042 $MtCO_2$ equivalent). The agriculture and food-processing sectors expand significantly in many countries but also cause major increases in land prices, particularly in land-scarce countries in Middle East, Europe, Japan, and Taiwan. Results also show the security of food and energy supply are improved along with environmental gains from lower emission levels. However, the energy sector is adversely affected and those countries with a heavy reliance on fossil fuel extraction and mining activities experience significant reductions in real GDP.

1. Introduction

In the context of increasing population and global warming, energy and food shortages represent major concerns faced by various world governments and form key elements of Sustainable Development Goals. There were around 821 million people in various regions experiencing food shortages in 2018. Further, people cannot afford to meet their demand for energy in numerous regions, for example in Ghana [1], the Czech Republic [2] amongst other developing nations [3]. Thus, increasing energy supply with lower costs from renewable resources may become crucial to ensure adequate power for production and living activities. Renewable power also helps to reduce greenhouse gas emissions in order to tackle climate change issues. Simultaneously, improving incomes particularly for the poor is also important to enhance

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their consumption power for foods meeting daily required calories.

In this context, technologies have been developed significantly in recent years resulting in major reductions in costs of utility-scale solar photovoltaics (PV) by 85% in 2010–2020 [4]. The weighted-average levelized cost of energy has reduced substantially from $0.4–$0.5/kWh in 2010 to around $0.1/kWh in 2019 across countries, such as Australia, China, Vietnam, Japan, the United States, and throughout Europe [5]. Solar and wind costs are also expected to continue to reduce by up to ~ 60% by 2025, encouraging strong application of solar home systems on a global scale.[1] Globally, renewable energy accounted for 26% of total power generation in 2018 and is forecasted to have a market share of 45% by 2040.[2] Cost reductions allow the private sector to develop rooftop solar PV systems (and in some instances, battery storage) for their own consumption. As a result, home rooftop solar PV systems have been facilitated in many countries, including Vietnam [6], Bangladesh [7], Uganda [8], Nicaragua [9], South Africa [10], China [11] and many other developing countries [12].

Komatsu, Kaneko, Shrestha and Ghosh [13] identified key determinants of the adoption of rooftop solar PV in Bangladesh, viz. household income levels, ownership of rechargeable storage, consumption of kerosene and the number of mobile phones. Mondal [14] observed solar home systems present significant financial and economic benefits to replace kerosene-based lamps in Bangladesh, while Mondal and Klein [15] indicated lower indoor air pollution due to the replacement of kerosene lamps, along with better and longer light quality - which is beneficial for children to study. Solar home system programs in Zambia were found to improve the quality of lighting, facilitate domestic work and hours of study. Families started to acquire televisions due to greater continuity of supply [16]. Laufer and Schäfer [17] estimated solar home systems also improve energy poverty metrics and living standards more broadly in Sri Lanka due to higher reliability of electricity supply. However, financial limits and relatively small support from the Government of Sri Lanka means installed capacity per household is still underweight relative to optimality - poor households do not have adequate financial resources to replace inoperative equipment. However, solar home systems are estimated to have negative impacts on revenues of industrial power sectors in Europe [18,19] and the United States [20]. Wee [21] estimated that a solar PV system enhances housing prices in Hawaii by 5%. However, studies of solar home systems in developed nations are relatively limited.

The purpose of this article is to examine impacts on the global economy when households are able to self-supply their demand for power at different levels (30%, 50%, 70% and 100% of household demand) and divert the money saved to increase food consumption. This study examines the impacts on 141 country regions around the world following the Global Trade Analysis Project data version 10a [22] by employing GTAP-E-PowerS [23] – a global electricity-detailed computable general equilibrium (CGE) model.

Findings and the methodology in this article offer numerous contributions/novelties to the academic literature vis-à-vis policy design and management practice.

- **Study originality**: In view of the literature, the economy-wide analysis of private energy savings from self-supplied power with a policy objective of increasing food security on a global scale has not, as far as we are aware, previously been conducted, particularly on global scale. Previous studies investigated other aspects of solar home systems such as determinants, challenges, social benefits, and others as outlined previously. The quantitative modelling in this study thus originates the analysis of energy systems on food, overall economies, and other sectors in numerous countries across continents, presenting new insights. The article also examines the impacts on the economies of 141 countries.
- **Sustainable management practice**:
  - Findings contribute to sustainable management of resources because upstream industries (e.g., coal mining, oil and gas extraction, petroleum product manufacturing, and agricultural product manufacturing) may be materially impacted from shifts in demand from power to food, causing affected industries to restructure production and resource exploitation strategies. In energy systems, how labour, capital and natural resources are managed are also impacted as they become crucial to sustainable development goals. Further, in food and agricultural systems, predictions of increasing trends in demand may lead to revised strategic plans for land and water management, along with labour training, investment, and food supply chains.
  - The quantitative modelling also helps to reveal appropriate strategies and international treaties to balance resource and land conversions in sustainable platforms, particularly in developing and forest-rich nations such as Brazil and Asia [24]. This is because global food systems will be affected from increasing food demands from every country. Food trade will be facilitated with increasingly high demand for production in comparatively advantaged countries.
- **New study trend**: The analysis may also create a new study trend through overall settings in hypothesising transfers from energy to food (or other product consumption) on a global scale due to rising levels of renewable power supply at the household level. Future studies may extend the findings from the current quantitative modelling as a benchmark or reference in specific contexts of a country or sub-national region. Down-scale studies would help to refine policy and management practices by combining economic models with electricity-detailed, agriculture-detailed, land-use, or water-resource models. The scenarios were set up based on the fact that current technologies are not yet economical to be applied to, or by, all households in all countries. Deployment also depends on renewable resources available across regions and seasons. But it seems inevitable that the market share of renewable energy resources will rise and be utilised by households across regions given existing technology development rates. It is assumed households in 'lump-sum'[3] increase their power self-supply from low to high levels. While it is not exactly clear how monetary savings from increased power self-supply is likely to be reallocated across different goods and services, it is assumed households use savings for increased food consumption. This phenomenon seems intuitive in low- and middle-income regions, where food poverty or shortages represent a non-trivial problem. Such an assumption may not be representative of relatively wealthy regions. However, the set of scenarios examining savings used for food consumption is worthy of investigation amongst other scenarios conducted in future studies or reports to the United Nations or other relevant bodies.

The balance of this article is organised as follows. Section 2 reviews studies of solar home systems, as well as wind and micro-hydro energies applied by households. Section 3 outlines the modelling approach, the database and scenario design. Section 4 analyses model results, while Section 5 presents policy implications. Concluding remarks follow.

1 https://www.reuters.com/article/us-renewables-cost-idUSKCN0Z10QD

2 https://www.c2es.org/content/renewable-energy/

3 It is also noted that there is only one household group in the model without separation into groups following different categories.

2. Modelling approach

2.1. Model

Country-wide impacts of policies and economic activities are often conducted using computable general equilibrium (CGE) approaches because a CGE model includes interactions of most actors (producers, consumers, exporters, importers, and investors) in an economy. Behaviours of these representative actors are modelled following economic theory, such as cost minimisation and utility maximisation given budget and technology constraints. There are often monetary (income) flows, and goods and services flows between sellers and buyers in a basic CGE model. Financial and capital flows can also be incorporated in a CGE model. In other words, a CGE model represents almost the entire activities of an economy at the sub-national level (e.g., Colorado, California, or New South Wales), country level (e.g., South Africa, Germany, Brazil, Australia, United States), or regional level (e.g., Africa, Southeast Asia, Latin America, or the Rest of the World), or all world countries. Data within a CGE model includes input–output tables showing real data statistics of all income flows of an economy. Such data shows how much each industry pays for input resources and taxes, how much money households receive and use for consumption, taxes and savings, how much tax revenues the government collects and uses for public consumption, amongst other things. All markets (e.g., labour and commodities markets) in a CGE model are initially in equilibrium representing an equilibrium quantity and price in each market. When a policy shock or model change occurs within the model, all model systems will change because they are all connected. All markets will be adjusted with new supply and demand, which in turn produces new equilibrium prices and quantities. Deviations from new and initial equilibrium results shown in a CGE model are expressed in terms of percentage changes or quantity/value changes.

In this article, a multi-country CGE model known as GTAP-E-PowerS [23] is employed to examine how the economies of 141 countries/regions around the world are affected when households are increasingly able to self-supply their power needs, and use the subsequent monetary savings to consume more food. In general, GTAP-E-PowerS possesses the general characteristics of a CGE model described previously. In addition, country economies in GTAP-E-PowerS are linked together via bilateral trade mechanisms. There are also transportation service sectors to transport products domestically and internationally.

Fig. 1 outlines the energy systems in GTAP-E-PowerS. There are three primary energy sectors (coal mining, crude oil extraction, and natural gas extraction), which produce these three energy inputs to other sectors used as energy materials in combustion processes or components to produce other commodities. For example, coal is used as combustion material to produce steel and cement; crude oil is used as a main product in chemical and petroleum manufacturing. Thermal coal, oil, natural gas and petroleum products are also used directly as combustion materials to generate power by households and numerous industries across agriculture, food manufacturing, transportation, manufacturing, and services. These four energy resources are the main inputs to produce electricity in most countries around the world. Fossil-based and renewable-based electricity represent the crucial power supplied to daily activities and manufacturing of most households and industrial sectors. In an economy, each industrial sector also demands intermediate inputs (materials) and primary resources (labour, capital and others) produced by various industrial and private sectors in order to produce their final products. Hence, whenever there are shocks to the supply of, or demand for electricity, supply chains will be affected and their impacts will spread throughout the whole economic system.

Note: Blue arrows indicate raw material flows used in extraction processes to produce main products, not used as energy materials for combustion. Red arrows indicate energy material flows used in combustion processes to produce electricity. Green arrows refer to energy supply flows, including electricity and raw energy materials used in combustion processes.

Fig. 2 shows how foodstuffs are supplied to households and industrial sectors. Agricultural sectors produce raw materials (animals, raw milk, sugar cane, paddy rice, etc.) for food processing and packing sectors in order to produce final products supplying markets, which are consumed by households and industrial sectors. Transportation, recreation, and accommodation industries, for example, consume foods to serve their customers. Agricultural sectors also supply their products directly to households and industrial sectors without going through intermediate sectors (i.e., food processing and packing sectors). Households can buy wheat directly from farms. Agriculture and food sectors also demand various inputs from other industries and households in their production processes. Hence, once supply or demand for these agriculture and food sectors are affected, other sectors are also influenced because supply and

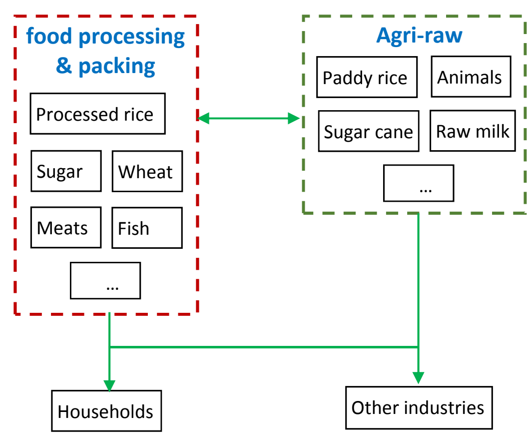

Fig. 2. Agriculture and food systems in GTAP-E-PowerS.

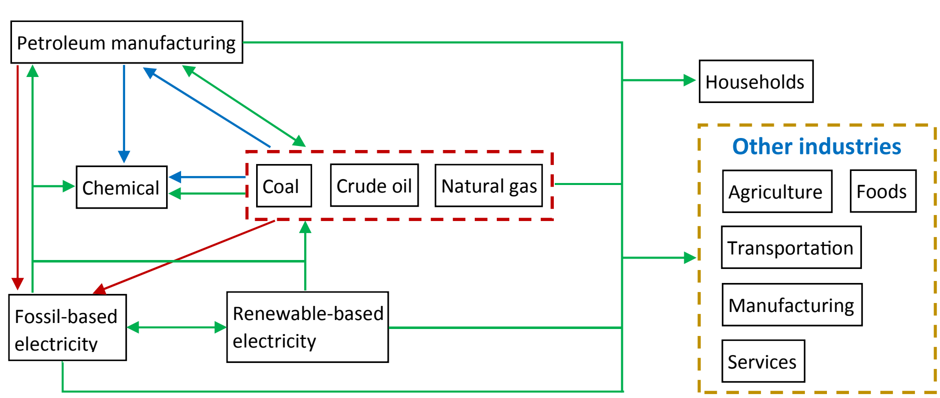

Fig. 1. Energy systems in GTAP-E-PowerS.

demand for their products, along with associated prices, change.

In the level form, transfers from power self-supply to food consumption in the private sector are outlined in Eqs. (1) and (2).

$$V_{ele} = VELE_I * (1 - \alpha) \quad (1)$$

$$V_{food} = VFOOD_I + VELE_I * \alpha \quad (2)$$

Where V_{ele} is the value of the private post-demand for electricity from industrial sectors (generators), $VELE_I$ is the value of the private pre-demand for electricity from industrial sectors, α is the ratio of power saving resulted from power self-supply, V_{food} is the value of the private post-demand for food, and $VFOOD_I$ is the value of the private post-demand for food. It is noted that since the activities are considered in the long term, installation costs are ignored. Maintenance costs are also excluded to simplify the calculation.

2.2. Data and scenario design

The GTAP-Power data version 10 with the 2014 base year is employed, which represents the latest dataset available [22]. This includes the world input–output tables of data from 141 countries/regions across the world. Since the following analysis seeks to examine impacts at a global scale, all 141 countries/regions are maintained within model calculations. There are 76 industrial sectors within the data, which are aggregated into 23 key sectors. Table 1 shows how households in countries around the world consume food, electricity, and all commodities, as well as shares of these consumption baskets in 2014. In general, budget shares for electricity by households were relatively small compared to consumption of food in all countries. Electricity supply accounted for 1–3% (on average) of total consumption in numerous countries, but the shares for food are very high in most countries, i.e., more than 10% and up to 59%. Various countries show food accounted for more than 30% of total consumption, such as Bangladesh (43.5%), Belarus (32.5%), Azerbaijan (30.7%), Morocco (36.9%), Benin (52.1%), Cameroon, (36.5%), Côte d'Ivoire (33.7%), Ghana (44.8%), Nigeria (58.7%), Senegal (38.7%), Togo (37.4%), Ethiopia (42.7%), Kenya (44%), Mozambique (37.5%), Tanzania (41.2%), Uganda (33.8%), and Zambia (49.6%). In line with a classic Engels Curve, this suggests households in low-income countries spend proportionally more of their incomes on food. Shares of electricity (on average) in these countries were relatively small owing to few electric appliances in low-income households. Globally, household consumption of electricity accounted for 2% of income (on average, noting that the pattern of electricity consumption may also typically follow an Engels Curve – see [25,26], while the share for food was 10.7%).

As noted earlier, in this article four scenarios are examined with households in all countries reducing their demand for grid-supplied electricity by 30%, 50%, 70%, and 100% as a result of self-supplied power via rooftop applications and other renewable energy resources, with savings used to consume more foods.

3. Result analysis

In this section results from 40 countries, which are the main economies in continents around the world, are reported. Results related to all 141 countries and regions are provided in the Supplement.

3.1. Impacts on electricity and fossil fuel mining and extraction sectors

When households are able to self-generate electricity used for their activities, they will reduce grid-supplied power demand produced by utility sectors. Depending on shares of power consumption by

Table 1
Households' consumption of food, electricity and all commodities in 2014 in selected countries (US$ billion). Note: Elec = Electricity; Total = consumption of all commodities; SoF = Share of food consumption relative to consumption of all commodities; SoE = Share of electricity consumption relative to consumption of all commodities.

Country	Food	Elec	Total	SoF	SoE	Country	Food	Elec	Total	SoF	SoE
Australia	44.1	11.8	789.0	5.6%	1.5%	Norway	21.2	4.5	217.6	9.7%	2.1%
China	735.1	78.8	3937.6	18.7%	2.0%	Belarus	15.7	3.9	48.4	32.5%	8.0%
Japan	192.4	64.5	2706.4	7.1%	2.4%	Romania	21.7	4.3	124.5	17.4%	3.4%
Indonesia	100.7	6.3	511.5	19.7%	1.2%	Russia	184.8	55.7	1081.1	17.1%	5.1%
Philippines	61.8	3.4	221.4	27.9%	1.5%	Ukraine	16.2	10.2	91.3	17.8%	11.1%
Vietnam	35.6	3.5	147.4	24.1%	2.4%	Kazakhstan	13.3	3.0	127.0	10.5%	2.4%
Bangladesh	54.5	2.6	125.3	43.5%	2.1%	Oman	1.7	1.1	26.4	6.6%	4.3%
India	207.1	38.3	1234.9	16.8%	3.1%	Iran	51.4	7.5	239.5	21.5%	3.1%
Pakistan	45.5	7.6	208.4	21.9%	3.7%	Israel	20.9	2.8	180.4	11.6%	1.5%
Canada	62.9	16.3	1025.1	6.1%	1.6%	Saudi Arabia	26.8	19.3	234.4	11.4%	8.2%
USA	542.4	155.1	11984.6	4.5%	1.3%	Turkey	70.9	8.6	566.5	12.5%	1.5%
Mexico	121.6	7.9	894.2	13.6%	0.9%	UAE	15.1	4.7	252.6	6.0%	1.9%
Argentina	35.7	5.2	360.6	9.9%	1.4%	Egypt	58.5	4.6	259.5	22.6%	1.8%
Brazil	177.4	26.7	1509.5	11.8%	1.8%	Morocco	25.5	1.9	69.1	36.9%	2.7%
Chile	18.9	1.8	165.1	11.4%	1.1%	Tunisia	7.0	0.6	34.7	20.1%	1.7%
Colombia	28.3	5.6	223.9	12.7%	2.5%	Benin	5.7	0.1	10.9	52.1%	0.5%
Peru	26.6	1.1	128.9	20.7%	0.8%	Cameroon	8.8	0.2	24.0	36.5%	1.0%
Venezuela	44.6	0.6	291.9	15.3%	0.2%	Oman	8.0	0.4	23.9	33.7%	1.6%
Dominican	10.1	1.0	47.7	21.3%	2.1%	Ghana	11.6	0.7	26.0	44.8%	2.5%
Caribbean	12.7	3.9	84.1	15.0%	4.7%	Nigeria	244.0	1.2	415.5	58.7%	0.3%
Belgium	30.4	3.7	306.5	9.9%	1.2%	Senegal	5.3	0.3	13.6	38.7%	1.9%
Denmark	11.8	11.3	172.9	6.8%	6.5%	Togo	1.8	0.0	4.9	37.4%	0.7%
Finland	12.0	6.9	147.7	8.1%	4.7%	Ethiopia	15.8	0.2	36.9	42.7%	0.6%
France	146.3	33.3	1618.9	9.0%	2.1%	Kenya	22.2	0.5	50.4	44.0%	1.0%
Germany	157.4	60.5	2128.4	7.4%	2.8%	Madagascar	2.4	0.1	8.3	28.8%	0.8%
Italy	100.7	21.9	1336.1	7.5%	1.6%	Mozambique	4.0	0.3	10.7	37.4%	2.8%
Netherlands	29.6	5.1	407.7	7.3%	1.2%	Tanzania	13.1	0.4	31.7	41.2%	1.2%
Poland	42.7	12.2	339.9	12.6%	3.6%	Uganda	6.0	0.2	17.8	33.8%	1.0%
Portugal	15.9	3.7	156.5	10.2%	2.4%	Zambia	6.7	0.7	13.6	49.6%	4.9%
Spain	72.7	20.1	830.8	8.8%	2.4%	Zimbabwe	2.4	0.6	11.3	21.0%	5.0%
Sweden	23.2	12.7	263.7	8.8%	4.8%	Namibia	1.4	0.0	8.5	16.8%	0.0%
UK	96.5	24.5	2001.6	4.8%	1.2%	South Africa	28.9	2.9	208.4	13.9%	1.4%
Switzerland	24.3	3.3	405.0	6.0%	0.8%	World	4852.4	917.9	45525.1	10.7%	2.0%

Source: Aguiar, et al. [22].

households in each country, the electricity generation sector will be impacted differently. In principle, when demand for grid-supplied electricity falls, price reductions will follow as the electricity generation sector reduces output, and consequentially, so too will inputs used in production processes be reduced.

Fig. 3 shows how the coal-fired power sector reduces output levels in each scenario across the 40 countries given differing levels of household power production (i.e., by 30%–100% across scenarios). The rates of

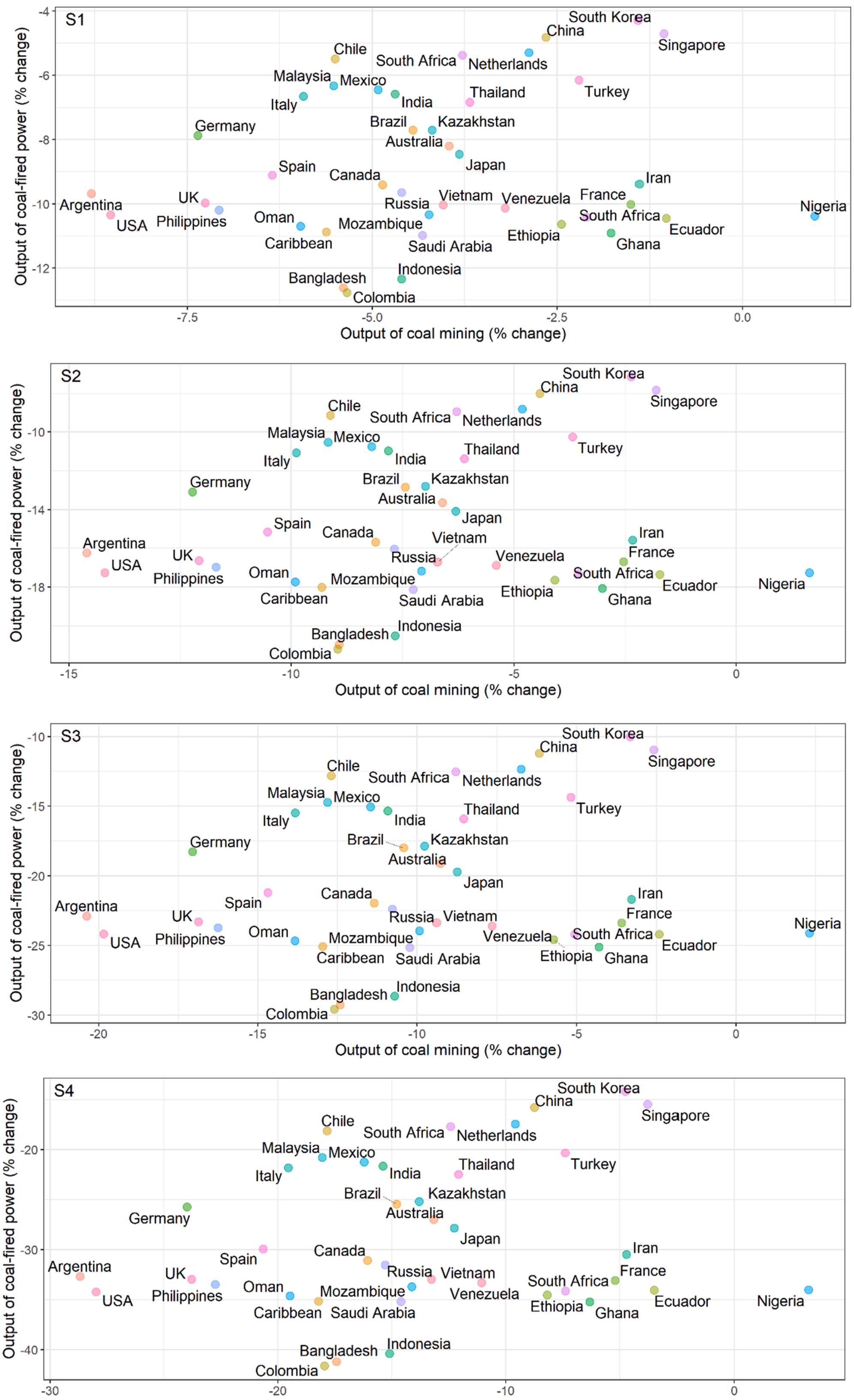

Fig. 3. Impact on output of coal-fired power and coal mining sectors in the 40 countries (% change). Notes: Scenario S1: households reduce demands for industrial electricity by 30% and use for food consumption; Scenario S2: households reduce demands for industrial electricity by 50% and use for food consumption; Scenario S3: households reduce demands for industrial electricity by 70% and use for food consumption; Scenario S4: households reduce demands for industrial electricity by 100% and use for food consumption.

output reduction become more pronounced as self-supply by households increases (e.g., by 4%–13% in S1, 8%–23% in S2, 10%–29% in S3, and 14%–42% in S4). Countries that experience massive utility-scale power reductions include the United States, the Philippines, Vietnam, Venezuela, South Africa, Ghana, Nigeria, Ethiopia, Ecuador, Bangladesh, Indonesia, and Colombia. In all scenarios, Bangladesh, Indonesia, and Colombia experience the highest reduction rates in the output levels of coal-fired electricity (e.g., by 40%–42% in S4). These

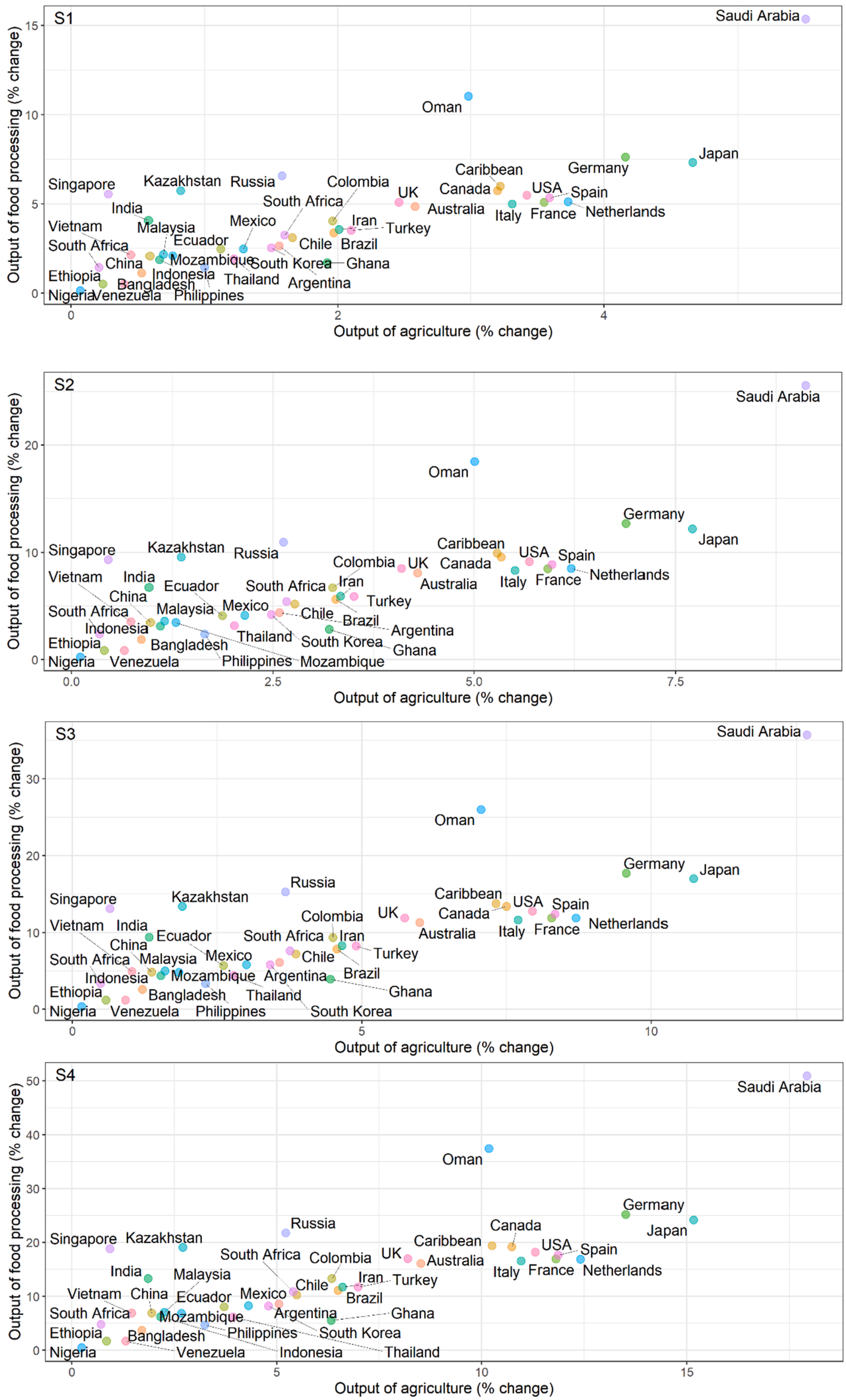

Fig. 4. Impact on output of agriculture and food processing sectors in the 40 countries across scenarios (% change).

outcomes arise due to higher shares of electricity demand by households relative to total electricity demand across all sectors (industries plus households). In particular, coal-fired electricity demand shares by households account for 38% ($44 million) in Bangladesh, 39% ($1,448 million) in Indonesia, and 46% ($264 million) in Colombia relative to total coal-fired power demand by all industrial and household sectors [22]. As a result, when households' electricity demand reduces (or disappears), the coal-fired power sector in these countries is adversely affected.

Fig. 3 also shows how output levels from the coal mining sector declines across the 40 countries following reductions in coal-fired power generation. It is worth noting that shocks are carried out at a global scale; hence, the coal mining sector faces not only substantial demand reductions from the coal-fired power generation sector in domestic markets, but also from trading partner countries. Moreover, many other sectors use coal to produce their output commodities. Consequently, impacts on output levels in the coal mining sector are not necessarily linear.

In all scenarios, the top five reduction rates by output levels in the coal mining sector in each scenario are Argentina, the United States, Germany, the United Kingdom, and the Philippines, viz. output levels of the coal mining sector in Argentina reduce by 9%–29% ($0.8–$2.7 million), 9%–28% ($6,086-$18,935 million) in the United States, 7%–24% ($793–$2,720 million) in Germany, 7%–24% ($96–$330 million) in the United Kingdom, and 7%–23% ($39–$128 million) in the Philippines. Australia, one of the largest producers of coal with a total output value of $62,638 million in 2014, will reduce its coal mining output by 4%–13% ($2,505–$8,143 million). In considering Australia, coal from Australia is exported to Japan ($16,494 million), China ($13,087 million), South Korea ($8,400 million), India ($7,560 million), Taiwan ($3,954 million), and Malaysia ($751 million) in 2014. Coal-fired power generation in these countries will contract at relatively small rates across scenarios compared to reduction rates in certain other countries (Fig. 3). Hence, negative impacts on the coal mining sector in Australia are comparatively moderate. It is noted that the coal-fired power sector in Nigeria does not exist (as also shown in the database). A tiny value (i.e., 0.00001) is assigned in the database for such a sector to enable tractable simulation runs (i.e., to avoid 'divide by zero' errors). It should be noted that the output value of the coal mining sector was only $5 million, a trivial number compared to the output value of the oil and gas extraction sector (i.e., $91,000 million).

3.2. Impacts on agriculture and food production

Transfer of private budgets from energy to food consumption will, all things being equal, increase demand for food and drive an expansion across food processing sectors. That is, increased demand for foods initially boosts the prices of foods, which will result in higher profits for producers. Given higher profit potentials, producers will expand their production to acquire higher revenues [27]. In the model, when demand increases, it will induce increases in supply and move the market to a new equilibrium with the new equilibrium price. It is noted that in this study food commodities/sectors are aggregated into one commodity/sector only; hence, there is no substitution across various food commodities. As a result, the aggregated food output level only increases. Fig. 4 shows the food processing sector experiencing significant increases in output across many countries. The top five countries across scenarios include Saudi Arabia (15%–51% or $3,271–$11,122 million), Oman (11%–37% or $221–$742 million), Germany (8%–25% or $17,259–$53,934 million), Japan (7%–24% or $19,078–$65,411 million), and Russia (7%–22% or $17,806–$55,961 million). Certain countries experience higher expansions in food processing for two primary reasons. First, shares of electricity consumption by households are relatively higher. For example, the electricity share of consumption is 8.2% in Saudi Arabia, 5.1% in Russia, 4.3% in Oman, 2.8% in Germany, and 2.4% in Japan (Table 1). This indicates when transferring part or all of savings (across scenarios) from consumption of electricity to food will drive total food consumption by households in these countries. Second, the share of food consumption by households (relative to total food consumption by all industrial and household sectors) are relatively high in most countries. In particular, these shares are 74% in Saudi Arabia, 57% in Russia, 60% in Oman, 62% in Germany, and 60% in Japan. As a result, increased food consumption from households can be expected to boost food-processing sector capacity.

The expansion of food processing sectors will drive further development of the agricultural sector (Fig. 4), which supplies the primary inputs to the food processing sector. Expansion of agricultural sectors in all countries is relatively small by comparison to the food processing sector. This is because food processing sector demand includes agricultural commodities as well as transportation and other services sectors, which consume agricultural products. However, there is no significant demand increase for agricultural products arising from the non-food processing sectors. Countries with the highest expansion in relative terms are Saudi Arabia (6%–18% or $278–$835 million), Japan (5%–15% or $2,516–$7,584 million), Germany (4%–14% or $1,804–$6,315 million), the Netherlands (4%–12% or $943–$2,829 million), Spain (4%–12% or $935–$2,806 million), France (4%–12% or $1,695–$5,085 million), and the United States (3%–11% or $6,877–$25,217 million).

3.3. Impact on land resources

The expansion of agricultural and food processing increases demand for key inputs, particularly land resources. Depending on land scarcity and agricultural production growth, rising demand for land drives prices differentially across countries and scenarios. Fig. 5 shows how the price of land increases across world countries in each scenario. In general, land prices in all countries increase at higher rates from Scenario S1 to Scenario S4 because of rising agricultural sector expansion. Land-scarce countries in Middle East, Europe, Japan, and Taiwan face substantial price increases compared to other countries. The top five countries vis-à-vis land price increases include Kuwait (from 28% to 100% in S1–S4), Saudi Arabia (from 20% to 71% in S1–S4), Denmark (from 18% to 66% in S1–S4), Japan (from 16% to 63% in S1–S4) and Bahrain (from 18% to 62% in S1–S4).

Land-rich countries such as Brazil, China, Australia, the United States, and Russia experience only moderate land price increases. For instance, the price of land increases by 7%–23% in Brazil, 3%–12% in China, 8%–28% in Australia, 9%–30% in the United States, and 8%–28% in Russia.

3.4. Impact on households

Power production at the household level enables monetary savings to be redirected to food consumption. However, these activities not only tie energy and food markets but also spread to other markets. Production levels of electricity generation, fossil fuel mining and extraction, agriculture and food processing sectors are materially affected, changing their output prices and demand for other inputs and services such as transportation and manufacturing products. In other words, demand for, and supply of, all commodities in every market will change, causing output supply prices of all commodities to change. Specifically, energy prices will decline due to lower (utility-scale) demand, and prices of agriculture and food commodities will increase because of higher demand.

Demand contractions within the utility-scale energy sector reduce demand for intermediate inputs. Conversely, the agriculture and food processing sector expansions enhance demand for inputs (all commodities in all relevant markets), increasing the prices of these commodities. Depending on the market shares and cost shares of energy, production in agriculture and food processing sectors (including adjacent sectors such as services and manufacturing products) will change. In most countries, energy sectors are major actors so that changes in their demand will

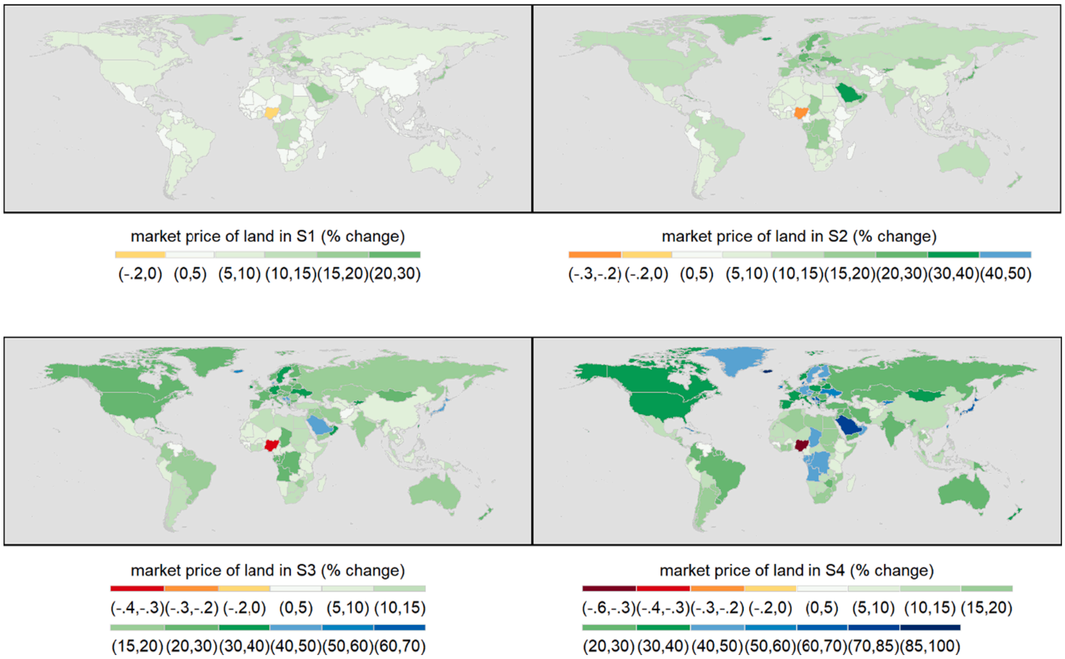

Fig. 5. Impact on the market price of land (% change).

impact prices of all other commodities. Thus, the price of non-energy and agriculture-food commodities will decline in many countries around the world.

Fig. 6 shows consumer price index (CPI) results for 40 countries across the scenarios. It is notable that CPI increases slightly across scenarios in many agricultural-based economies, including Ethiopia, Ghana, Brazil, Chile, Argentina, Ecuador, India, Vietnam, Bangladesh, and the Philippines. This is because agriculture and food commodity prices increase significantly in these countries, and outweigh price reductions in the energy sector. Indeed, many countries experience slight CPI decreases because agriculture and food commodities prices increase modestly, while the price of energy and other commodities decline at relatively higher rates. However, in all scenarios, the overall price index changes only slightly.

Fig. 6 shows aggregate demand impacts by households across the 40 countries over the four scenarios. In general, consumption of electricity is transferred to food consumption; hence, the combined electricity and food consumption levels in each country can be considered largely constant. However, agricultural commodity prices increase significantly, which results in the contraction of demand by households for these commodities. Although household demand for non-electricity services and other manufacturing product commodities increases marginally (i.e., due to lower prices of these commodities), changes are not sufficient to offset major reductions in aggregate demand by households for agricultural commodities. As a result, aggregate final consumption levels by households decline in most countries across scenarios. The top five countries that experience major reductions in aggregate final consumption by households include Oman (from −1.03% to −3.37% in S1-S4), Saudi Arabia (from −0.91% to −2.94% in S1-S4), Mozambique (from −0.87% to −2.82% in S1-S4), Iran (from −0.76% to −2.50% in S1-S4), and Colombia (from −0.69% to −2.24% in S1-S4). Some countries such as Turkey, the Netherlands, Argentina, and Ecuador, however, experience small increases in aggregate private final consumption due to relatively small impacts on demand for agricultural commodities, while relatively larger positive impacts on demand for non-electricity and services commodities can be seen.

3.5. *Impact on overall economic performance and emission levels*

It is evident that energy, services and manufacturing sectors are major sectors in most countries with much higher market shares compared to the shares for agriculture and food processing sectors. Hence, negative impacts on the performance of energy sectors, and consequently on services and manufacturing sectors through demand reactions, downgrade most economies. This is because expansion of agriculture and food sectors is not adequate to compensate for losses in the other sectors. Results show that countries with revenues primarily derived from fossil fuel extraction and mining activities experience material losses in real GDP (Fig. 7). For example, Brunei experiences contractions in the real GDP by 0.97%–3.40% ($166–$582 million) over the four scenarios, 0.73%–2.55% ($1,189–$2,867 million) in Kuwait, and 0.69%–2.32% ($1,144–$4,870 million) in Qatar. Other countries with major negative impacts on energy, services and manufacturing sectors will also experience notable declines in real GDP. Kyrgyzstan experiences the highest rates of reduction vis-à-vis real GDP across scenarios by 2.41%–7.84% ($180–$586 million), followed by Albania with 1.33%–4.40% ($176–$584 million), and 0.99%–3.32% ($563–$1,881 million) in Bulgaria.

Major economies such as the United States, China, Germany, France, the United Kingdom, and Australia experience only moderate contractions in real GDP due to the diversified nature of their exposures. In particular, real GDP declines by 0.08%–0.25% ($13,036–$42,864 million) in the United States, 0.14%–0.49% ($14,734–$50,366 million) in China, 0.33%–1.09% ($12,764–$42,323 million) in Germany, 0.13%–0.42% ($3,624–$12,003 million) in France, 0.04%–0.15% ($1,251–$4,351 million) in the United Kingdom, and by 0.17%–0.55% ($2,406–$7,946 million) in Australia. Small negative impacts in real GDP in these countries are evident in their energy, services and manufacturing sectors.

Some countries experience small increases in real GDP. Jordan, for example, experiences the highest increase in real GDP, by 0.29%–0.87% ($102–$313 million) because services sectors with slight expansions are major sectors relative to energy sectors. Agriculture and food processing sectors, which account for major shares compared to energy sectors, also gain material expansions. Other countries with positive changes in real GDP follow similar patterns and include Turkey with 0.18%–0.57%

Fig. 6. Impact on the consumer price index and aggregate private consumption in the 40 countries across scenarios (% change).

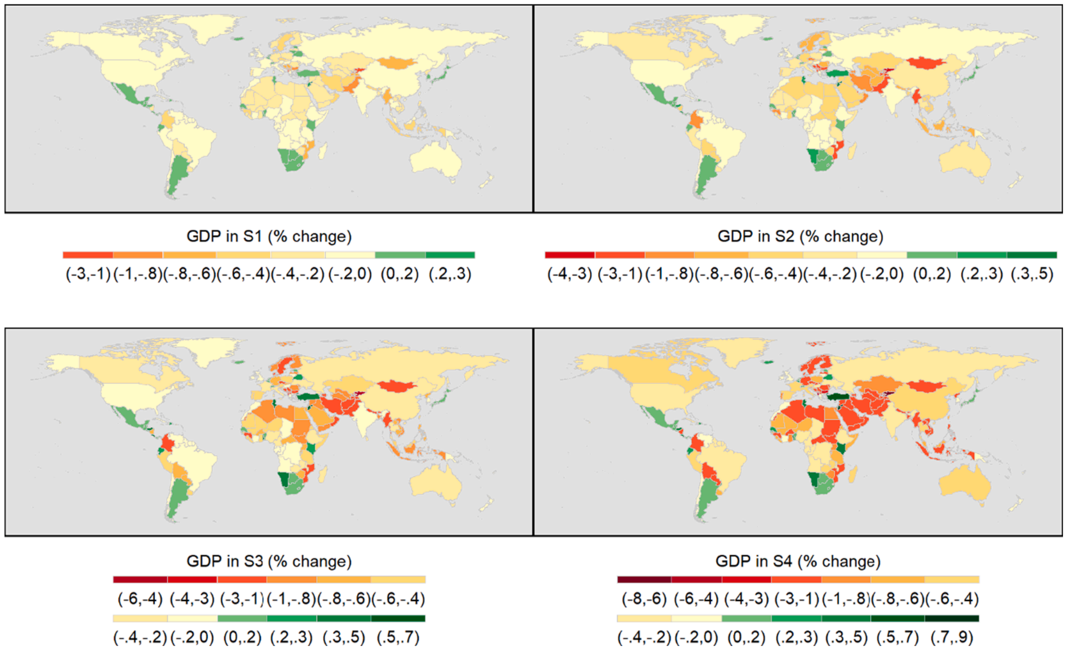

Fig. 7. Impact on real GDP (% change).

($1,407–$4,547 million), Tunisia 0.15%–0.49% ($73–$231 million), Namibia 0.14%–0.45% ($17–$58 million), and other countries in Africa and central America (e.g., Costa Rica, Togo, Honduras, Kenya, Belarus, Dominican Republic, and Senegal). These positively-impacted countries have major shares of agriculture, food and services sectors relative to their energy sector; hence, expansions in these non-energy sectors boost the growths of these economies.

Fig. 8 shows impacts on real GDP, GHG emissions levels, and welfare measured in terms of equivalent variation in the 40 countries. Impacts on welfare follow the patterns of impacts on real GDP. Since welfare is measured in terms of dollar values, the magnitude of impacts depends on the relative size of economies. Turkey shows the highest increases in economic welfare, at $1,832–$6,002 million because of positive changes in the structure of the economy and size of the economy, followed by Japan at $1,846–$4,707 million, India $959–$2,344 million, Argentina $726–$2,321 million, and South Korea $728–$2,085 million. The top five countries with the highest economic welfare reductions are Germany ($11,791–$39,158 million), China ($10,468–$35,925 million), the United States ($7,593–$24,993 million), Russia ($4,335–$15,254 million), and Saudi Arabia ($3,868–$13,449 million) due to contractions in their economies.

Transfers from energy consumption to food consumption due to household self-supply, however, exhibit positive impacts on the environment with less GHG emissions released into the atmosphere. Global CO_2e emission levels reduce by 2.24% (924 $MtCO_2e$) in S1, 3.73% (1,539 $MtCO_2e$) in S2, 5.22% (2,153 $MtCO_2e$) in S3, and 7.38% (3,042 $MtCO_2e$) in S4. Such reductions in emissions arise from reduced fossil-based power generation and energy mining and extraction sectors.

Many countries also experience high emission abatement due to contractions in their energy sectors, leading to lower emissions from fossil fuel combustion. Saudi Arabia experiences the highest emission abatements of 5.45%–17.91% (31–101 $MtCO_2e$), followed by Russia 4.00%–13.14% (76–248 $MtCO_2e$), Japan 3.29%–10.92% (37–122 $MtCO_2e$), the United States 3.23%–10.66% (199–656 $MtCO_2e$), Indonesia 3.11%–10.19% (25–82 $MtCO_2e$), and Oman 2.86%–9.33% (3–9 $MtCO_2e$). China also contributes to major emission abatement of 2.10%–6.91% (208–683 $MtCO_2e$), along with India with abatement of 2.16%–7.13% (63–207 $MtCO_2e$).

4. Policy implications

Using the monetary savings from rooftop solar PV applications on food consumption results in complex outcomes in various sectors and economies around the world. The higher the savings used for consuming foods, the higher the impact that countries experience. To generalise, power generation and food processing sectors are primarily affected due to the consumption switch between these two groups of commodities. Lower demands for utility-scale power by households leads to reductions in grid-supplied electricity output levels. This is amplified in countries where the demand for electricity by households is high relative to the total final demand for electricity by all sectors (i.e. industries plus households). These countries included Bangladesh (38%), Indonesia (39%), and Colombia (46%). In these countries, increased demand for food leads to major expansions in the production levels of the food processing sector.

Expansion of the food processing sector and contractions in the power generation sector will consequently impact all other sectors of the economy. In particular, reduced production levels in the utility-scale power generation sector lead to lower final demand for intermediate inputs produced by other sectors, particularly fossil fuel mining and extraction sectors. As a result, these energy sectors contract in output levels. The coal mining sector in two major producing countries (the United States and Australia) reduce output levels significantly, by 9%–28% ($6,086-$18,935 million) in the United States and 4%–13% ($2,505–$8,143 million) in Australia. In general, contractions in utility-scale power generation and all other energy sectors produce better results for the environment because with less fossil fuels burnt, less GHG emissions are released into the atmosphere. Modelling results show that when households around the world are able to self-supply their power needs from renewable resources over the range of 30%–100%, the world economy is able to reduce CO_2e emission levels by 2.24%–7.38% (or 924–3,042 $MtCO_2e$). Of these, two major emitters, the United States and China, contribute very sizeable emission reductions, viz. 199–656 $MtCO_2e$ in the United States and 208–683 $MtCO_2e$ in China. Such outcomes on GHG emission abatement have important policy implications on the global efforts to transform the world economy to a cleaner and more sustainable production environment, with less emitted GHG emissions. Such outcomes would reduce pressure on governments around the world to reduce emissions by imposing higher carbon prices

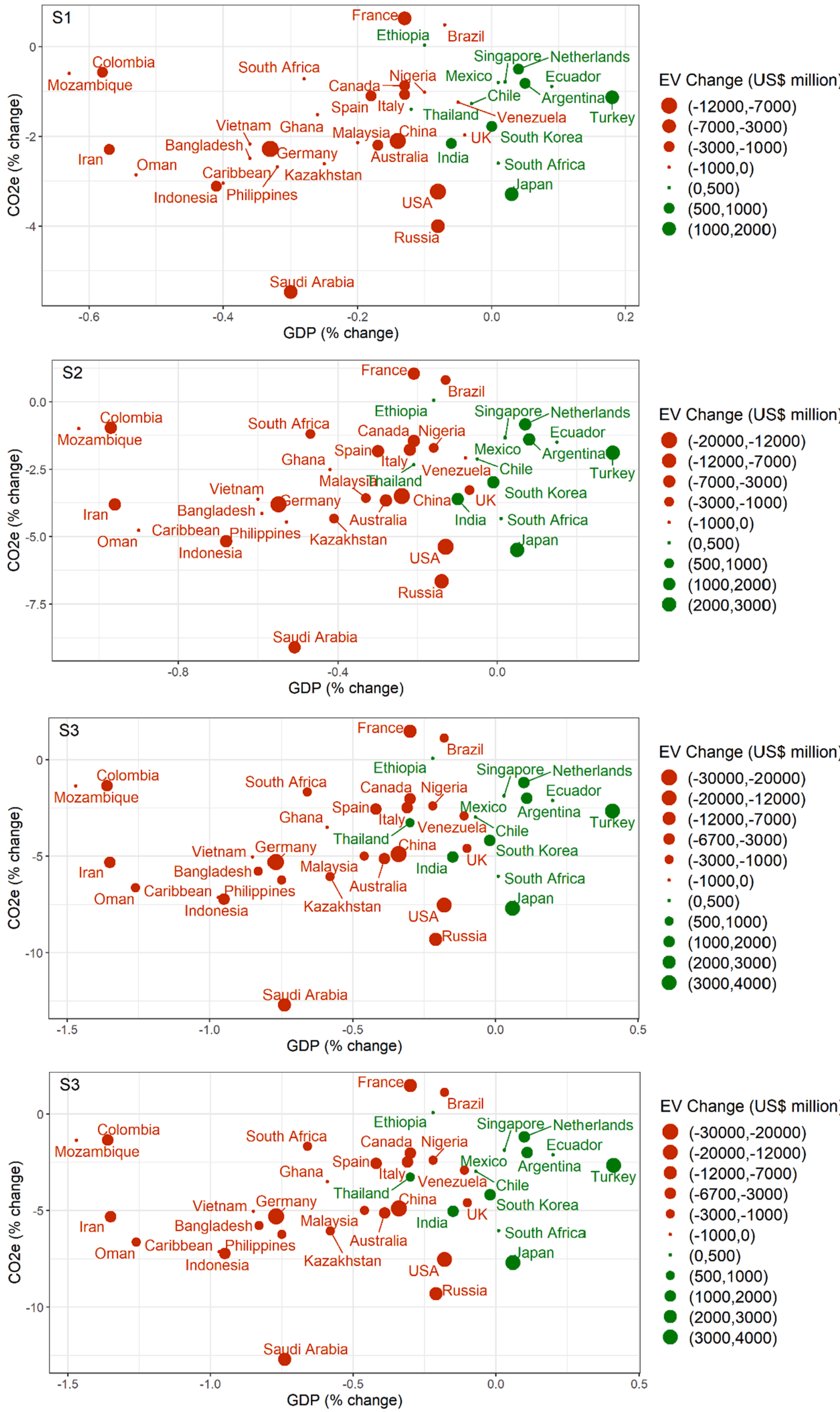

Fig. 8. Impact on real GDP, CO2e emission levels, and equivalent variation.

on emissions.

Expansion by the food processing sector, on the other hand, increases demand for inputs, particularly raw agricultural commodities. This leads to increased output levels by agricultural sectors, and in turn leads to increased demand for land resources. Land-scarce countries in Middle East, Europe, Japan, and Taiwan face substantial land price increases of up to 100% in Scenario S4. Land-rich countries such as Brazil, China, Australia, the United States, and Russia, on the other hand, experience moderate increases in land prices of 20%–30% in Scenario S4. Increased food demand, however, can result in major concerns for the environment with unexpected land conversions from forests to arable and crop land because of limited supply. Such conversions may release huge amounts of GHG emissions as forest land absorbs relatively high amounts of carbon compared to other land types [28]. This issue may require further attention in future studies.

Increased demand for land and other natural resources will also result in higher pressure on these resources, and will presumably force increased productivity. However, climate change is adversely affecting these resources [29]; hence, if technology development is not compatible with the required demand to increase productivity, land degradation and/or illegal land conversions from forest lands to crops lands may result.

The consumption switch from energy to food commodities has positive impacts on the environment by lowering GHG emission levels; however, it is not necessarily better off for economic activities generally. As modelling results show, output levels of energy sectors reduce significantly, resulting in contractions in other sectors such as services and manufacturing sectors. Countries that have a heavy reliance on fossil fuel extraction and mining activities experience significant losses in real GPD, including Brunei (reductions of 0.73%–2.55% or $1,189–$2,867 million), Kuwait (0.73%–2.55% or $1,189–$2,867 million), and Qatar (0.69%–2.32% or $1,144–$4,870 million). Only countries with less dependence on energy resources and major agricultural and services sectors experience slight increases in real GDP, including Jordan, Turkey, Namibia and other countries in Africa and Central America. Private final consumption (households) also experiences reductions in many countries because of higher agricultural commodity prices, particularly in Oman, Saudi Arabia, Mozambique, Iran, and Colombia.

Although there are some concerns regarding the economic performance of certain countries, a consumption switch from energy to food commodities is likely to deliver certain benefits. From a final consumer perspective, both energy and food security are enhanced. This should have significant implications for reducing food and energy insecurity in regions such as Africa, Southeast Asia and the Pacific Islands. It should also help relieve the burden on stretched power systems in middle- and low-income countries thereby ensuring a better overall power supply to the whole economy. For example, Vietnam still plans to continue with a heavy reliance on fossil fuel resources in the coming decade to generate electricity along with renewable-based power so that the country can meet rising power demand from industrial and household sectors [30]. As a result, if households in Vietnam are able to self-supply power for their needs, it reduces the burden for the Government of Vietnam, including its reliance on fossil-based technologies, while fostering the development of renewable energy.

The analysis has, however, been conducted with limitations that arise from the assumptions. In particular, upfront installation and periodic maintenance costs of home power systems are not considered. In countries such as Australia, the payback of such systems is typically measured in "single digit" years and thus our analysis should be considered an equilibrium examination after the payback period has ended. Installation costs vary significantly across countries and regions around the world, and thus some consideration of this variation would be useful (i.e., long run support to lower costs and reduce 'payback' concerns).

It would also be desirable for various land types to be included in models to enable competition between land types, and to show how lands are converted for different uses. Such value-added considerations for future studies will produce more refined results on GHG emission levels released from land-use change in future studies.

5. Conclusion

This article employs a global CGE model, GTAP-E-PowerS, to examine the impacts of how households in all countries/regions around the world might use monetary energy savings to increase food consumption arising from self-supplied power from renewable resources.

Results showed that impacts became larger when households were able to self-produce more power, leading to reduced production levels in the power generation sector, as well as fossil fuel mining and extraction sectors. In particular, coal-fired power generation output levels reduced by 14%–42% in countries including the United States, the Philippines, Vietnam, Venezuela, South Africa, Ghana, Nigeria, Ethiopia, Ecuador, Bangladesh, Indonesia, and Colombia. The coal mining sector reduced output considerably in the United States (9%–28% or $6,086-$18,935 million), and in Australia (4%–13% or $2,505–$8,143 million). The food processing and agricultural sectors were, however, found to expand substantially in numerous countries in all continents, which places pressure on land and drives up prices in many countries, particularly land-scarce regions. Regarding the macroeconomy, many countries could experience contractions in overall performance, as measured by real GDP contractions. Countries that rely on fossil fuel resources such as Brunei, Kuwait, and Qatar, experience relatively large economic contractions in real GDP, by up to 3.4%. However, the GHG emission levels in many countries were likely to reduce substantially because of contractions in energy sectors (e.g., a reduction by 5.45%–17.91% (31–101 $MtCO_2e$) in Saudi Arabia, by 4.00%–13.14% (76–248 $MtCO_2e$) in Russia, and by 3.23%–10.66% (199–656 $MtCO_2e$) in the United States). Consequently, the world emission levels reduced by up to 7.38% or 3,042 $MtCO_2e$.

In summary, while a consumption switch from energy to food commodities may result in negative impacts on the energy sector, it may contribute to Sustainable Development Goals by enhancing food and energy security, as well as having cleaner and more sustainable production systems with less emitted GHG emissions.

The current study also establishes platforms for future studies, which can extend the employed assumptions and settings. For example, self-power supply capability between urban and rural households or among income groups may not equal; hence, splitting households to different groups to enable more detailed and practical analysis is demanded. In addition, differentiation of technology development and socioeconomic conditions among countries/regions around the world should also be considered because ability to develop home renewable power systems across countries is not identical across countries, particularly between developed and developing nations. In future studies, we also expect to examine additional scenarios on how households use monetary savings for other consumer baskets. Industrial sectors in this instance might be affected differently compared to the current findings due to such allocations. Development of home and factorial solar systems can also be studied together to examine potential impacts on different sectors, particularly on electricity generation and fossil fuel mining sectors.

Credit authorship statement

Duong Binh Nguyen: Conceptualization, Formal analysis, Funding acquisition, Investigation, Methodology, Project administration, Resources, Software, Supervision, Validation, Visualization, Writing – original draft, Writing – review & editing. **Duy Nong:** Conceptualization, Data curation, Formal analysis, Funding acquisition, Investigation, Methodology, Resources, Software, Validation, Visualization, Writing – original draft, Writing – review & editing. **Paul Simshauser:** Conceptualization, Formal analysis, Investigation, Validation, Writing –

original draft, Writing – review & editing. **Thong Nguyen-Huy:** Conceptualization, Validation, Visualization, Writing – original draft, Writing – review & editing.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary material

Supplementary data to this article can be found online at https://doi.org/10.1016/j.apenergy.2021.118126.

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