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Sustainability of Utilizing Renewable and Nuclear Energy in Saudi Arabia Using Different Types of Life Cycle Assessment

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Sustainability of Utilizing Renewable and Nuclear Energy in Saudi Arabia Using Different Types of Life Cycle Assessment

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by

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Abstract

Evaluating the global environmental impacts of the current and future energy policies in Saudi Arabia using Life cycle assessment (LCA) method was the main objective of this dissertation. First, the attributional life cycle assessment (ALCA) framework was used to evaluate the Saudi's air conditioning systems, as they are responsible for about 70% of the total Saudi residential electricity consumption. The ALCA's results showed that the AC use phase produces the largest share of the environmental impact and the magnitude of the environmental impacts is influenced by the type of primary fuel used for electricity generation.

Emerging non-fossil sources of electricity may be the intuitive solution to reduce environmental impacts. Saudi Arabia has an ambitious plan to meet 50% of its electricity needs with renewable and nuclear energy. Implementing this plan will free up more of the Saudi oil for export, affecting the country and the rest of the world, since Saudi is the world largest oil exporter. To predict global economic shifts that would be triggered by that plan, a modified version of well-known computable general equilibrium (CGE) model, the Global Trade Analysis Project (GTAP), was used. The study showed that fossil fuel energy prices and ease of substitution for the fossil fuel electricity technologies are the main drivers for the emergence of renewable and nuclear energy.

As the GTAP's CO_2 emissions data only account for burned fossil fuels, there is a need to perform the study using a comprehensive method. That was done by performing a consequential perspective LCA. The results of this LCA showed that harmful environmental impacts would be reduced in Saudi Arabia. For the rest of the world, the impacts were largely negative.

Finally, an ex-ante analysis was done to study the economic, social and environmental impacts of large-scale global electricity generation targets to utilize renewable and nuclear energy by 2030. The study showed a deteriorated GDP in most regions. The world would face a loss of 4.45 million jobs. The environment benefits of the targeted renewable and nuclear energy would be slight and not enough to mitigate the global temperature rise.

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- Chapter three is: **Almutairi, K.**, Thoma, G., Durand-Morat, A. (2018). Assessment of Economic and CO_2 Emission Impacts of Deploying Renewable and Nuclear Energy in Saudi Arabia using a Modified GTAP-E. Renewable Energy, under review.

- Chapter five is: **Almutairi, K.**, Thoma, G., Durand-Morat, A. (2018). Ex-ante Analysis of Economic, Social and Environmental Impacts of Large-scale Renewable and Nuclear Energy Targets for Global Electricity Generation by 2030. Energy, under review.

1 Introduction

Burning Fossil fuels has an adverse impact on the environment and public health [1] and is largely responsible for the global climate change that is driven by greenhouse gas emissions [2,3]. Saudi Arabia, like other developing countries, has experienced rapid energy demand and industrial growth in recent years, which drives increased emissions. The consumption of primary energy is expected to double by 2030 with concomitant environmental impacts [4]. For the purpose of mitigating global climate change, it is important that the Kingdom effectively manage its emissions. Assessing the current and future energy policies that the Saudi government plans to implement and their environmental impacts requires a comprehensive tool. The life cycle assessment (LCA) method, specifically the attributional and consequential types, seems suitable for these studies. LCA is a holistic method that evaluates the environmental burdens associated with a product or process for each stage of its life cycle from extraction to the end of life. LCA can be used to assess opportunities to reduce harm to the environment. Thus, the main objective of this dissertation is to evaluate the global environmental impacts of the current and future energy policies in Saudi Arabia using an LCA method. Moreover, the subsequent economic stimulus of those planned polices and their effect on the social system are studied.

This dissertation consists of a number of related investigations. The first involves assessing the environmental performance of the residential cooling systems in Saudi Arabia, identifying the activities with the greatest impacts on the environment, and recommending possible changes to improve the entire system's environmental performance. That is done by using an attributional life cycle assessment (ALCA) framework. The residential sector was chosen as it is responsible for about 50% of the total Saudi electricity consumption [5], of which the air-conditioning (AC) systems consume 70% [6]. SimaPro 8 software [7] was used to perform the study. The entire system's modeling was done using the Ecoinvent V3 database (allocation at the point of substitution system model) [8], and the applied impact assessment method was ImpactWorld+ [9]. As the economic aspect is an important pillar of sustainability and has a great influence on decisions, the assessment includes the following economic tools: life cycle cost (LCC), payback period (PBP), net present value (NPV) and internal rate of return (IRR) analyses from the perspectives of customers and government, respectively.

The attributional life cycle assessment (ALCA) of the air-conditioning (AC) systems showed that the use phase causes the greatest environmental impact, and the magnitude of the impact is influenced by the type of primary fuel used to generate electricity. The greatest reduction of environmental impact may be achieved by generating electricity using non-fossil sources; this will require some policy decisions. The second investigation addresses this topic, assessing the potential economic and CO_2 emission impact of deploying renewable and nuclear energy in Saudi Arabia. This assessment uses using a modified GTAP-E model. As a response to the massive anticipated demand for electricity that will exceed 120 GW in 2032, Saudi policy-makers plan an ambitious deployment of renewable and nuclear energy [10]. The anticipated demand for energy is expected to consume 80% of Saudi oil produced in 2032 [11] if the country continues utilizing fossil fuels to meet its energy needs. This will have an effect on the country and global economy, as the Saudi's oil exports represents a big portion of the international oil market. The country is responsible for about 32% (as it exports more than 7 million barrels per day (MBD)) of the production of the Organization of the Petroleum Exporting Countries (OPEC), which in turn makes up 60% of international traded petroleum [12]. Committing to its role in maintaining the stability of the international oil market, Saudi Arabia is planning to meet half of its future energy demands from renewable and nuclear energy. The proposed program is called King Abdallah City for

Atomic and Renewable Energy (K.A.CARE). The suggested electricity mix, under this program, will be as follows: 60 GW (45.6 %) from hydrocarbons, 41 GW (31.16%) from solar, 17.6 GW (13.37%) from nuclear, 9 GW (6.84%) from wind, 3 GW (2.28%) from waste and 1 GW (0.76%) from geothermal [10]. Thus, any change or interruption to the Saudi's oil production ability has an impact on the global price of oil. A suitable approach called a multi-sector multi-region computable general equilibrium (CGE) model is used. That is a result of its ability to capture the interdependent linkages between production and consumption in a country, and the effects of international trade flows [13]. In addition, using a model that incorporates both energy and environmental effects is important, for if the K.A.CARE program frees more Saudi oil to be exported, it will affect the utilization and substitution of different types of energy in other regions. The GTAP-E modeling framework incorporates these features and is used to study the economic and CO_2 emissions impact of the proposed Saudi energy policy.

The CO_2 emissions data in GTAP do not include all greenhouse emissions; they are only coming from fossil fuel combustion. Not including other sources of greenhouse gas emissions (GHG), like land use and agricultural activities, might be misleading. Therefore, a method with the ability to include non-fossil fuel GHG emissions is needed. Moreover, it even better to use a holistic method that can quantify the consumed resources and relevant emissions and relate them to resources they deplete and the environmental and health impacts. This was the objective of the subsequent analysis where the previous GTAP-E results of the two scenarios (with/without renewable and nuclear energy) were modeled using a full life cycle assessment (LCA). The United Nations (UN) Comtrade database was used to convert monetary units, GTAP outputs, to physical units to compute the environmental impacts. SimaPro software [7] was used to build the two scenarios, the entire system was modeled using Ecoinvent v3 database [8], and the applied impact assessment method was Recipe [14].

The last investigation is an ex-ante analysis that assesses the economic, social and environmental impacts of large-scale renewable and nuclear energy targets for global electricity generation by 2030. Different regions were examined to understand how their economics and the well-being of their people could be impacted by their planned target, as different impacts might be shown based on the structures of their economies and their local natural resources. To achieve that, computable general equilibrium (CGE) model, the Global Trade Analysis Project (GTAP), is modified and used. The study took into account the technological improvement of each type of electricity technology by using the learning rate method [15]. By considering the employment effects, social impact is accounted for. Both direct and indirect employment were considered; the ones created in the electricity technologies sectors are direct, and the ones that created in other sectors as a result of the changes in the electricity sectors are indirect.

Each chapter of this dissertation represents an investigation, which has already been written as a stand-alone published or publishable work. Therefore, the dissertation follows the “published/submitted papers” style as per the University of Arkansas thesis and dissertation guide. Chapter 2 is an article published in *Energy and Building* titled “Life cycle assessment and economic analysis of residential air conditioning in Saudi Arabia” [16]. Chapter 3 represents a paper submitted to *renewable energy* titled “Assessment of Economic and CO_2 Emission Impacts of Deploying Renewable and Nuclear Energy in Saudi Arabia using a Modified GTAP-E.” Chapter 4 is a ready manuscript titled “Macro Life Cycle Assessment based on Computable General Equilibrium Model to Study the Environmental Impacts of Utilizing Renewable Energy by Oil Giant Country.” Chapter 5 represents a paper submitted to the *energy* titled “Ex-ante Analysis of

Economic, Social and Environmental Impacts of Large-scale Renewable and Nuclear Energy Targets for Global Electricity Generation by 2030." Chapter 6 is the dissertation's conclusion.

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2 Life cycle assessment and economic analysis of residential air conditioning in Saudi Arabia

2.1 Abstract

Buildings consume 79 % of Saudi electricity, of which 70 % is consumed by air conditioning (AC) systems as a result of the high ambient temperatures during the long summer season and heavily subsidized cost of electricity. Fossil fuels are burned as the primary energy source in power plants causing environmental impacts. A cradle-to grave regional Life Cycle Assessment (LCA) of residential building air conditioning has been performed to evaluate these impacts. The results show that the use phase is responsible for largest share of the environmental impacts; and that the type of primary fuel used influences the magnitude of the impacts in each region. Water related impacts are dominated by the manufacturing phase and the End-of-Life (EOL) phase results in environmental benefits by reduction in the need for virgin materials. The overall contribution of transportation is minor. Economic considerations influence decisions more than environmental concerns in a developing country like Saudi Arabia. To evaluate the relationship of economics to environmental effects, Life Cycle Cost (LCC), and Payback Period (PBP) are included with the use of Monte Carlo Simulation (MCS) to model the effect of the variability in input prices on the uncertainty associated with the final results.

2.2 Introduction

In Saudi Arabia, there is extensive use of indoor air conditioning systems as a result of the high ambient temperatures during the long summer [1]. The Electricity & Cogeneration Regulatory Authority annual report (2012) presents the proportion of electrical energy consumed by various sectors in Saudi Arabia, as is shown in Figure 2-1. The figure shows that 50% of the Kingdom's electricity is consumed by the residential sector [2]. Furthermore, the demand for electricity in the Kingdom is increasing an average of 8% per year, due to a heavily subsidized cost structure [3] and population growth (2.34% annually). In response of this population growth there are plans to construct 1.65 million new homes over the next few years [4]. Table 2-1 shows the actual increase in and demand for power generation by comparing the major Saudi Electricity Company (SEC) indicators between 2000 and 2012 [5]. Because of the hot climate, electricity consumption increases substantially during the summer (June-September) [3]; and the summer peak-period electricity usage occurs between 13:00 to 17:00 each day [6].

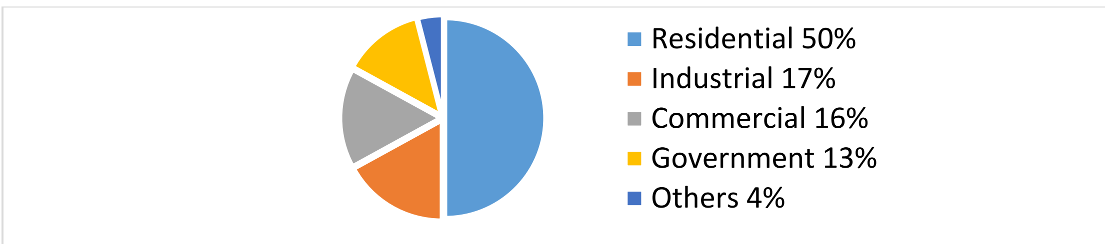

Figure 2-1 Distribution of Saudi electricity consumption by sector in 2012 [3].

Table 2-1 Comparison of SEC major indicators for two years [5].

	2000	2012	Growth %
Generation capacity (MW)	24,083	53,588	122.5
Transmission networks lengths (km)	29,166	51,881	77.9
Distribution networks lengths (km)	219,076	438,130	100
Number of customers (million)	3.5	6.7	91.3
The number of cities, villages and settlements electricity reaches	7,406	12,450	22.3

Seventy-nine percent of Saudi electricity is consumed in the operation of buildings (residential, commercial and government) [3], compared with 30-40% worldwide [7,8]. Air-conditioning (AC) consumes 70% of the country's total electricity during summer season [1]. Moreover, 70 % of total residential consumption is for AC [3], which is considered high compared to other regions of the world as shown in Table 2-2 [8]. This huge demand for electricity increases fossil energy consumption. Table 2-3 shows that natural gas and crude oil were the primary energy sources for most of the electricity produced (74%), with the balance produced from diesel and heavy fuel oil for the timeframe of this study, 2012 [5]. The proportion of natural gas reached its highest level in 2007, but has fallen over the following years as shown in Table 2-3. This decrease in natural gas consumption is a result of a royal decree in 2006 stating that the largest power plants in the country would be fueled by crude oil in the future. A switch back to natural gas might take place if large gas reserves are discovered or the country decides to import gas [9]. Therefore, the amount of gas used in power plants is expected to remain constant and its proportion of overall fuel mix will decrease over time as new plants fueled by crude oil come online.

Table 2-2 Residential building energy consumption and its space conditioning share for comparison purpose [8]

	Residential energy consumption (%)	Space conditioning share (%)
USA	22	53
UK	28	62
Spain	15	42
European Union	26	68

Table 2-3 Fuel types percentages in energy production over the last seven years [5, 10-14].

Year	Natural Gas	Crude Oil	Diesel	Heavy Fuel Oil
2007	52	11	18	19
2008	45	20	22	13
2009	38	34	22	6
2010	34	40	22	4
2011	37	37	21	5
2012	39	35	20	6

The burning of fossil fuels has an adverse impact on the environment and public health [15] and is largely responsible for the greenhouse gas emissions driving global climate change [16, 17]. Moreover, as in other developing countries, the Kingdom has experienced rapid industrial growth in recent years. This rapid development drives increased emissions. It is expected that the consumption of primary energy will almost double by 2030 with concomitant environmental impacts [6]. It is important that the emissions in the Kingdom be managed effectively for the purpose of helping mitigate global climate change.

A survey conducted by Proctor Engineering group and AMAD Technical Consultation and Laboratories estimates that more than 95% of air conditioners in Saudi Arabia are one of two types: window and split units [18]. A window AC is one in which all the components exist in one single unit that is mounted in a window of the room. In contrast, the split AC consists of two units: indoor unit (cooling coil, blower and air filter) and outdoor unit (compressor, condenser coil and expansion tube), with tubing connection. A comprehensive assessment of a residential AC system's resource use intensity, electricity consumption and environmental impacts requires life cycle assessment and life cycle cost perspectives.

An attributional life cycle assessment (ALCA) framework for evaluating air conditioning systems manufactured according to two energy efficiency standards is applied in this study. ALCA gives a good understanding of the systems' energy and environmental performance and is appropriate for benchmarking studies. The cradle-to-grave assessment includes manufacturing, transportation, use phase and end of life (EOL) recycle or disposal of the AC unit itself. As in most developing countries, economic aspects generally have greater influence on decisions than concern for the environment [19]. To understand these trade-offs, life cycle cost (LCC) assessment, payback period (PBP),net present value (NPV) and internal rate of return (IRR) analyses from the perspectives of a customer and government are included in this study. This study investigates the environmental burdens of residential cooling systems in Saudi Arabia, identifies the activities that are responsible for the greatest impacts on the environment, and recommends possible changes that should improve the environmental performance of the entire system.

2.3 Methodology and Data Sources

The goal of this study is to investigate the environmental performance of the residential cooling systems in Saudi Arabia through life cycle assessment (LCA). LCA is a methodology that evaluates the environmental burdens of products and processes and can be used to assess opportunities for environmental improvements. The function of an air-conditioning system is to keep a house comfortable. The functional unit of this study is the climate control of 1 m^2 of living area (the residential buildings' characteristics are described by Algarni [4]) maintained at 75 F of each type of residential building for one year, which allows the comparison of different types of buildings in different regions. For the cradle-to-grave life cycle assessment, the system needed to provide the functional unit was divided into several subsystems: AC manufacturing phase (includes materials extraction and production), transportation phase, fossil fuel production (fuel extraction, refinery and natural gas plants), power plant electricity production, the cooling or climate control phase, and the EOL disposal phase as illustrated in Figure 2-2. Thus the system boundary extends from raw material extraction through end-of-life disposal of used AC units. Each sub-system was modeled to estimate its energy and materials requirements. The study was performed with the use of software SimaPro 8 [20]. Ecoinvent v3 database [21] was used for modeling the entire system and ImpactWorld+ method [22] was applied for the impact assessment. ImpactWorld+ is a regionalized method that assesses and differentiates emissions occurring in different geographical locations across the globe, which leads to a regionally specific understanding of potential impacts. Twenty endpoint categories are included under the two damage categories. Human health includes effects from global warming, water use, respiratory inorganics and organic, carcinogens and non-carcinogens, ionizing radiation and ozone layer depletion. Ecosystem quality includes effects arising from global warming, acidification, land occupation, water use, water table lowering, thermally polluted water, water stream use and management, eutrophication, ecotoxicity and ionizing radiation. The method does not have normalization or weighting. In ImpactWorld+, damage to human health is expressed in Disability-Adjusted Life Years (DALY). This metric is developed from statistics about human health in a certain region according to loss and disability caused by a disease during a typical lifetime. For instance, a damage score of one is defined as one life lost or one person was suffering four years from disability. Ecosystem quality is measured by Potentially Disappeared Fraction of Species

(PDF.m^2.yrs). For instance, a damage score of one means that all species disappeared from one m^2 during 10 years [22].

Algarni [4] has calculated the cooling energy consumption for common residential buildings, which are apartment, traditional house and villa, in all the 13 provinces of Saudi Arabia. The buildings' characteristics are a double-glazed window type, concrete slab roof and floor with concrete block wall with cement mortar outside and inside with an R-value of 9.19 $ft^2 \cdot °F \cdot h/Btu$. Full details of buildings are clearly described in Algarni's work [4], and based on the weather data of every provinces they were simulated. The efficiency of the AC significantly influences the environmental performance of the air conditioning system. Saudi Electricity Company, SEC, provides the electricity for most of the Kingdom. Central, Eastern, Western and Southern are the four operating regions of SEC. Small companies serve some isolated, remote areas [23]. The power plant design and the primary fuel mix are different for each operating region [23, 24]. Therefore, the LCA was performed with region-specific LCI for electricity generation (Table 2-5: the primary fuel mix for each region).

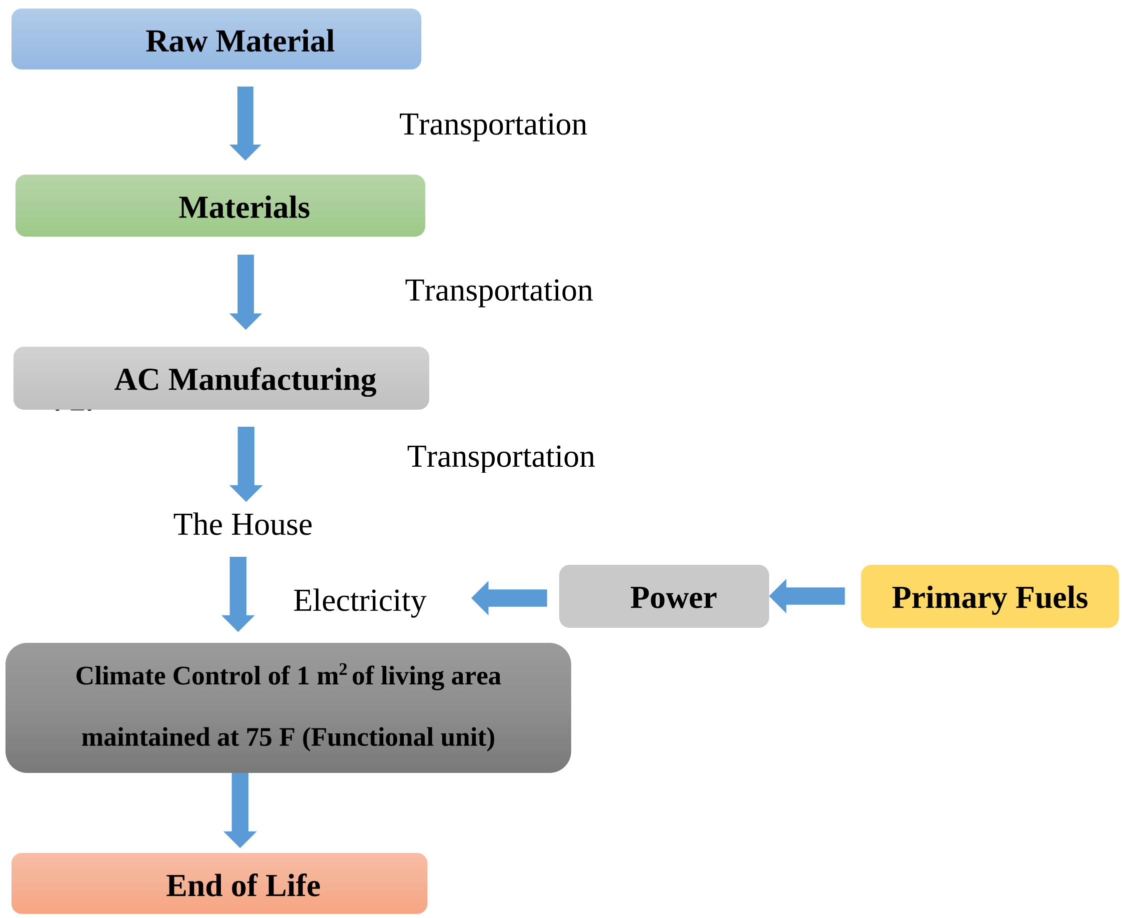

Figure 2-2 Air Conditioner Life Cycle.

2.3.1 Air Conditioner

The main components of an air conditioning unit are the compressor, heat exchanger (evaporator and condenser copper coils), controls, motor and fans [18]. The material of the AC components was determined based on a study done by the MIT Environmentally Benign Manufacturing Laboratory which studied appliance remanufacturing and energy saving [25]. The material constituents are given in Table 2-4, and the manufacturing energy intensity is 19.7 MJ/Kg of AC unit [25]. The weight of an 18,000 BTU window AC unit, which is the most common window AC in Saudi Arabia, is 55 kg and 69 kg for the 24,000 BTU split unit. HFC-134a (1,1,1,2-

tetrafluoroethane) is used as the refrigerant. The refrigerant mass charge varies from 1.1 kg to 1.9 kg (considered in the uncertainty analysis) [26], 1.6 kg was used as the average value in this work [27]. It was assumed that half of the refrigerant leaks during the AC's lifetime and so it is replaced during the use phase [28]. The transportation of the finished AC from the manufacturing factory (local or foreign) to the retailers, from the retailers to the residential building and finally to the end of life (EOL) phase is considered in this study. According to the Central Department of Statistics & Information (exports and imports statistics) in Saudi Arabia [29] and the National Commercial Bank report on the Kingdom's manufacturing capacity of AC units, domestic production meets 51.86 % of domestic demand [30]. The remaining demand is mainly met by importing ACs from the following countries: China (31.6%), Thailand (9.38%), Bahrain (3.83%) and South Korea (2.18%) [30]. The major local manufacturing factories exist in three cities: Jeddah (Saudi Air Condition Factory), Riyadh (National Factory for Air Conditions) and Dammam (Zamil Air Condition Factory) [30]. The distances between these cities and their nearest province were used as an estimate for transportation distances between the factory and retailers for the domestic production; and the nautical distances (except for Bahrain) for the imported ones. The average lifetime of a window unit is 10 years, and the average lifetime of split unit is 15 years [18]. The functional unit of this LCA is a one year of climate control for 1 m^2 of residance, so the emissions of the manufacturing phase are amortized over 10 and 15 years for the window and split units, respectively.

Table 2-4 the construction material constituents of AC unit [25].

	Material	Weight Percentage %
Metals		
Non Ferrous	Aluminum	6.21
	Copper	17
Ferrous	Iron	7.13
	Stainless steel	1.47
	Steel	35.11
Plastics	HDPE	0.07
	PP	0.82
	PS	6.55
	EPS	0.39
	HiPS	16.17
	PVC	4.04
	PA-6	1.27
	PBT	0.6
	ABS	0.21
	lacquer	0.86
	Rubber	0.17
	Others	1.93

The use phase energy consumption depends on three factors: the length of operation, the unit's capacity and its Energy Efficiency Ratio (EER), which is the ratio of cooling capacity in BTU/h to the input power (watt).

$$\textbf{Annual Energy Use} = \frac{\textbf{Capacity}}{\boldsymbol{EER}} * \textbf{ Operating time} \quad (\mathbf{1})$$

The average EER of the unit in Saudi Arabia is 8.5, which is below international standards [18]. This study also evaluates EER of 11, to model the economic and environmental impacts of increasing energy efficiency of the air-conditioning units.

The transportation of the AC's components (only the finished AC) was not considered in this study because of data limitation and knowledge that its effect is quite small after modeling the worst case scenario (importing steel from Japan through transoceanic ship). Installation of the AC at the house and the material waste from installation were not be taken into account for the same reason.

In the EOL modeling, disassembly for recovery of component materials is assumed. It is assumed that metals are 100% recyclable, non-metals are 50% recyclable [31-35] while the other 50% goes to sanitary landfills which is the dominant disposal method in Saudi Arabia [36]. There are no completed datasets available for recycling processes in evoinvent, but suggestions are provided regarding EOL modeling. These suggestions were used in handling the recycling processes. Due to lack of data, a few materials (less than 4 weight percentage, including PBT, ABS, lacquer and others) were not considered in the EOL modeling.

2.3.2 Electricity generation

The fossil energy use and greenhouse gas emissions from electricity generation come from four kinds of power plants in Saudi Arabia. The four designs and their relative contribution to the generating capacity of the Kingdom in 2012 were: natural gas unit 61.11%, steam unit (can be fueled with natural gas or oil) 32.46%, combined-cycle unit 5.41 % and diesel unit 1.02% [5]. The percentage contribution of primary fuels is different for each operating area as shown in Table 2-5 [23, 24]. The oil in the table includes crude oil, diesel and heavy fuel oil. The most recent release of the Ecoinvent database has the specific Life Cycle Inventory (LCI) data for electricity generation and supply in Saudi Arabia. The electricity line losses during the transmission and distribution are 9.3% [2].

Table 2-5 Electricity generation mix by the type of fuel in all regions [23, 24].

Fuel Source	Eastern	Western	Central	Southern
Natural gas (%)	98.75	0	67.35	0
Oil (%)	1.25	100	32.65	100

2.4 Results and interpretation

2.4.1 Life cycle impact assessment results

The results for the functional unit of (1 m^2) of climate controlled space are presented and discussed for the ImpactWorld+ assessment method. Because the ImpactWorld+ method does not have normalization, ReCiPe [37] with world normalization (average person per year) was used to identify the most important categories for more in-depth analysis using ImpactWorld+ as shown in Figure 2-3 which presents a comparison between all types of residential building in the eastern region . The normalization results (Figure 2-3) indicate that climate change, ozone depletion, terrestrial acidification, freshwater eutrophication, human toxicity, freshwater ecotoxicity, marine ecotoxicity and fossil depletion are important categories.

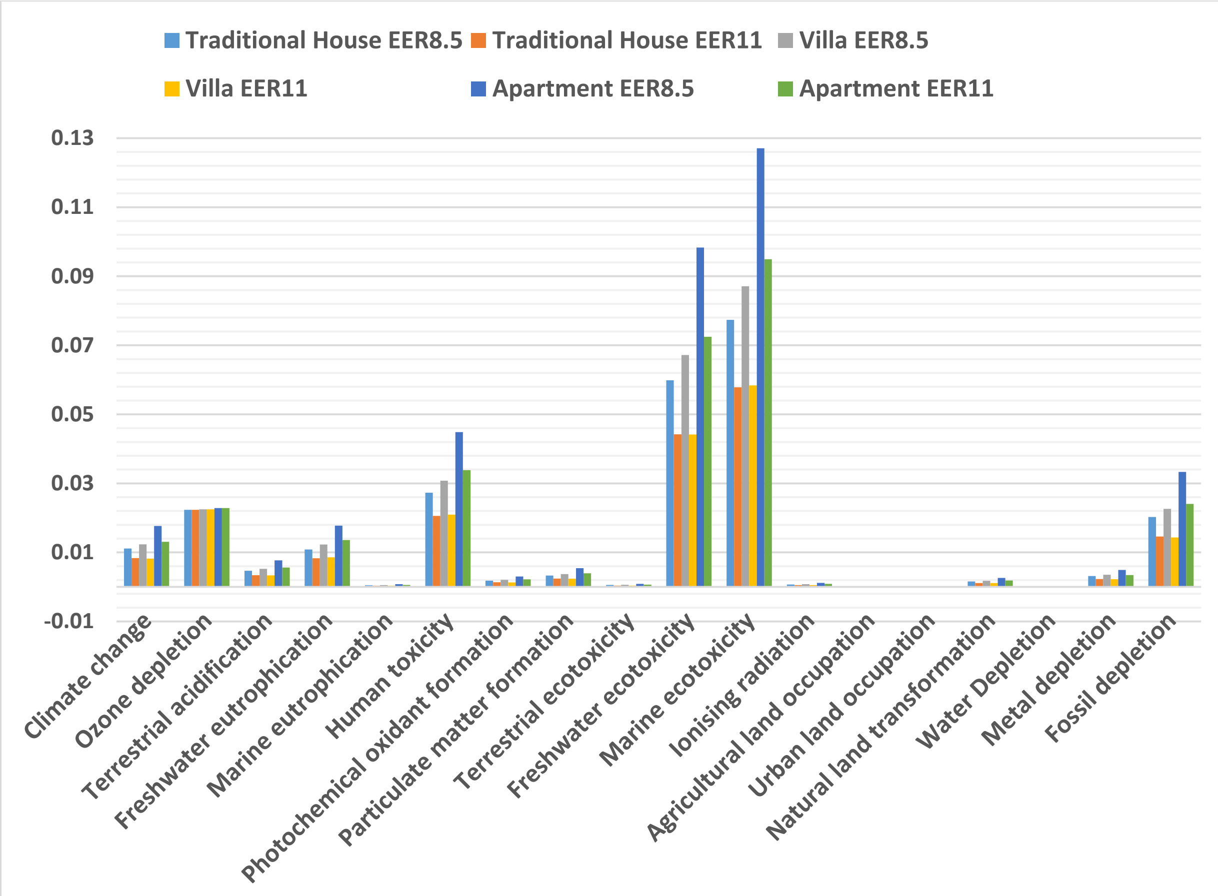

Figure 2-3 World normalization for ReCiPe midpoint (H) LCIA framework

Figure 2-4(a), (b), (c) presents a contribution analysis of potential impacts per stage, process, substance and location across all of the important impact categories for the system (EER 8.5) of a traditional house in the eastern region (the fuel mix is mainly natural gas) of Saudi Arabia ((a) has a caption that illustrates and facilitates understanding this figure). The other types of residential buildings in the other regions follow almost the same pattern. It is not surprising that the use phase dominates most of the impacts, except water related impacts that are dominated by manufacturing (column 1 in Figure 2-4). EOL results in environmental benefits for water related impacts, long term aquatic ecotoxicity, long term carcinogens and non-carcinogens. The transportation stage plays a very minor role in most impacts.

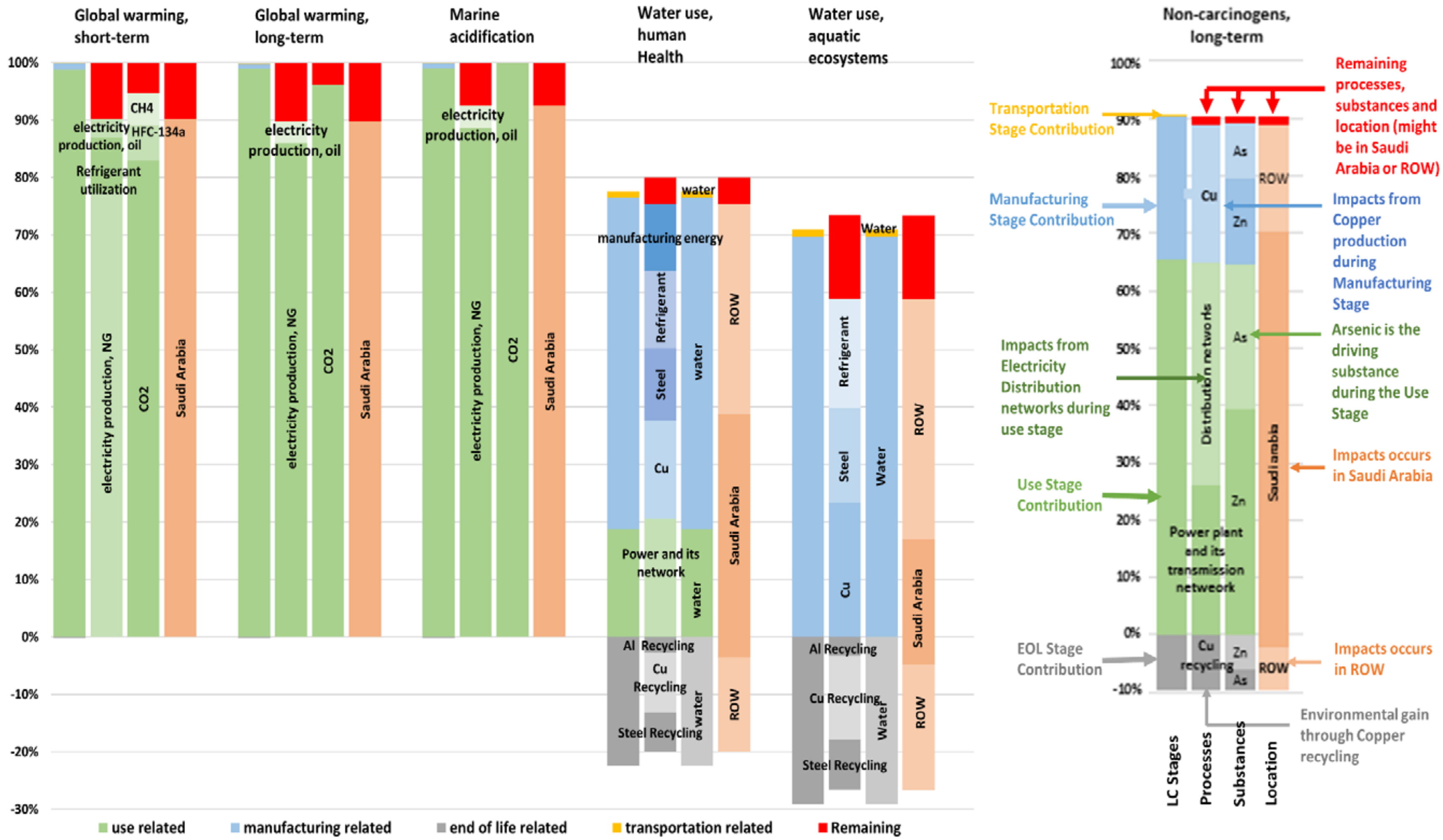

Figure 2-4(a). Contribution analysis of LC stage (Column 1), common processes (Column 2), driving substances (Column 3) and impact location (Column 4) with explanation for the chart.

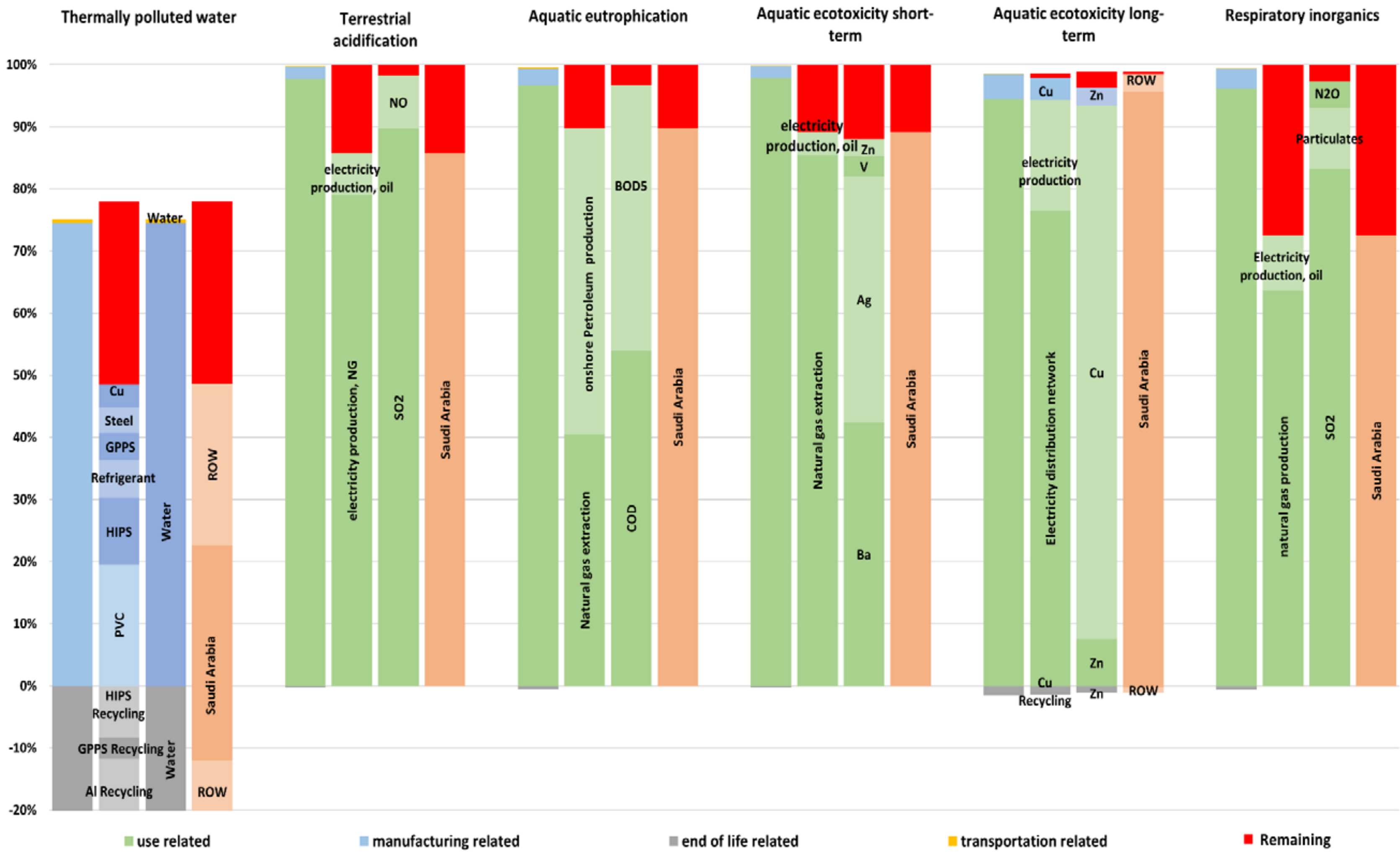

Figure 2-5(b). Contribution analysis of LC stage (Column 1), common processes (Column 2), driving substances (Column 3) and impact location (Column 4).

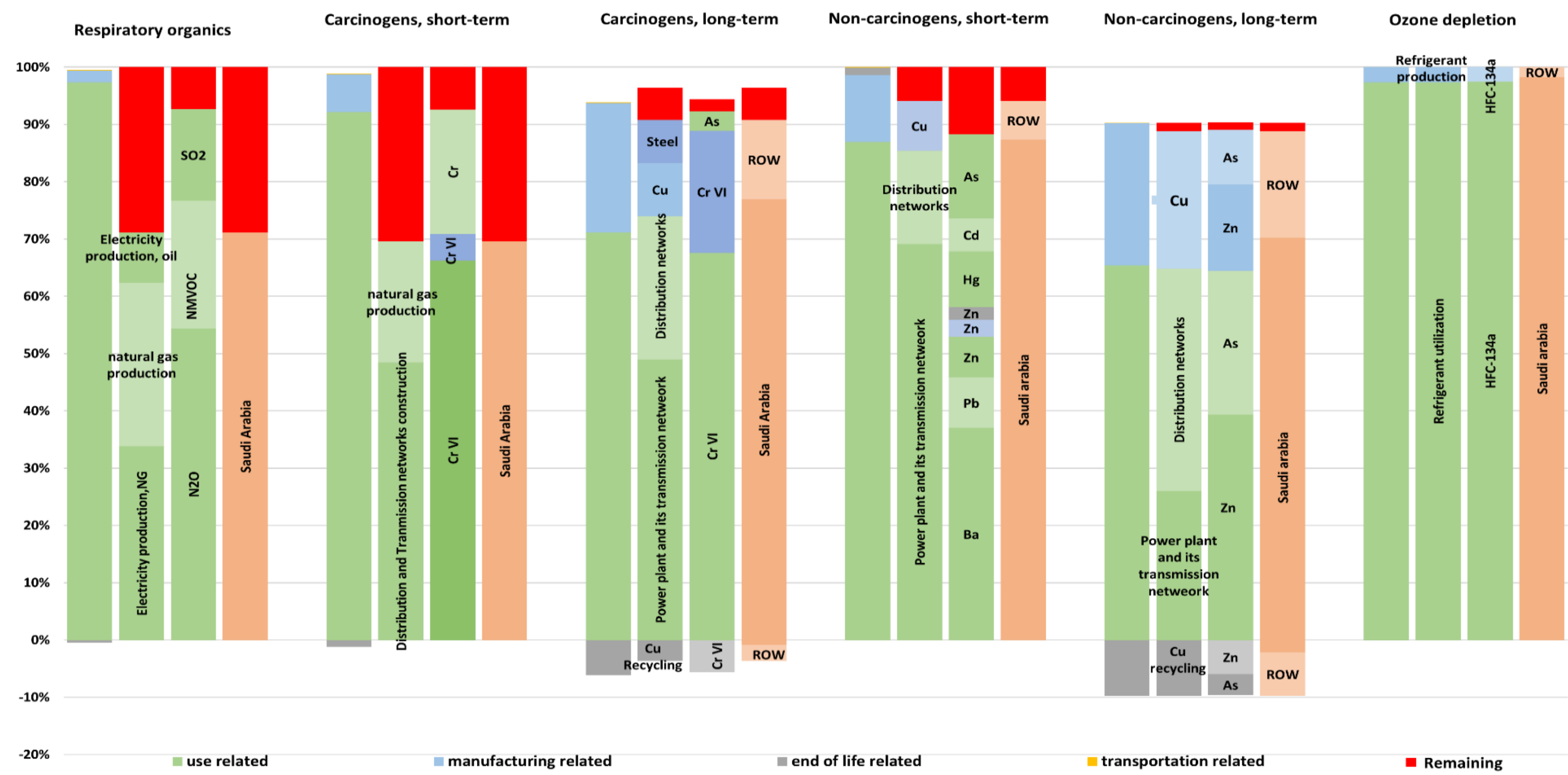

Figure 2-6(c). Contribution analysis of LC stage (Column 1), common processes (Column 2), driving substances (Column 3) and impact location (Column 4).

- The lighter and darker shades of green are related to the use phase in all columns.
- The lighter and darker shades of blue are related to the manufacturing phase in all columns.
- The lighter and darker shades of grey are related to the end of life phase in all columns.
- The chemical elements listed above in the second column represents impacts from their production.

Regarding the most impacting processes (column 2 in Figure 2-4), electricity production, which includes the extraction transport and combustion of the primary fuel, transmission and distribution networks, has a significant contribution to most categories. Most of the electricity consumption, of course, occurs in the use phase. The impact of transmission and distribution networks is mostly a result of the production of copper and steel and the way of handling their mine tailings disposal. The exception is ozone depletion (dominated by refrigerant loss). For the categories that are dominated by the manufacturing phase, copper, steel and refrigerant production are the responsible processes. For thermally polluted water impact, plastics manufacturing (polyvinylchloride (PVC), high impact polystyrene (HIPS) and general purpose polystyrene (GPPS)) are the largest contributing process. For EOL, recycling of copper, aluminum and steel plays an important role in reducing water use impact, as there are avoided emissions from reduced need for virgin material. Recycling of HIPS and GPPS has a role lowering the impact of thermally polluted water. Recycling copper benefits each of long term aquatic ecotoxicity, long term carcinogens and non-carcinogens. However, the credit of copper recycling is highly uncertain as the used ecoinvent database has a warning about using it without modification if its impact was considerable as in this case. Because of the lack of data of copper recycling technology in Saudi Arabia and as one of this study's goal is to provide information to decision-makers, it was used here to show a hotspot of environmental gain. It is important to mention that the impact reduction from EOL and manufacturing processes are shown as negative values.

The driving substance (column 3 in Figure 2-4) for global warming and marine acidification is carbon dioxide emitted from the power plants. In water use and thermally polluted water impacts, the effect is to water that might originally from a well, river, lake or unspecified origin (according to ecoinvent). In Saudi Arabia, the majority of power and industry plants are located near the coasts and use mainly seawater in their cooling system (once-through cooling system) [38, 39]; however, some Saudi industries meet their water demands through groundwater [40]. Sulfur dioxide is the driving substance for both of terrestrial acidification and respiratory inorganic impact. Aquatic eutrophication results from biochemical oxygen demand and chemical oxygen demand, while the contribution of phosphate and phosphorus are less than 2%. Barium and silver are the driving substances for short term aquatic ecotoxicity; and zinc and copper are the dominant substances for long term aquatic ecotoxicity. The main driving substances of respiratory inorganic impact are nitrous oxide (N2O) and non-methane volatile organic compound (NMVOC). Chromium VI is the main source for short term and long term carcinogen impact. Short term non-carcinogen human health impacts are mainly caused by barium, zinc, mercury, lead, cadmium and arsenic. Zinc and arsenic are the driving substances for long term non-carcinogens. Finally, it is not surprising that the ozone depletion is derived by refrigerant loss.

Most of the potential environmental impacts occur in Saudi Arabia (column 4 in Figure 2-4). Because the LCI-data for manufacturing is scarce for Saudi Arabia, most of the inventories are made using data from other countries; it was assumed that the manufacturing technology is the same. Global warming impact is occurring globally but it was assigned to Saudi Arabia because the main processes that emit CO_2 occur there. The decisions of assigning the impacts to Saudi Arabia or the remainder of the world (ROW) were made based on the import/export statistics as shown in Table 2-6.

The magnitude of some impacts is a result of the embodied energy used in the materials manufacturing or the waste management that might differ from place to place even for the same technology. As already mentioned, the results show that burning fossil fuels to generate electricity is the main source of most impacts. For the country that is rich in a variety of natural resources like sun and wind, considering clean energy technologies is an option that may have the greatest positive impacts on the environment, and its consequences are worth researching.

Table 2-6 Import/export statistics according to the Central Department of Statistics & Information [29].

	Import (Tons)	Export (Tons)	import/export	Examples of top countries of Imports
ALUMINIUM AND ARTICLES THEREOF	648819	321893	2.02	Bahrain, Qatar, UAE, China
COPPER AND ARTICLES THEREOF	404619	116655	3.47	Congo, Chile, Peru
IRON & STEEL	13910511	1807926	7.69	Turkey, Germany, USA
HDPE	46781	4057219	0.01	UAE, South Korea, Italy
PP	59427	3894348	0.02	UAE, South Korea, Belgium
EPS	4868	585	8.32	France, USA, Belgium
PS	12985	98789	0.13	France, USA, Belgium
PVC	133124	45376	2.93	USA, Japan, Taiwan
PA	49996	1881	26.58	Germany, USA, Italy
PBT (polyesters)	31659	12173	2.6	India, UAE, Italy
ABS (styrene)	21466	1557454	0.01	Malaysia, Taiwan, South Korea
Rubber	530000	29000	18.28	India, South Korea, Malaysia

2.4.2 Uncertainty analysis

LCIA results for 1 m^2 of climate controlled space was analyzed using 1000 Monte Carlo analysis runs with the basis the AC's composition might be higher or lower by 10% with lognormal distribution for a traditional house with EER 8.5 in the eastern region as shown in Table 2-7. Global warming, acidification, thermally polluted water and water use show less uncertain results. There is a higher level of uncertainty for short term aquatic ecotoxicity, short and long term carcinogens and short and long term non-carcinogens. The negative 2.5% confidence interval value was a result of this higher uncertainty, particularly regarding potential benefits of the end of life treatment.

Table 2-7 Result of 1,000 Monte Carlo simulations for uncertainty analysis.

Impact category	Unit	Mean	CV (Coefficient of Variation)	2.50%	97.50%
Aquatic ecotoxicity, long-term	PDF.m2.yr	1.94E+00	45.10%	8.31E-01	4.14E+00
Aquatic ecotoxicity, short-term	PDF.m2.yr	8.70E-02	61.10%	9.75E-03	2.24E-01
Aquatic eutrophication	PDF.m2.yr	4.12E-02	37.80%	2.15E-02	7.86E-02
Carcinogens, long-term	DALY	4.61E-06	68.40%	2.05E-06	1.22E-05
Carcinogens, short-term	DALY	4.53E-06	31.50%	2.38E-06	7.86E-06
Global warming, long-term, ecosystem	PDF.m2.yr	2.95E+01	3.80%	2.73E+01	3.17E+01
Global warming, short-term, ecosystem	PDF.m2.yr	1.46E+01	4.68%	1.33E+01	1.60E+01
Marine acidification, long-term	PDF.m2.yr	9.98E+00	3.84%	9.25E+00	1.08E+01
Non-carcinogens, long-term	DALY	9.77E-06	157%	2.13E-06	3.44E-05
Non-carcinogens, short-term	DALY	6.51E-06	241%	-2.68E-05	3.81E-05
Ozone layer depletion	DALY	1.53E-06	33.50%	7.28E-07	2.65E-06
Respiratory inorganics	DALY	8.21E-06	41.50%	4.19E-06	1.67E-05
Respiratory organics	DALY	4.45E-09	20.30%	3.10E-09	6.52E-09
Terrestrial acidification	PDF.m2.yr	2.07E+00	43.40%	9.97E-01	4.37E+00
Thermally polluted water	PDF.m2.yr	1.95E-07	4.61%	1.80E-07	2.15E-07
Water use impacts, aquatic ecosystems	PDF.m2.yr	1.45E-06	8.13%	1.24E-06	1.70E-06
Water use impacts, human health	DALY	2.20E-07	18.60%	1.68E-07	3.19E-07

2.5 Economic analysis for AC system in Jazan and Abha (highest and lowest consumption)

Life cycle costing, LCC, is the analysis of all of the expenses a customer pays during the lifetime of the AC. It includes the expenses of purchasing and operating the unit (includes the costs of energy expenditure, repair and maintenance). The repair cost was calculated according to the following expression [41]:

$$\boldsymbol{Repair\ cost} = \frac{\boldsymbol{0.5 \times Unit's\ price}}{\boldsymbol{Unit's\ lifetime}} \qquad (2)$$

While the maintenance cost is 2.5% of the unit price [42]. Disposal expense was not included because of the normal practice for dealing with old AC units in Saudi Arabia is to sell them to repair shops for a low price or sometimes for free. Payback period, PBP, is the required time to return the difference in initial investment of purchasing a more efficient air conditioner through its lower operating cost [OC] [43]. PBP was calculated by using the following equation [41]:

$$\boldsymbol{PBP} = \frac{\boldsymbol{\Delta\ intial\ prices}}{\boldsymbol{\Delta OC}} \qquad (3)$$

LCC assesses the purchase decision by quantifying the future savings due to the current investments that enhance energy efficiency. This is important for a developing country like Saudi Arabia where the economic aspects have more influence than the environmental concerns [19]. The LCC and PBP models were constructed using Microsoft Excel. To model both the uncertainty and variability of LCC and PBP, Monte Carlo Simulation (MCS) was used through using risk solver platform in excel. The results were analyzed using 1000 samples per Monte Carlo simulation run with the basis that the prices might be higher or lower by 10%. This work includes the LCC and PBP analyses for the highest and lowest cooling energy consumption in Saudi's provinces for each of the residential buildings that use AC with 8.5 EER and 11 EER as shown in Table 2-8. LCC is calculated based on the current subsidized electricity rates (as shown in Table 2-9), where each barrel of oil is sold to electricity companies in the range of \$5 to \$15. The current global market price is significantly higher; electricity prices paid by consumers in the Kingdom of Saudi Arabia among the lowest globally [2].

Table 2-8 LCC and PBP of Jazan, the province with highest cooling consumption, and Abha the province with lowest cooling consumption based on subsidized electricity prices.

	apartment			Traditional House			Villa		
	LCC (\$) EER 8.5	LCC (\$) EER 11	PBP (years)	LCC (\$) EER 8.5	LCC (\$) EER 11	PBP (years)	LCC (\$) EER 8.5	LCC (\$) EER 11	PBP (years)
Jazan	3318	3335	10.7	7700	6353	2.4	15518	9978	0.7
Abha	2274	2584	16.5	4146	4464	9.7	5747	5342	5

Table 2-8 shows that the use of a more efficient air conditioner is not attractive from the customer’s perspective in Abha for the apartment and traditional house, but it might be slightly attractive in Jazan for the apartment. On other hand, even with subsidized electricity prices, the more efficient AC in Jazan is attractive for the traditional house and villa.

Table 2-9 Current cost (subsidized) for residential consumption [2].

Monthly Consumption (kWh)	(US cents/kWh)
1-2,000	1.3
2,001-4,000	2.7
4,001-6,000	3.2
6,001-7,000	4
7,001-8,000	5.3
8,001-9,000	5.9
9,001-10,000	6.4
More than 10,000	6.9

Results of MCS for Jazan province, which has the highest energy demand, are presented in Table 2-10 to show how input uncertainty affects LCC and PBP; and a paired t-test was performed to see if these data are significantly different from each other or not.

Table 2-10 Results of 1,000 Monte Carlo simulations for uncertainty analysis of LCC & PBP for Jazan province.

	Mean	Standard Deviation	Paired t-test	P value	t-test result
apartment					
LCC ($) EER 8.5	3318	47.6	-0.47	>0.5	Statistically not different
LCC ($) EER 11	3334	58.7			
PBP (years)	10.7	3.2			
Villa					
LCC ($) EER 8.5	15518	69.3	54.4	<0.001	Statistically different
LCC ($) EER 11	9978	89.6			
PBP (years)	0.7	0.17			
Traditional House					
LCC ($) EER 8.5	7700	70	30.23	<0.001	Statistically different
LCC ($) EER 11	6353	89			
PBP (years)	2.4	0.54			

The subsidized electricity rates and global high prices of oil and gas suggest consideration of the government's perspective. Table 2-11 shows the LCC and PBP based on the non-subsidized electricity prices, which would be US cents 21.3 per kWh [2]. It shows government decision-makers how attractive the use of the more efficient air conditioners would be. It especially proves that moving to the more efficient units will free additional oil to be exported. Removing the subsidies is not currently in the Saudi's decision-makers agenda, but comparing the results of Tables 2-8 and 2-11 may encourage them to consider other options that may not look economically effective like the alternative energy production, or moving part of the subsidies to air conditioner manufacturing as a means of encouraging production of more efficient units.

Table 2-11 LCC and PBP of Jazan, the province with highest cooling consumption, and Abha the province with lowest cooling consumption based on non-subsidized electricity prices [2].

	apartment			Traditional House			Villa		
	LCC ($) EER 8.5	LCC ($) EER 11	PBP (years)	LCC ($) EER 8.5	LCC ($) EER 11	PBP (years)	LCC ($) EER 8.5	LCC ($) EER 11	PBP (years)
Jazan	27152	20478	0.4	68174	50245	0.2	126355	81096	0.1
Abha	10447	8465	1.1	26626	20640	0.6	51750	34686	0.2

To account for the fact that the customer’s expenses are distributed across time, a discounted cash flow analysis giving a net present value (NPV) for the two alternative ACs also was calculated for the subsidized and non-subsidized electricity prices as shown in Tables 2-12 and 2-13. According to the Federal Reserve Bank (FRB) of St. Louis, the discount rate for Saudi Arabia is been 0.25 % in the last 5 years [44]; the NPV results show that the use of a more efficient AC is attractive for the traditional house and villa in Jazan; and only for villa in Abha when based on subsidized electricity prices. That matches the LCC and PBP results. The use of more efficient AC is always attractive considering the non-subsidized electricity prices as shown in Table 2-13. It is important to mention that the results of NPV represent cash outflows because the customer is always spending and how much he could save by getting a more efficient AC is the investment of the project.

Table 2-12 NPV of Jazan, the province with highest cooling consumption, and Abha the province with lowest cooling consumption based on subsidized electricity prices.

	apartment		Traditional House		Villa	
Discount Factor	0.25%		0.25%		0.25%	
	NPV ($) EER 8.5	NPV ($) EER 11	NPV ($) EER 8.5	NPV ($) EER 11	NPV ($) EER 8.5	NPV ($) EER 11
Jazan	3289	3306	7615	6293	15327	9868
Abha	2256	2566	4110	4429	5689	5295

Table 2-13 NPV of Jazan, the province with highest cooling consumption, and Abha the province with lowest cooling consumption based on non-subsidized electricity prices.

	apartment		Traditional House		Villa	
Discount Factor	0.25%		0.25%		0.25%	
	NPV ($) EER 8.5	NPV ($) EER 11	NPV ($) EER 8.5	NPV ($) EER 11	NPV ($) EER 8.5	NPV ($) EER 11
Jazan	26796	20217	67754	50194	125144	80625
Abha	10318	8367	26284	20373	51553	34228

Internal rate of return (IRR) for the two alternative ACs also was also calculated for the subsidized and non-subsidized electricity prices as shown in Tables 2-14 and 2-15.The results of IRR match with NPV about which AC is more economical.

Table 2-14 IRR of Jazan, the province with highest cooling consumption, and Abha the province with lowest cooling consumption based on subsidized electricity prices.

	apartment	Traditional House	Villa
	IRR	IRR	IRR
Jazan	-1%	41%	145%
Abha	-9%	-21%	15%

Table 2-15 IRR of Jazan, the province with highest cooling consumption, and Abha the province with lowest cooling consumption based on non-subsidized electricity prices.

	apartment	Traditional House	Villa
	IRR	IRR	IRR
Jazan	262%	443%	1108%
Abha	85%	156%	437%

2.6 Conclusion

The LCA and LCC were modeled for the whole air conditioning system in the four operating areas of the Saudi Electricity Company SEC. The aim of this work is to provide a good understanding of the effect of energy efficiency on environmental and economic performance. The following phases were included in the LCA: AC manufacturing (includes materials extraction and production), transportation, power plant electricity production, fossil fuel production (fuel extraction, refinery and natural gas plants), the cooling or climate control or use phase, and the EOL disposal phase. The results show that the use phase is responsible for largest share of the environmental impacts; and the type of primary fuel used for electricity generation influences the magnitude of the impacts in each region. Water related impacts are dominated by the manufacturing phase. The EOL phase results in environmental benefits by reduction in the need for virgin materials. The role of transportation is minor. Regarding the economic analysis, using a more efficient air conditioner is not attractive to the customer for the apartment and traditional house in the Saudi provinces where the cooling energy consumption is the lowest. It is marginally attractive for the apartment and is attractive for the traditional house and villa in regions requiring the greatest consumption of cooling power. From the government's perspective, the use of more efficient air conditioners is always beneficial from an economic perspective, as well as improving environmental quality. Emerging non-fossil sources of electricity may have the greatest positive impacts on the environment and require some policy decisions. There may also be energy efficiency measures that result in decreased energy need to maintain comfortable living conditions. Providing a full assessment of these alternative energy supplies in Saudi Arabia requires a consequential lifecycle perspective, which is beyond the scope of this paper, but will be the subject of future work.

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3 Assessment of Economic and CO_2 Emission Impacts of Deploying Renewable and Nuclear Energy in Saudi Arabia using a Modified GTAP-E

3.1 Abstract

This study assesses the economic and CO_2 emission impacts of the planned deployment of renewable and nuclear energy in Saudi Arabia, proposed by King Abdallah City for Atomic and Renewable Energy (K.A.CARE). As Saudi is the largest oil exporter worldwide, any interruption of this commodity will not only be important for the country itself, but also the rest of the world. A well-known Computable general equilibrium (CGE) model, the Global Trade Analysis Project (GTAP), is modified and used to predict global economic shifts that would be triggered by different scenarios (K.A.CARE energy plan and a scenario without renewable or nuclear energy). Both scenarios are for 2032 which requires considering the change in the macroeconomic variables that reflect economic growth. The study shows that the emergence of renewable and nuclear energy is mainly driven by fossil fuel energy prices and ease of substitution for the fossil fuel electricity technologies. Implementing policy, like carbon tax, will raise the price of fossil fuel technologies and foster the shift to renewable and nuclear technologies. As a result, a higher percentage reduction of CO_2 emissions will be achieved.

3.2 Introduction

Saudi Arabia has an ambitious plan for the deployment of renewable and nuclear energy by 2032 [1]. The anticipated demand for electricity will exceed 120 GW [1], which is almost double current capacity [2]. This demand growth is driven by projected population and industrial growth. Thus, the consumption of fossil fuel, which is currently the primary source for electricity production, is expected to increase [3,4]. With the current pace of energy consumption, the domestic demand of fossil fuels will reach 8.3 million barrels of oil equivalent per day in 2028 compared to 3.4 million barrels of oil equivalent per day in 2010 [1], and will consume about 80 % of the Saudi oil production by 2032 [5]. Saudi Arabia has a significant impact on the international oil market; the country exports more than 7 million barrel per day (MBD) of crude oil. That represents about 32% of the Organization of the Petroleum Exporting Countries (OPEC) production, which represents 60% of the total petroleum traded internationally (OPEC Annual Statistical Bulletin, 2016). Any interruption or change in Saudi oil production affects the global price of oil as shown in Figure 3-1 [7]. It is worth pointing out that the official selling price (OSP) of the Saudi oil is determined by the Saudi Arabian Oil Company, which is well-known as ARAMCO. It bases its oil pricing on the consumer's location and the quality of the sold crude; and it calculates its OSP by adding a differential to a specific crude oil benchmark price. For ARAMCO's exports to Asia, the crude oil benchmark is Dubai and Oman crude prices; Brent benchmark is used for the exports to Europe and Mediterranean. For North America, the West Texas Intermediate was used until 2010, when the country switched to the Argus Sour Crude Index (ASCI) because the ASCI is more representative for the quality of exported oil to that region [8]. In general, all the benchmarks follow the same trend.

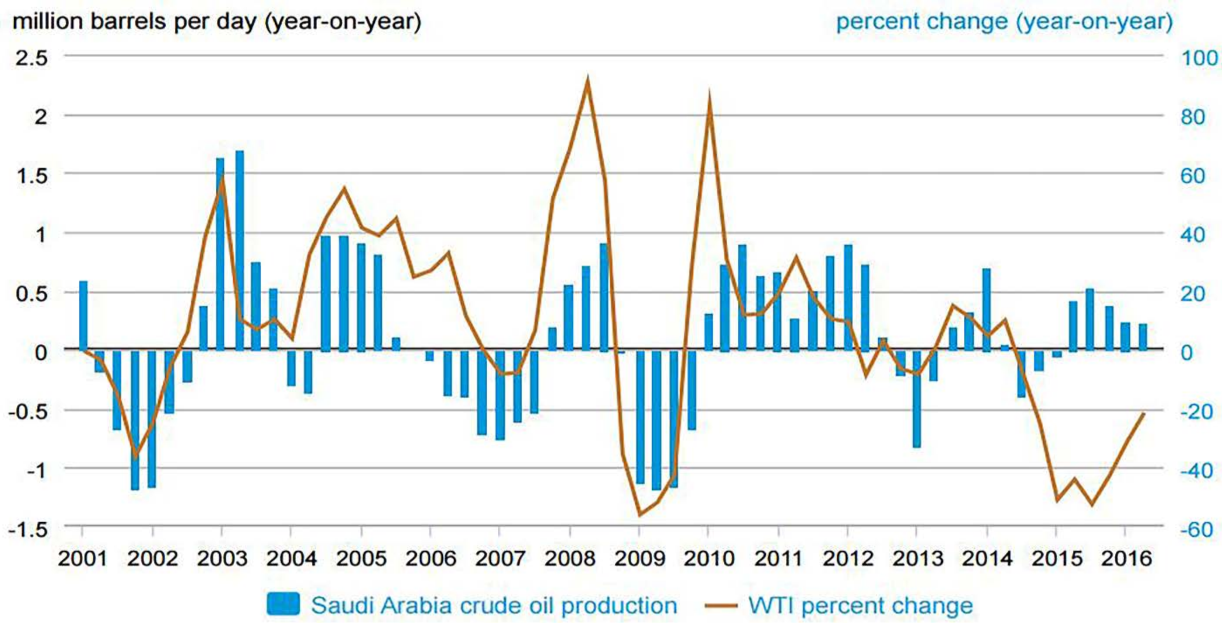

Figure 3-1 Changes in Saudi oil production and West Texas Intermediate (WTI) crude oil prices. Sources: U.S. Energy Information Administration, Thomson Reuters [7]

Moreover, even the spare capacity, which Energy Information Administration (EIA) defines as the production capacity of oil that can be brought on-line in 30 days and sustained for three months, has an effect on the oil prices. Saudi Arabia has the largest spare capacity, typically between 1.5 to 2 MBD, to manage the market. Figure 3-2 shows how OPEC's spare capacity influences oil prices [7]. The levels of OPEC's spare capacity were relatively low (below 2.5 million barrels per day) during the period of 2003-2008 influencing the escalation of oil prices. The effect of spare capacity on oil prices decreases with a higher oil inventory.

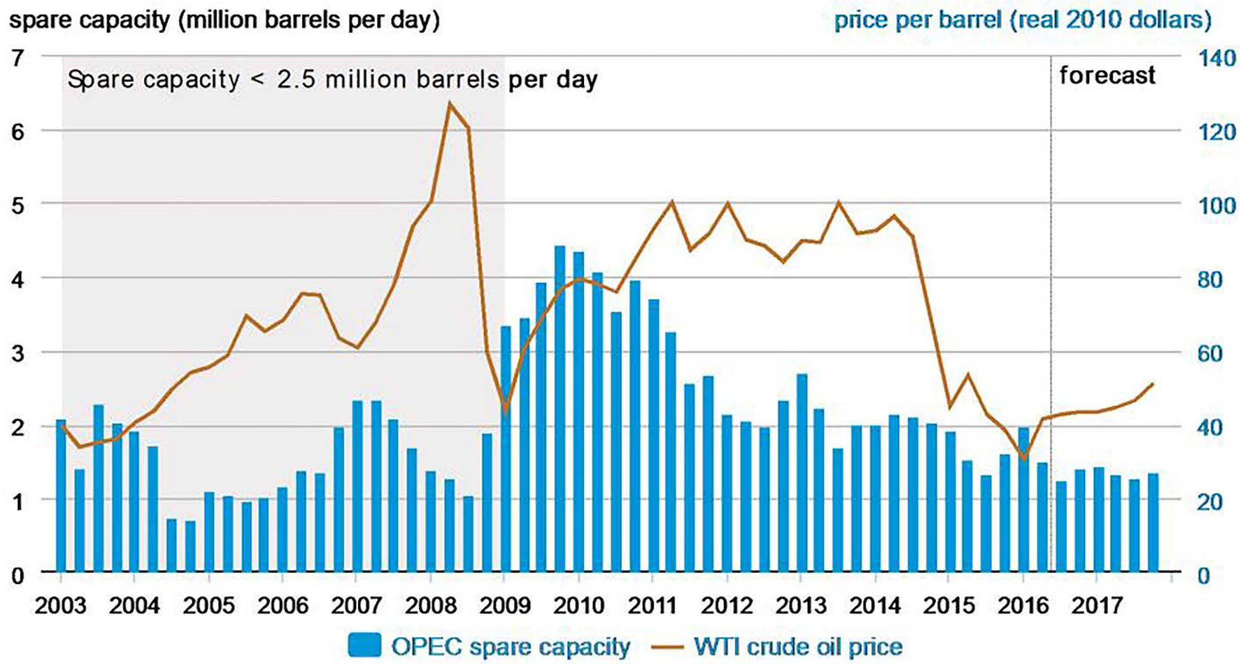

Figure 3-2 OPEC's spare capacity and WTI crude oil prices.

Sources: U.S. Energy Information Administration, Thomson Reuters [7]

Saudi Arabia has committed to continue its leadership in the oil market by planning an energy program that will enable the country to meet half of its growing demands from renewable and nuclear energy. This program was proposed by King Abdallah City for Atomic and Renewable Energy (K.A.CARE). K.A.CARE recommends that by 2032 the country's energy mix should be the following: 60 GW (45.6 %) from hydrocarbons, 41 GW (31.16%) from solar, 17.6 GW (13.37%) from nuclear, 9 GW (6.84%) from wind, 3 GW (2.28%) from waste and 1 GW (0.76%) from geothermal [1]. It is important to mention that the recent announcement of the Saudi 2030 vision, or the report that the K.A.CARE plan was postponed to 2040 [5] does not mean the abandonment of the K.A.CARE plan. The K.A.CARE program is still current; but it will be managed by the Ministry of Energy, Industry and Mineral Resources (MEIM). (M. Al-Abdalla, personal communication, July 4, 2017)

Because the oil sector in Saudi Arabia and its trade represent a big portion of the total economy of the country and Saudi Arabian oil exports effect on energy prices, any significant change in Saudi's oil export will alter the energy market globally, having potentially important economic and possibly greenhouse gas consequences. Thus, partial equilibrium analysis of the sector will not be sufficient to project future impacts to international trade, production, consumption and, the social and environmental spheres [9]. For that, a multi-sector multi-region computable general equilibrium (CGE) model is a more suitable approach to capture the interdependent linkages between production and consumption in a country in addition to capturing the effects of international trade flows [10]. Furthermore, as the impacts of the Saudi renewable and nuclear energy plan will affect the utilization of different types of energy and the substitution between them, it is important to use a modeling framework that incorporates both energy and environmental effects. We use the GTAP-E modeling framework to assess the economic and environmental impact of the proposed energy policy in Saudi Arabia. Because the original production function specified in GTAP-E does not allow for substitution between the different electricity technologies, and also because the GTAP-E database does not include all the energy sources contemplated in K.A.CARE, several changes in the model and database were made. Detailed description of these changes is included in the methodology section.

The purpose of this work is to provide an understanding of the long term economic and environmental impacts (carbon dioxide emissions) of the proposed plan of supplying 50 % of the electricity generation from renewable sources in the world's largest oil exporter, Saudi Arabia. The remainder of the paper is organized as follows. Section 2 summarizes the history and improvement of renewable and nuclear energy in Saudi Arabia. Section 3 presents the modeling framework, the methodology used to modify the model, and database to support simulations of different electricity technologies. In section 4, the simulation scenarios and their economic and environmental results are presented. The results of a sensitivity analysis are presented in Section 5. Finally, conclusions are provided.

3.3 Renewable and nuclear energy in Saudi Arabia

Saudi Arabia has one of the highest insolation rates in the world. As a result, solar energy applications in Saudi Arabia have been growing since the early 1960s, when the French established the first photovoltaic (PV) at Madinah's airport [11]. In 1977, King Abdulaziz City of Science and Technology (KACST) initiated the systemized major research and development of solar energy technologies [12]. A number of international joint programs have been conducted by the Energy Research Institute (ERI) at KACST. The first joint program was with the U. S., and this project established cooperation in the field of solar energy under the Solar Energy Research American Saudi (SOLERAS) [11]. Two traditional villages were supplied with solar energy by SOLERAS, and the project concluded in 1997 [13,14]. Another joint program with the Federal Republic of Germany (HYSOLAR) in 1986 aimed to develop and demonstrate solar hydrogen production [15]. As it is important to have exact measurements of solar radiation in different locations of the country, the Saudi Atlas Project, which is a joint R&D project between the ERI and the National Research Energy Laboratory (NREL) in the U.S., selected twelve cities and collected solar radiation measurements [16]. In 2008, the former Saudi Oil Minister, Ali Al-Naimi, stated that Saudi Arabia has a strategic plan to improve its solar energy expertise. He said to the French Newsletter Petrostrategies: "One of the research efforts that we are going to undertake is to see how we make Saudi Arabia a center for solar energy research, and hopefully over the next 30-50 years, we will be a major megawatt exporter" [11]. Saudi Aramco built a solar power plant with a capacity of 10 MW in December 2011 [17]; another 20 MW solar plant will be built by King

Abdullah University of Science and Technology [18]. As a reflection on the progress toward the use of solar energy, there are currently two factories producing flat plate collectors in Saudi Arabia [19].

There is also an ambitious plan for addition of nuclear energy in Saudi Arabia. A 2010 royal decree stated that the development of nuclear energy is essential to meet Saudi's growing requirements. The Saudi government announced a plan for its first bids in nuclear reactors, their construction is planned to be completed in 2022 [20]. The leaders of Gulf Cooperation Council (GCC) held a meeting in Riyadh in 2006, and announced their joint nuclear energy development program. In 2007, they had an agreement with the International Atomic Energy Agency (IAEA) to perform a feasibility study about nuclear energy in GCC. The feasibility study expected that by 2025 nuclear energy will become operational in the region. After establishing K.A.CARE in 2010, the Saudi nuclear program began to gain momentum. The country has signed bilateral cooperation agreements on nuclear power with different countries including France, South Korea, Argentina, and China [21].The Korean Atomic Energy Research Institute and K.A.CARE signed a nuclear engineering agreement in September 2015, and it will stay effective until November 2018. In addition, Saudi Arabia has sent 41 trainees to South Korea to study and be trained on the nuclear power plant [22].

Regarding wind energy applications in Saudi Arabia, KACST prepared the wind atlas for different locations of the country, which shows that the average wind speeds in certain regions is more than 4 m/s (that is above the cut-in speeds of modern wind energy conversion systems) at a 20 m height. It is expected that the speed would be higher at a height of 100 m, which is the typical height of modern wind turbines. Moreover, the feasibility of different wind turbine capacities were analyzed by using the RETScreen software for five different coastal regions. The analysis concluded that Yanbu and Dhahran, on the north west and east coasts respectively, were economically feasible. [23]

As a result of population growth and urbanization, the quantity of municipal solid waste (MSW) has increased significantly. With an average of 1.4 kg/capita/day, the country generates 14 million tons of MSW annually. The dominant method for the disposal of MSW is landfilling [24]. This is leading the country to invest to utilize its high energy content through MSW incineration technology. The country is also evaluating geothermal options for electricity generation [1].

3.4 Methodology

Implementing the K.A.CARE renewable energy proposal and freeing Saudi's oil to be exported will impact the local and worldwide economy. We use GTAP-E (Burniaux and Truong, 2002), an energy-environmental version of the CGE GTAP Model (Hertel, 1997). The model describes the optimizing behavioral equations of three agents: government, private household and saving in each region. A regional household collects all the regional incomes, and distributes this income to the three agents according to a Cobb-Douglas utility function; the saving's income is subsequently translated into investment. The regional household receives its income by providing the factors of production (labor, capital, land, and natural resources) to firms, and also through taxes. Firms' behavior is governed by the profit maximization condition subject to a production function, while firms combine the factors of production and intermediate inputs to produce a final good. The government demands are determined by a Cobb-Douglas function; while private household demands are governed by a constant difference of elasticity function[1]. In trade, goods are differentiated by their origin according to the Armington assumption [25]. For more details on the GTAP model see Hertel (1997).

GTAP-E is an extension of the standard GTAP model, where energy substitution has been incorporated. It enables study of the consequences of changes in the energy market [27,28]. As all renewable and nuclear energy technologies in the model are aggregated in a single sector, some modifications to the model (by adding new nests to depict the use of renewable and nuclear technologies) and its database were made. In the following subsections, a detailed explanation of these modifications is presented.

3.4.1 Data base modifications

The GTAP 9 database is used in this study. It depicts the economic situation in year 2011, and features 140 countries and 57 GTAP commodity sectors [29]. For this study the database was aggregated into 6 countries/regions and 19 commodities as shown in appendices A.1 and A.2. Since the GTAP-E source database does not have a disaggregated electricity sector, which this study is mainly about, disaggregated electricity production technologies were imported from the GTAP-POWER database [30]. Moreover, because the utilization rates for renewable and nuclear technologies for Saudi Arabia were zero in the database, as the country has not started to utilize them, small shares were introduced artificially to allow for their growing contribution until the

[1] Constant difference of elasticity is nonhomotheteic. It means as consumers' income change, they can spend more on luxury goods and less share of their budget on necessities, based on the income elasticity for each good [10].

Saudi 2032 goals are reached. This approach matches the recommendation by The General Equilibrium Model for Economy-Energy-Environment (GEM-E3) manual that states:

"The shares of each technology in power generation in the base year are introduced from energy balance statistics. Some of the potential technologies that may develop in the future are not used in the base year. Since the production function for power generation is calibrated to the base year, it is necessary to introduce artificially small shares even for the non-existing technologies in order to allow for the possibility of their penetration in the future under market conditions." [31]

Capital expenses of planned and completed renewable and nuclear projects, from Saudi Arabia and other Gulf Cooperation Council (GCC) countries [32], were used to include an accounting of the total expense of the small shares of new technologies. As the new technologies are capital intensive, the input cost of capital, labor, and operations and maintenance (O&M) were taken from the literature (appendix A.3) [21,31,33–37]. Annual expenses (dollars of purchase by each new renewable energy technology from the other GTAP sectors) were estimated based on the GTAP-Power database for the specific countries expected to construct the renewable energy projects for Saudi Arabia. The new Saudi sectors were created according to the fractional contribution from each sector to annual expenses from the corresponding renewable energy technology subsector from the country constructing the new renewable energy infrastructures in Saudi Arabia. Each new sector's internal consumption of its own electricity was determined according to the proportion of the proposed total generation of each technology in 2032. Technologies that will not be used in Saudi Arabia like coal and hydro were set to zero. In addition, two new parameters were added to allow for substitution between the newly added renewable energy nests, as explained in the following subsection.

3.4.2 Model modifications

In GTAP-E, firms' needs for the factors of production and intermediate inputs are based on nested constant elasticity of substitution functions as shown in Figure 3-3. Crude oil, gas and petroleum products are bundled together in one nest to represent the non-coal energy sources for the firms with a substitution elasticity of $\sigma_{ELFNCOAL}$ to allow substitution between them (crude oil, gas and petroleum products), as shown at the bottom of Figure 3-3. The non-coal energy nest is bundled with coal to make a new nest called non-electricity energy with the substitution elasticity of $\sigma_{ELFNELY}$. The non-electricity nest is bundled with the aggregated electricity sector to form the energy nest with a substitution elasticity of σ_{ELFENY}. The energy nest and capital are combined to make the capital-energy nest that is combined with the other endowments to make the endowment-energy nest with substitution elasticities of σ_{ELFKEN} and $\sigma_{ELFVEAN}$, respectively. Finally, the total output nest combines the endowment-energy nest and the non-energy inputs according to a Leontief technology (no substitution between them). One of the main differences between GTAP and GTAP-E is the energy sectors were moved to the endowment nest to allow for substitution. As this study is analyzing the introduction of renewable and nuclear energy, an important modification was made by adding new nests that allow for the substitution between the new technologies and the standard energy sectors. The modifications include adding two electricity nests as shown in Figure 3-4. The first nest combines the transmission and distribution sector (TandD) and the other electricity technologies (Technologies) with a substitution elasticity of zero, as has been suggested in the literature [31,38,39]. The Technologies nest includes eight new technologies (elyoil, elygas, elycoal, wind, nuclear, solar, hydro, and elyother) with a substitution elasticity of 5 as suggested by the OECD ENV-Linkages Model Version 3 [40]. This elasticity was chosen because this study is a long term simulation, until 2032, and simulation length is an important factor in affecting the magnitude of the supply elasticities [41]. This makes building new plants possible and thus substitution feasible, linked to long-term structural prices change among these technologies. As the elasticity of substitution parameter between the electricity technologies is an important factor in determining the ease of substituting one electricity technology for another [42], the sensitivity of the model to this parameter is studied in section 5. Adding new nests implies some modifications to the model by changing and adding new sets and equations as shown in appendix B.

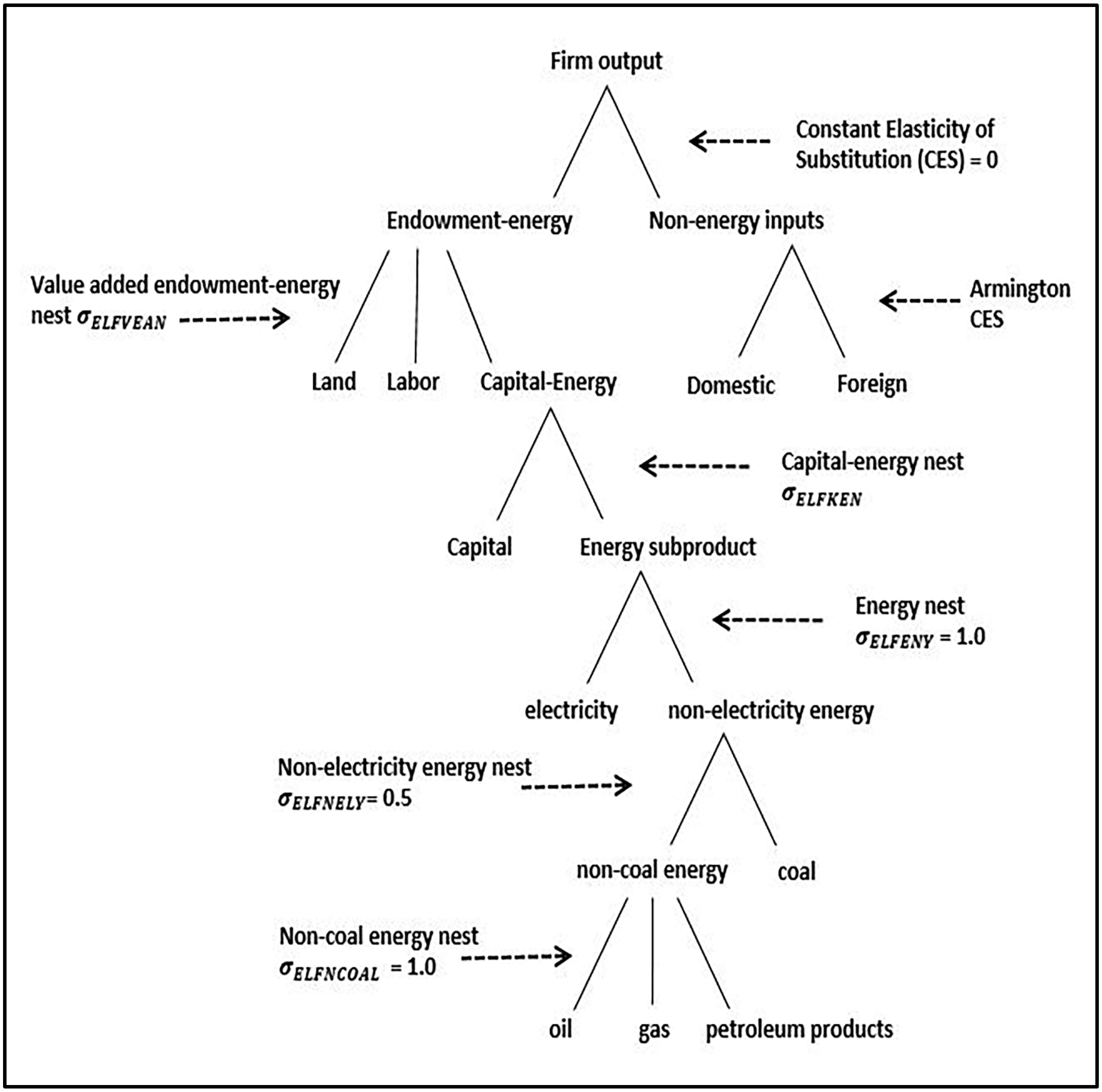

Figure 3-3 Original GTAP-E production structure [27].

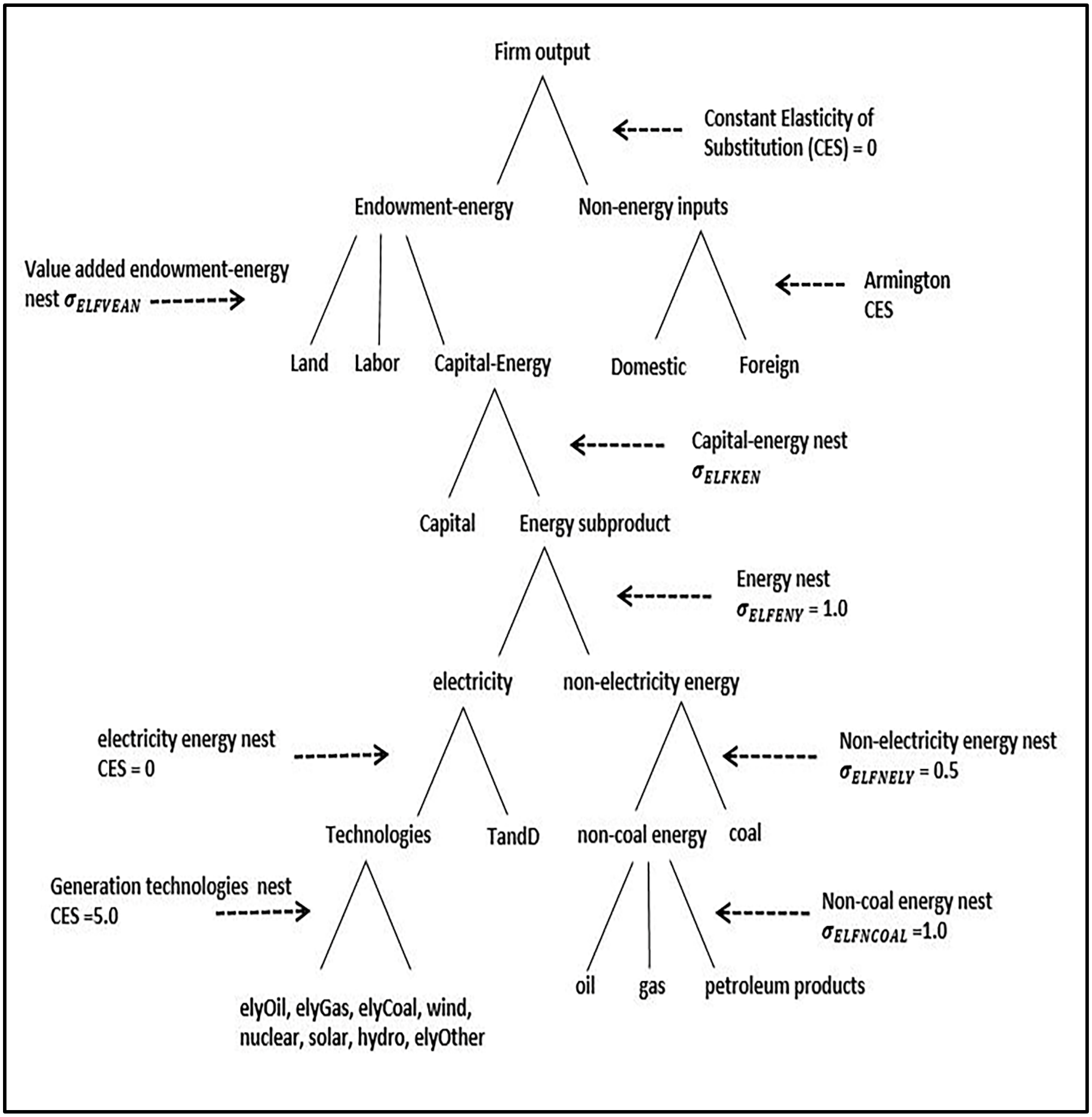

Figure 3-4 Modified GTAP-E production structure.

3.4.3 Simulation Scenarios

Two different scenarios were developed to achieve the goals of this analysis. Both scenarios are for 2032 which requires considering the change in the macroeconomic variables to reflect the growth of the economy. Several sources were used to provide estimates for the projected data. The U.S. Census Bureau was used to estimate global population growth [43]. The projected growth in the gross domestic product and capital were obtained from estimates in the literature [43,44]. The International Labor Organization (ILO) was used for the labor growth projections [45].

The first of the two scenarios represents implementation of K.A.CARE, where half of the total projected electricity demand will be supplied by renewable and nuclear energy by 3032, which results in a situation in which Saudi's ability to export oil is not affected compared to the situation today. The second scenario simulates the situation of 2032 without implementation of renewable or nuclear energy in Saudi Arabia, but instead meeting the future energy demand for electricity production through continued use of fossil fuels. Scenario 2 focuses on oil use only, as the country has decided to use its natural gas as a feedstock for other industries [3]; and as both the recent announced National Transformation Program (NTP) 2020 and Saudi Vision 2030 have identified the petrochemical sector as one of the main sectors to diversify the Saudi economy away from fossil fuel dependence [46]. In scenario 2, Saudi Arabia's ability to export oil is affected as proposed by [47,48]. They have suggested that if the current growth (5 % annually) of Saudi Arabia's domestic oil consumption continues, it will have major implications for its oil production and export level. The actual growth of consumption has been underestimated by the International Energy Agency (IEA) and US Department of Energy (DOE) in their projections [47].

The finite nature of fossil fuels is crucial in this study since deployment of renewable and nuclear energy is strongly affected by the abundance and prices of fossil fuels. Hence, we adopted the “peak oil” theory proposed by Hubbert to enable an accounting of the depletion of oil during the simulation period [49]. The Hubbert curve explains how petroleum production rate of a region or the whole planet follows a bell-shaped curve [49]. As economic growth requires extracting and using more fossil fuels, exploitation of lower quality and harder to access resources becomes necessary, which is more expensive [50]. To simulate this situation in the GTAP model, the price indices of the global oil, gas and coal (pxwcom) sectors were shocked according to predicted fossil fuel prices. This was accomplished by swapping the price indices with the technology change variable for these sectors (aosec) to achieve model closure. This simulates the price increases as a result of technical difficulties of extraction. The predicted fossil fuel prices were taken from the Department of Energy and Climate Change ((DECC) predictions of fossil fuels [51] for the central and high price predictions as the low prices are less than the fossil fuel prices in 2011 (GTAP-9 bilateral merchandise trade data year)) (Appendix C). Table 3-1 summarizes the two scenarios.

Table 3-1 Scenarios analyzed

Scenario	**Description**
1. K.A.CARE	Account for the evolution of the global economy until 2032 Central fossil fuel prices Implementation of renewable and nuclear energy in Saudi Arabia
2. Baseline	Account for the evolution of the global economy until 2032 Higher fossil fuel prices No renewable and nuclear, and increase fossil fuels use in Saudi Arabia

3.5 Results

This section presents the simulated economic and CO_2 emission impacts of implementing K.A.CARE's goals. A comparison of the effects without renewable or nuclear energy generated electricity is made to show the magnitude of the impacts that Saudi Arabia's goals for implementing renewable energy systems may have on the country and the world. To identify the changes that govern the results, the total effect was decomposed into subtotals following Harrison et al. [52]. The decomposition is based on the effects due to changes in fossil fuel prices, evolution of the economy, and the share of each electricity technology.

The decomposition of the results shows that both economic evolution and fossil fuel prices have significant effects. For evolution of the economy, the results are expected as it reflects an increase in the production in all economic sectors that matches with literature projections [53]. The differences between the two scenarios (K.A.CARE and Baseline) are shown in Table 3-2. The electricity production sectors were shocked exogenously for Saudi Arabia, thus ensuring that the mix of renewables was achieved in the simulation. The lower exogenous fossil fuel price leads to a lower electricity production from renewable and nuclear energy for the other regions as shown in Table 3-2 for the total decomposed effect, and Table 3-3 for the decomposed effect of fossil fuel prices. This shift away from renewable and nuclear energy leads to an increase in the production of fossil fuel sectors outside Saudi Arabia. In addition, as shown at the bottom production nest in Figures 3-3 and 3-4, there is a substitution between oil, gas, and petroleum and coal (Oil_pcts). Because of that substitutability, the output of the petroleum and coal (Oil_pcts) sector increases less than oil and gas in all the regions, except Saudi Arabia where it actually decreases. The coal sector in all regions was affected less than the oil and gas sectors because of a higher projected price increase for oil and gas in the baseline vis-à-vis the K.A.CARE scenario (appendix C), which in turn reduced the effect on the amount of electricity generated from coal. The large projected GDP increase in both China and India, and smaller increases in the rest of world led to a large increase of production for all sectors in these countries, especially energy intensive industries. Because of the small role of gas in China's energy mix, a large (percentage change of a small number) increase is shown as a result of K.A.CARE scenario compared to the baseline. The relatively large percentage decrease in coal use for Saudi Arabia, which is not known for coal use, is due to a percentage change of a small number, which the database has for Saudi Arabia. For the decomposed effect of K.A.CARE, it stands to greatly impact the Saudi economy and, through trade, other economies to a lesser extent (Table 3-4). In general, the sectorial outputs, excluding the new electricity technologies, have increased in the other regions, except Saudi, due to the improvement in their terms of trade[2] because of lower cost fossil fuels (Table 3-5). As Saudi Arabia loses export competitiveness for a number of commodities, its sectorial outputs decreased (Tables 3-2 and 3-3). These commodities are agriculture, forestry, and fishing (agriFood), petroleum products (oil_pcts), energy intensive industries (En_Int_ind), water and construction (water_Cons), communication (Transcomm), and other services (OthServices). That is a result of the energy subproduct price decreases, which drives the costs in the other regions down, and as a result makes Saudi Arabian domestic production less competitive against imports.

[2] Terms of trade (tot) measures the power of a country's exports to purchase imports. Its improvement means that a country can buy more imports for each unit of the exports it sells.

Table 3-2 Sectorial output (% difference) (K.A.CARE compared to Baseline scenario).

qo	KSA	USA	EUROPE	CHINA	INDIA	ROW
AgriFood	-2.59	0.59	2.04	0.5	0.7	1.01
Coal	-10.24	11.01	16.83	35.16	-1.65	10.54
Oil	45.5	44.48	42.25	45.01	43.5	42.27
gas	53.22	72.02	78.24	162.15	75.76	74.37
oil_pcts	-37.34	46.7	37.89	35.3	41.97	32.94
En_Int_ind	-24.59	-3.36	3.46	-0.16	5.47	3.09
other_ind	1.21	-0.75	0.68	0	-1.45	1.75
water_Cons	-72.89	5.62	-0.84	4.43	4.96	-4.39
Transcomm	-43.37	2.24	3.27	1.99	3.81	0.13
OthServices	-20	-0.03	-0.85	1.63	0.3	-1.72
TandD	0	-0.64	2.17	1.82	-5.83	0.61
elygas	0	105.66	113.77	95.17	126.24	88.19
elyoil	-71.6	84.56	69.45	73.82	76.37	41.96
elycoal	0	0.83	-11.06	32.66	-21.5	-23.02
nuclear	700	-58.67	-71.19	-91.66	-83.27	-88.85
wind	800	-62.86	-74.92	-97.21	-89.32	-92.21
hydro	0	-64.83	-74.81	-99.48	-91.96	-91.91
solar	4000	-66.85	-79.8	-103.32	-95.59	-94.61
elyother	300	1.39	-44.91	-40.16	-44.19	-62.9

For Tables 3-2 and 3-3:

- Two ranges for the same scale were used: one for KSA and one for other regions.
- the heat map spectrum scale is as following:

KSA -72.9 lowest **highest 4000**

Others-103.3 **162.2**

Table 3-3 the decomposed Sectorial output (% difference) as a result of fossil fuel prices (K.A.CARE compared to Baseline scenario).

qo	KSA	USA	EUROPE	CHINA	INDIA	ROW
AgriFood	0.61	0.59	2.02	0.5	0.68	0.98
Coal	-2.76	11.02	16.86	35.18	-1.63	10.52
Oil	44.32	45.22	43.03	45.74	44.36	43.07
gas	50.19	72.08	78.3	162.3	75.82	74.4
oil_pcts	-36.89	46.79	38.02	35.4	42.45	32.93
En_Int_ind	-21.35	-3.33	3.37	-0.16	5.43	3.01
other_ind	0.03	-0.75	0.66	0.007	-1.47	1.7
water_Cons	-67.66	5.53	-0.96	4.37	4.91	-4.52
Transcomm	-37.7	2.22	3.27	1.99	3.8	0.09
OthServices	-17.49	-0.03	-0.85	1.63	0.3	-1.73
TandD	0	-0.66	2.16	1.82	-5.85	0.58
elygas	0	105.64	113.73	95.23	126.14	88.1
elyoil	0	84.61	69.56	73.99	76.23	41.84
elycoal	0	0.81	-11.08	32.64	-21.51	-23.04
nuclear	0	-58.65	-71.17	-91.65	-83.22	-88.78
wind	0	-62.85	-74.91	-97.2	-89.28	-92.15
hydro	0	-64.81	-74.8	-99.85	-91.92	-91.87
solar	0	-66.84	-79.77	-103.3	-95.55	-94.46
elyother	0	1.42	-44.89	-40.1	-44.2	-63.18

Table 3-4 The decomposed sectorial output (% difference) as a result of K.A.CARE implementation of renewable energy (K.A.CARE compared to Baseline scenario).

qo	KSA	USA	EUROPE	CHINA	INDIA	ROW
AgriFood	-3.2	0.00	0.01	0.001	0.01	0.03
Coal	-7.48	-0.01	-0.02	-0.02	-0.013	0.01
Oil	1.19	-0.75	-0.77	-0.72	-0.86	-0.81
gas	3.02	-0.07	-0.05	-0.15	-0.05	-0.03
oil_pcts	-0.44	-0.10	-0.14	-0.09	-0.50	0.01
En_Int_ind	-3.24	-0.03	0.00	-0.012	0.05	0.08
other_ind	1.17	0.001	0.02	-0.009	0.02	0.06
water_Cons	-5.23	0.10	0.12	0.07	0.06	0.13
Transcomm	-5.67	0.01	0.01	0.00	0.02	0.03
OthServices	-2.5	0.00	0.01	0.006	0.01	0.02
TandD	0.00	0.00	0.00	0.00	0.01	0.04
elygas	0.00	0.01	0.04	-0.08	0.10	0.09
elyoil	-71.6	-0.05	-0.10	-0.16	0.13	0.12
elycoal	0.00	0.01	0.03	0.03	-0.01	0.01
nuclear	700	-0.01	-0.02	-0.01	-0.05	-0.07
wind	800	0.00	-0.02	-0.01	-0.05	-0.06
hydro	0.00	0.00	-0.02	-0.01	-0.04	-0.05
solar	4000	0.00	-0.02	-0.02	-0.05	-0.05
elyother	300	-0.03	-0.02	-0.06	0.00	-0.01

Table 3-5 the decomposition of terms of trade (% difference) (K.A.CARE compared to Baseline scenario).

Region	Total Effect	Decomposition of shocks	
		Fossil fuel prices	K.A.CARE
KSA	-50.98	-50.53	-0.45
USA	7.05	7.02	0.02
EUROPE	1.3	1.3	0.008
CHINA	10.11	10.1	0.01
INDIA	14.03	14.03	-0.01
ROW	-4.44	-4.44	0.009

Comparing the K.A.CARE and Baseline scenarios, economic welfare (as measured by equivalent variation[3]) improves in the USA, Europe, China and India due to lower fossil fuel prices as they are net importers of fossil fuels (USA is a net coal exporter but by small amount), but worsens in Saudi Arabia and ROW (Table 3-6). That is because the lower oil price means that the Saudi's export earnings decreases.

Table 3-6 The decomposition of equivalent variation ($ US millions) (K.A.CARE compared to Baseline scenario).

Region	Total Effect	Decomposition of shocks	
		Fossil fuel prices	K.A.CARE
KSA	-224947	-205136	-19812
USA	230045	229551	494
EUROPE	95374	95181	194
CHINA	158174	158237	-62
INDIA	86093	86131	-39
ROW	-364150	-364614	459

[3] The amount of money a person or a whole economy would be willing to give up (or be paid) to receive the same utility they had before a specified change in economy.

Table 3-7 shows two interesting points. The first is that lower oil prices led to decreased government revenue in Saudi Arabia and Europe. For Saudi Arabia, the reason is very clear as oil revenue represents more than 80% of the government revenue, and lower prices means lower revenue. The reason for the decrease government revenue in Europe is that taxes on oil in Europe are the highest worldwide, and less expensive oil means less tax to the government.

Table 3-7 The decomposition of per capita government expenditure (K.A.CARE compared to Baseline scenario).

Region	Total Effect	Decomposition of shocks	
		Fossil fuel prices	K.A.CARE
KSA	-33.18	-31.36	-1.83
USA	-0.5	-0.5	0.008
EUROPE	-2.53	-2.53	0.001
CHINA	0.86	0.87	0.002
INDIA	1.53	1.53	0.00
ROW	-3.5	-3.5	0.001

Regarding CO_2 emissions, Saudi Arabia showed a slight decrease in its emissions (Table 3-8), because of less electricity generated from oil, and smaller increase in most other sectorial outputs in the K.A.CARE scenario relative to the baseline. A shift away from renewable energy and the higher production of other sectors were the reasons for higher CO_2 emissions in other regions. For India, the increase is lower than other regions because of a larger reduction in electricity generated from coal.

Table 3-8 The decomposition of CO_2 emission (percentage difference), and CO_2 differences (K.A.CARE compared to Baseline scenario).

Region	Total Effect	Decomposition of shocks		million tonne-CO_2
		Fossil fuel prices	K.A.CARE	
KSA	-1.91	15.18	-17.08	-6.97
USA	40.99	41	-0.007	2093.83
EUROPE	45.73	45.73	-0.004	2614.17
CHINA	36.01	36.02	-0.004	2607.91
INDIA	13.39	13.4	-0.005	237.23
ROW	35.95	35.93	0.02	3097.30

3.6 Systematic Sensitivity Analysis

A substitution elasticity of 5, as suggested by the OECD ENV-Linkages Model Version 3 [40], is used between the electricity technologies. This parameter is an important factor in determining the degree of substitution of one electricity technology for another due to price changes. To account for the uncertainty stemming from this parameter, a systematic sensitivity analysis is done. A 50 % decrease and increase of the initial value were used as lower and upper bounds using the Gaussian Quadrature method [54]. We assume triangular distribution for the parameter as its value is most likely to be near the mean. The difference between the mean values of the two scenarios and their standard deviations of the electricity generations technologies (Saudi Arabia is not included as its electricity generation was exogenously shocked) are presented in Figure 3-5. The variation of the technology penetration shows the sensitivity of the model to this parameter. It demonstrates that the magnitude of the new technologies' deployment is strongly affected by the substitutability between the electricity generation technologies. When fossil fuel prices decrease (under the K.A.CARE relative to baseline), then the adoption of renewable and nuclear energy decrease. The smaller effect on the electricity generated from the coal is due to the fact that the coal sector, in all regions, is affected less than the oil and gas sectors because of the higher projected price increase for oil and gas in the baseline (appendix C).

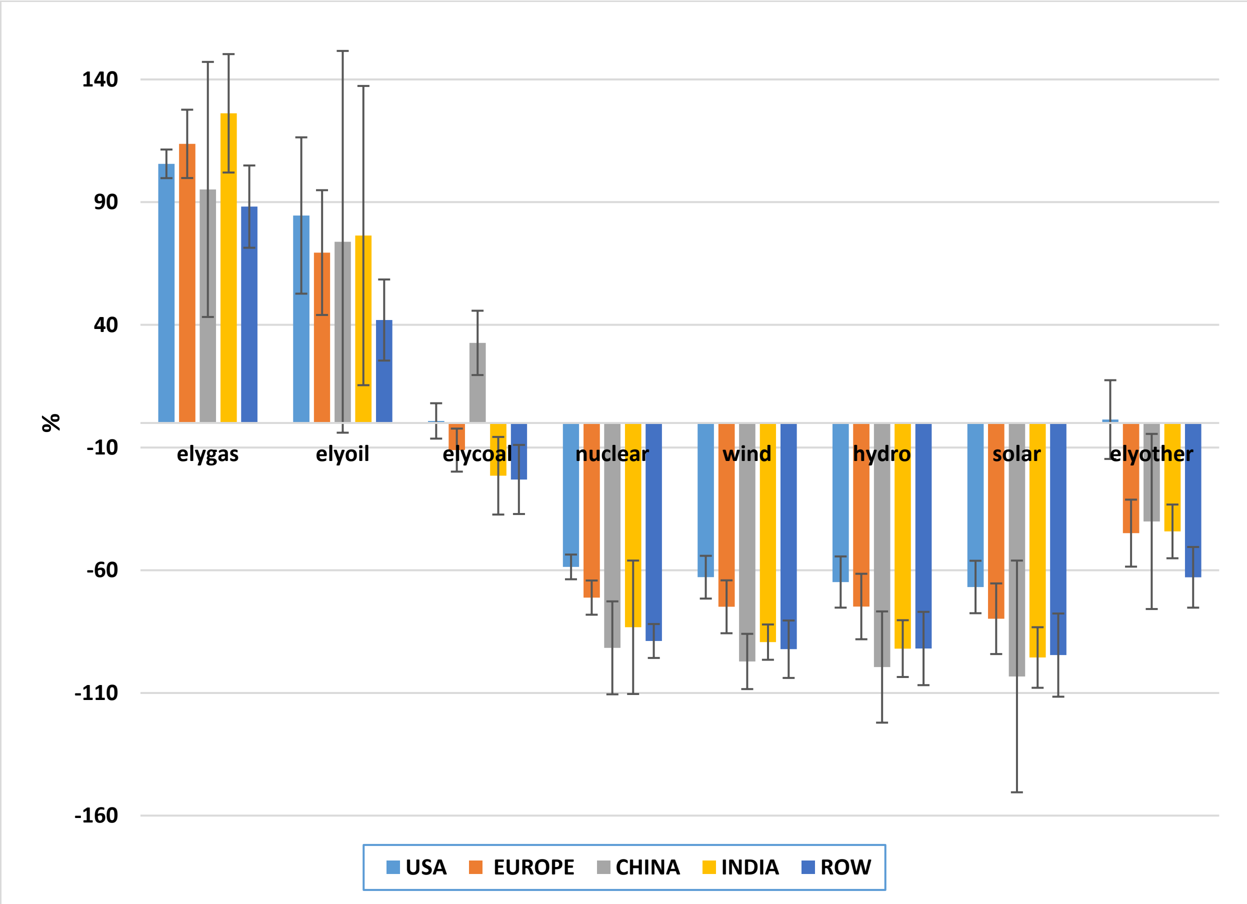

Figure 3-5 Electricity technologies output mean differences (K.A.CARE compared to Baseline scenario)

3.7 Conclusions

This study assessed the economic and CO_2 emissions impacts of deploying renewable and nuclear energy in Saudi Arabia. Because of its large impact on the international oil market, any influence on this sector will not only be important for Saudi Arabia itself, but also the entire world. Two scenarios were developed to account for market conditions up to 2032 under business as usual (baseline) and K.A.CARE conditions. The lower prices of fossil fuels projected by 2032, under the K.A.CARE scenario, decrease the cost of production of most sectors, except renewable and nuclear technologies, in all regions except Saudi Arabia. As a result of that, the welfare and the terms of trade of those regions improve. On the other hand, the opposite result is predicted in Saudi Arabia, where lower fossil fuel prices decrease welfare and worsen the terms of trade, increasing imports and reducing output in most sectors. The lower exogenous fossil fuel prices lead to a lower electricity production from renewable and nuclear energy for the other regions; and as a result an increase in the production of fossil fuel sectors. The emergence of renewable and nuclear energy is mainly driven by energy prices and ease of substitution between them and fossil fuel electricity technologies. Implementing a policy that incentivizes the substitution between the electricity technologies, and raises the price of fossil fuel, like a carbon tax, will increase the shift to renewable and nuclear technologies. As a result, a larger reduction of CO_2 emissions will be obtained. This can be seen in the case of Europe in this study where the tax on oil use is the highest, which led to more CO_2 reduction through the larger shift to the renewable and nuclear technology. However, the lack of wide and comprehensive convention of a carbon tax might lead to carbon leakage associated with imports from regions that do not adopt a similar tax. Since GTAP's data for the CO_2 emissions are coming strictly from fossil fuel combustion, not all greenhouse gas emissions are included. That might be misleading as land use and agricultural activities are other major sources of greenhouse gas emissions. A holistic method incorporating more environmental impacts, including non-fossil fuel GHG emissions, is needed. A method that is able to quantify all relevant emissions and consumed resources and relate them to their respective environmental and health impacts and resources depletion is needed. That will be the goal of a subsequent analysis where the results of the two scenarios (with/without renewable and nuclear energy) will be modeled using a full life cycle assessment (LCA).

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3.9 Appendixes

Appendix A

Appendix Table A.1: Aggregations of GTAP-E regions

GTAP-E region	Member Countries
KSA	Saudi Arabia
USA	United States
EUROPE	Austria, Belgium, Cyprus, Czech Republic, Denmark, Estonia, Finland, France, Germany, Greece, Hungary, Ireland, Italy, Latvia, Lithuania, Luxembourg, Malta, Netherlands, Poland, Portugal, Slovakia, Slovenia, Spain, Sweden, United Kingdom, Switzerland, Norway, Rest of EFTA, Albania, Bulgaria, Belarus, Croatia, Romania, Russian Federation, Ukraine, Rest of Eastern Europe, Rest of Europe
CHINA	China
INDIA	India
ROW	Australia, New Zealand, Rest of Oceania, Hong Kong, Japan, Korea Republic, Mongolia, Taiwan, Rest of East Asia, Brunei Darussalam, Cambodia, Indonesia, Lao People's Democratic Republic, Malaysia, Philippines, Singapore, Thailand, Viet Nam, Rest of Southeast Asia, Bangladesh, Nepal, Pakistan, Sri Lanka, Rest of South Asia, Canada, Mexico, Rest of North America, Argentina, Bolivia, Brazil, Chile, Colombia, Ecuador, Paraguay, Peru, Uruguay, Venezuela, Rest of South America, Costa Rica, Guatemala, Honduras, Nicaragua, Panama, El Salvador, Rest of Central America, Dominican Republic, Jamaica, Puerto Rico, Trinidad and Tobago, Caribbean, Kazakhstan, Kyrgyzstan, Rest of Former Soviet Union, Armenia, Azerbaijan, Georgia, Bahrain, Iran, Israel, Jordan, Kuwait, Oman, Qatar, Turkey, United Arab Emirates, Rest of Western Asia, Egypt, Morocco, Tunisia, Rest of North Africa, Benin, Burkina Faso, Cameroon, Cote d'Ivoire, Ghana, Guinea, Nigeria, Senegal, Togo, Rest of Western Africa, Central Africa, South Central Africa, Ethiopia, Kenya, Madagascar, Malawi, Mauritius, Mozambique, Rwanda, Tanzania, Uganda, Zambia, Zimbabwe, Rest of Eastern Africa, Botswana, Namibia, South Africa, Rest of South African Customs Union, Rest of the World

Appendix Table A.2: Aggregations of GTAP-E sectors

GTAP-E Sector	Description	Comprising
AgriFood	Agriculture,forestry,& fishing	Paddy rice, Wheat, Cereal grains nec, Vegetables, fruit, nuts, Oil seeds, Sugar cane, sugar beet, Plant-based fibers, Crops nec, Bovine cattle, sheep and goats, horses, Animal products nec, Raw milk, Wool, silk-worm cocoons, Forestry, Fishing
Coal	Coal mining	Coal
Oil	Oil extraction	Oil
gas	Gas extraction & distribution	Gas, Gas manufacture, distribution
oil_pcts	Petroleum, coal products	Petroleum, coal products
En_Int_ind	Energy intensive industries	Minerals nec, Chemical, rubber, plastic products, Mineral products nec, Ferrous metals, Metals nec
other_ind	other industries	Bovine meat products, Meat products nec, Vegetable oils and fats, Dairy products, Processed rice, Sugar, Food products nec, Beverages and tobacco products, Textiles, Wearing apparel, Leather products, Wood products, Paper products, publishing, Metal products, Motor vehicles and parts, Transport equipment nec, Electronic equipment, Machinery and equipment nec, Manufactures nec
water_Cons	water and Construction	Water, Construction
Transcomm	Transport and Communication	Trade, Transport nec, Water transport, Air transport, Communication
OthServices	Other Services	Financial services nec, Insurance, Business services nec, Recreational and other services, Public Administration, Defense, Education, Health, Dwellings
TandD	transmission & distrubuition	Electricity transmission & distrubuition
elygas	Electricity from gas	Gas base and peak load
elyoil	Electricity from oil	Oil base and peak load
elycoal	Electricity from coal	Coal base load
nuclear	Electricity from nuclear	Nuclear base load
wind	Electricity from wind	Wind base load
hydro	Hydroelectric	Hydro base and peak load
solar	Electricity from solar	Solar peak load
elyother	Electricity from others	Other base load

Appendix Table A.3: Estimated Electricity Technologies’ Cost Shares for Saudi Arabia

	Nuclear	Wind	Solar	Elyother
Labor	4.2	4.4	4.8	8
Capital	87.6	80	91.2	63.1
Operations and Maintenance	8.1	15.6	3.9	28.9
Total	100	100	100	100

Appendix B

Model Modifications

The GTAP-E model was re-coded and new sets and equations were added; all were in the same style of the standard following McDougall, R. and A. Golub [27].

The following sets' modifications and new sets were added:

- **Set** EGY_COMM *# energy commodities #* (coal, oil, gas, oil_pcts, TandD, nuclear, elycoal, elygas, elyoil, wind, hydro, elyother, solar);
- ENY_GCOMM *# inputs into government energy subutility #*(coal, oil, gas, oil_pcts, TandD, nuclear, elycoal, elygas, elyoil, wind, hydro, elyother, solar);
- **Set** ENY_PCOMM *#inputs into private energy subutility#* (coal, oil, gas, oil_pcts, TandD, nuclear, elycoal, elygas, elyoil, wind, hydro, elyother, solar);
- **Set** SUBF_COMM *# subproducts in demand by firms #* (vaen, ken, eny, ely, elyGen, nely, ncoal);
- **Set** ELYGEN_FCOMM *# inputs into electricity generation energy subproduction #*(nuclear, elycoal, elygas, elyoil, wind, hydro, elyother, solar);
- **Set** ELY_FCOMM *# inputs into electricity energy subproduction #* (TandD, elyGen);
- **Set** ENY_FCOMM *# inputs into energy subproduction #* (ely, nely);

For the two added nests, the following coding was used (same style of :

-Electricity Generation Energy Nest

```
Set
    ELYGEN_FCOMM # inputs into electricity generation energy subproduction #
    (nuclear, elycoal, elygas, elyoil, wind, hydro, elyother, solar);
Subset
    ELYGEN_FCOMM is subset of FIRM_COMM;

Formula (all,j,PROD_COMM)(all,r,REG)
    VFAS("elyGen",j,r) = sum(i,ELYGEN_FCOMM, VFA(i,j,r));
Formula (all,j,PROD_COMM)(all,r,REG)
    VFA("elyGen",j,r) = VFAS("elyGen",j,r);

Coefficient
    FSIZE_ELYGEN # size of ELYGEN_FCOMM set #;
Formula
    FSIZE_ELYGEN = sum(i,ELYGEN_FCOMM, 1);

Coefficient (all,i,ELYGEN_FCOMM)(all,j,PROD_COMM)(all,r,REG)
```

```
    FSHELYGEN(i,j,r)
    # share of i in cost to j of electricity generation energy subproduct #;
Formula (all,i,ELYGEN_FCOMM)(all,j,PROD_COMM)(all,r,REG: VFAS("elyGen",j,r) = 0)
    FSHELYGEN(i,j,r) = 1.0 / FSIZE_ELYGEN;
Formula (all,i,ELYGEN_FCOMM)(all,j,PROD_COMM)(all,r,REG: VFAS("elyGen",j,r) > 0)
    FSHELYGEN(i,j,r) = VFA(i,j,r) / VFAS("elyGen",j,r);

Equation ELYGENFPRICE # price of electricity generation energy subproduct #
(all,j,PROD_COMM)(all,r,REG)
    pf("elyGen",j,r) =
        sum(k,ELYGEN_FCOMM, FSHELYGEN(k,j,r) * [pf(k,j,r) - af(k,j,r)]);

Coefficient (parameter) (all,j,PROD_COMM)(all,r,REG)
    ELFELYGEN(j,r)
    # elasticity of substitution in electricity generation energy subproduction #;
Read
    ELFELYGEN from file GTAPPARM header "EFLG";

Equation ELYGFDEMAND
# demand for inputs into electricity generation energy subproduction #
(all,i,ELYGEN_FCOMM)(all,j,PROD_COMM)(all,r,REG)
    qf(i,j,r) = -af(i,j,r) + qf("elyGen",j,r)
        - ELFELYGEN(j,r) * [pf(i,j,r) - af(i,j,r) - pf("elyGen",j,r)];
```

- Electricity Energy Nest

```
 Set
    ELY_FCOMM # inputs into electricity energy subproduction #
    (TandD, elyGen);
Subset
    ELY_FCOMM is subset of FIRM_COMM;

Formula (all,j,PROD_COMM)(all,r,REG)
    VFAS("ely",j,r) = sum(i,ELY_FCOMM, VFA(i,j,r));
Formula (all,j,PROD_COMM)(all,r,REG)
    VFA("ely",j,r) = VFAS("ely",j,r);

Coefficient
    FSIZE_ELY # size of ELY_FCOMM set #;
Formula
    FSIZE_ELY = sum(i,ELY_FCOMM, 1);

Coefficient (all,i,ELY_FCOMM)(all,j,PROD_COMM)(all,r,REG)
    FSHELY(i,j,r)
    # share of i in cost to j of electricity energy subproduct #;
Formula (all,i,ELY_FCOMM)(all,j,PROD_COMM)(all,r,REG: VFAS("ely",j,r) = 0)
    FSHELY(i,j,r) = 1.0 / FSIZE_ELY;
Formula (all,i,ELY_FCOMM)(all,j,PROD_COMM)(all,r,REG: VFAS("ely",j,r) > 0)
    FSHELY(i,j,r) = VFA(i,j,r) / VFAS("ely",j,r);
```

```
Equation ELYFPRICE # price of non-electricity energy subproduct #
(all,j,PROD_COMM)(all,r,REG)
    pf("ely",j,r) =
        sum(k,ELY_FCOMM, FSHELY(k,j,r) * [pf(k,j,r) - af(k,j,r)]);

Coefficient (parameter) (all,j,PROD_COMM)(all,r,REG)
    ELFELY(j,r)
    # elasticity of substitution in electricity energy subproduction #;
Read
    ELFELY from file GTAPPARM header "EFLT";

Equation ELYFDEMAND
# demand for inputs into electricity energy subproduction #
(all,i,ELY_FCOMM)(all,j,PROD_COMM)(all,r,REG)
    qf(i,j,r) = -af(i,j,r) + qf("ely",j,r)
        - ELFELY(j,r) * [pf(i,j,r) - af(i,j,r) - pf("ely",j,r)];
```

Appendix C

Fossil fuel price projection for 2032 in real 2015 USD

	Central	High
Oil	120	185
Coal	87	109.6
Gas	68	99

4 Macro Life Cycle Assessment based on Computable General Equilibrium Model to Study the Environmental Impacts of Utilizing Renewable Energy by Oil Giant Country

4.1 Introduction

With the expected rise in population and income in emerging economies, the global demand for energy will increase. That emphasizes the importance of having affordable and secure energy sources on the one hand and achieving sustainable greenhouse gas (GHG) emissions reduction on the other hand [1]. Some well-intentioned sustainable policies might have an unintended side effects, and failing to account for these side effects could lead to myopic and overly optimistic projections [2]. Saudi Arabia, the biggest oil exporter worldwide, is caught between two interlocking challenges. The first is the subject of a report from Chatham House institute called "Burning Oil to be Cool", which elaborates on the hidden Saudi energy crisis. According to the report, the Saudi massive domestic oil consumption causes pollution to the environment and erode the country's ability to export oil causing volatility in the global oil market, and as a result, a crisis in the Saudi and world economies [3]. The second is similar to a phenomenon that is called "the green paradox" where a policy intended to stimulate the green technologies might lead to more environmental damage by bringing more fossil fuels into use [4]. Saudi Arabia's anticipated electricity demand will be double its current capacity and will exceed 120 GW by 2032. Its current primary source for electricity generation is fossil fuel; 8.3 million barrels of oil equivalent per day in 2028 are expected to be burned domestically if the current energy consumption trend continues. That is more than twice what was burned in 2010 (3.4 million barrels of oil equivalent per day). With that pattern of consumption, the country will be consuming 80 % of its oil production by 2032. That represents a threat to the international oil market as the country's oil exports, which are more than 7 million barrels per day (MBD), make up 32% of the production of the Organization of the Petroleum Exporting Countries (OPEC), which in turn forms 60% of the international traded petroleum. Thus, the global price of oil is sensitive to any change or interruption in Saudi oil exports. Knowing its role in the global oil market, and hoping to maintain leadership instead of succumbing to the consequences of its own consumption, the country plans to diversify its electricity mix through a deployment of renewable and nuclear energy by 2032. This program is called King Abdallah City for Atomic and Renewable Energy (K.A.CARE), and under this plan, more than half of Saudi's energy needs will be met by non-fossil sources. In K.A.CARE, the suggested electricity mix will be as follows: 60 GW (45.6 %) from hydrocarbons, 41 GW (31.16%) from solar, 17.6 GW (13.37%) from nuclear, 9 GW (6.84%) from wind, 3 GW (2.28%) from waste and 1 GW (0.76%) from geothermal [5]. K.A.CARE is still current even with the recent announcement of the Saudi 2030 vision, and the Ministry of Energy, Industry and Mineral Resources (MEIM) will manage it. (M. Al-Abdalla, personal communication, July 4, 2017)

As the Saudi ability to export oil will be altered if and when K.A.CARE program is implemented, the global oil price will be affected, potentially inducing changes in the electricity mixes utilized in other parts of the world. The speed and extent of these changes will vary based on elasticity of substitution of one source of energy for another in each region, resulting in different non-linear environmental impacts. Thus, using a method that can account for the large-scale direct and induced consequences of K.A.CARE is mandatory. Life cycle assessment (LCA) is a holistic method to track and evaluate the environmental impacts associated with a process or a system at each phase of the product's life cycle from the extraction of natural resources to the end of life phase (cradle to grave). The consequential LCA (CLCA) perspective appears suitable here as this analysis depends on the broad consequences of a potential change in Saudi Arabia [6]. In addition, as the changes K.A.CARE could make are non-marginal and affect other regions' economies, an integration of LCA modeling and computable general equilibrium (CGE) economic model seems well-suited, as recommended by Danders [7,8].

The objective of this work is to evaluate the environmental impacts of the proposed plan of K.A.CARE where half of the electricity generation will be met by renewable and nuclear sources in a developing oil giant country like Saudi Arabia. The remainder of the paper is organized as follows. Section 2 presents the methodology and databases used to support simulations of different scenarios. In section 3, the simulation results are presented, and a validation of the results using historical data is provided. Finally, conclusions are drawn.

4.2 Methodology

The potential environmental impacts of K.A.CARE were evaluated using the consequential LCA perspective, where the K.A.CARE's consequences were tracked by using a computable general equilibrium (CGE) economic model called GTAP-E. It features 57 GTAP sectors for each of the 140 countries in its database, and its reference year is 2011 [9]. In this study, the countries and sectors were aggregated as shown in appendices A.1 and A.2. Figure 4-1 depicts the steps of the method. The goals of the analysis are achieved by developing two different scenarios in GTAP-E: K.A.CARE and Business as Usual (BAU). They both are for 2032, which requires considering the evolution of macroeconomic variables (e.g. population, GDP, capital, labor) as a reflection for economic growth. K.A.CARE simulates the situation where renewable and nuclear energy will supply half of the total Saudi projected electricity demand in 2032. Business as Usual (BAU) represents a scenario in which Saudi continues using fossil fuels to meet all its future demand for electricity, which in turn, affects its ability to export oil. For more information about the model and details of scenarios, see [5]. The GTAP database could be seen as our initial equilibrium. The studied scenarios were introduced to the model as shocks, which define global economic perturbations and lead to new equilibria. Thus, the functional unit of each scenario of this study is the entire domestic production of each region, and by modeling all the regions, we are modeling the whole world. As the outputs and interdependence of sectors in GTAP are presented in monetary units, which is not what environmental databases require, they were converted to physical units to compute the environmental impacts. The United Nations (UN) Comtrade database for the same reference year of GTAP [10], which has a traded commodities as a value (in US dollar) and weight (in kg), is used for the conversion for each specific region. The classification of the UN Comtrade database is based on the Harmonized System (HS), which is a coding system to describe commodities. GTAP has concordances between its sectors and the HS codes. The HS is a fairly detailed representation of all world trade items classified based on the nature of the materials in 5224 subheadings [11]. As it is time-consuming to include all those products for all the regions, they were sorted from highest to lowest according to their mass of production, and about 70-80% of them were modeled in detail; the remaining commodities were modeled in less detail by using the Central Product Classification (CPC) system, which is more aggregated than the HS system [12]. Sectors like coal, oil and gas were modeled solely based on the HS, as they do not include many products; that gives the study the advantage of having detailed information about the types of coal, oil and gas products produced in each region. That makes a big difference when it comes to analyzing the environmental impacts of those sectors; e.g. coal in the HS is classified into several types with different carbon content: anthracitic, bituminous, briquettes, lignite, and peat. Specific regional variations in each sector were considered; e.g. whether gas drilling is onshore or offshore. The GTAP sectors' processes are mapped to physical units in ecoinvent, which is a well-documented life cycle inventory database with thousands of products and processes [13,14]. As the ecoinvent database is a background database where the complete supply chain of any process is included, it is important to avoid double counting. That was done in the GTAP input-out (IO) table by subtracting the inputs of sectors that were accounted for in previously modeled sectors, considering their interdependence where each industry (sector) in every column purchases inputs from every other industry in every row. It is very confusing to do that in ecoinvent, as each process there includes multiple other processes that in turn include still more processes. Electricity mix was modeled by itself completely and removed from all other sectors' processes in ecoinvent; that was done by exporting the results of the other sectors' processes to an excel sheet and removing all electricity inputs by filtering electricity units. Sectors like transportation and retail activities were not modeled by themselves since the ecoinvent market processes were used, and they already include the average transport and retail activates of each product [15]. For processes like some food products that do not exist in the ecoinvent database, even though they exist in other database inventory libraries, we created them to avoid mixing libraries. SimaPro software [16] was used to build the two scenarios; the Recipe impact method was used to translate the long list of resources extracted and hazardous substances into 18 mid-point impact categories as defined in Table 4-1 [17]. A comparison between the two scenarios was performed to evaluate which of them has more or less damaging environmental impact, and to differentiate between consequences of the studied policy and those of economic growth.

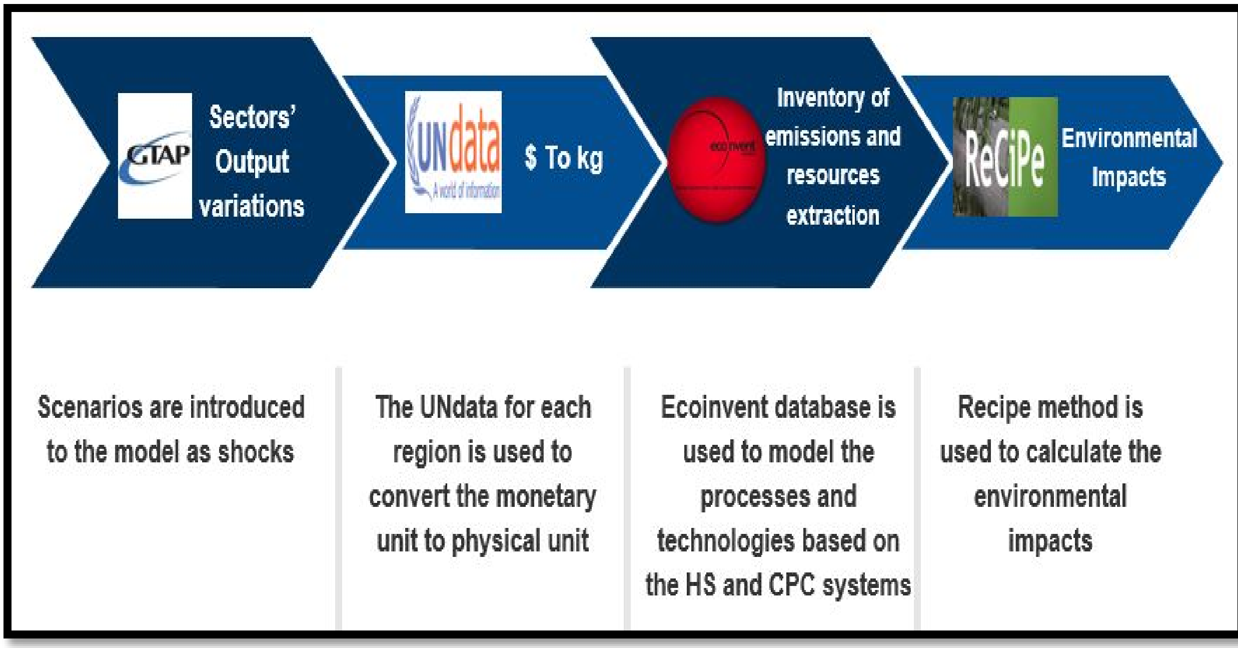

Figure 4-1 the methodology's steps

Table 4-1 Recipe impact categories

Impact category	Unit	Scale
Climate change	kg CO_2 eq	Global, regional, local
Agricultural land occupation	m2a	Global
Fossil depletion	kg oil eq	Global, regional, local
Freshwater eutrophication	kg P eq	Local
Freshwater ecotoxicity	kg 1,4-DB eq	Local
Human toxicity	kg 1,4-DB eq	Global, regional, local
Ionising radiation	kBq U235 eq	Local
Marine ecotoxicity	kg 1,4-DB eq	Local
Marine eutrophication	kg N eq	Local
Metal depletion	kg Fe eq	Global, regional, local
Natural land transformation	m2	Global, regional, local
Ozone depletion	kg CFC-11 eq	Global
Particulate matter formation	kg PM10 eq	Global, regional, local
Photochemical oxidant formation	kg NMVOC	Regional, local
Terrestrial acidification	kg SO2 eq	Regional, local
Terrestrial ecotoxicity	kg 1,4-DB eq	Local
Urban land occupation	m2a	Global, regional, local
Water depletion	m3	Regional, local

4.3 Results and Interpretations

The environmental impacts of the two scenarios are presented and interpreted in this section. First, to validate the legitimacy of the method used, a comparison of the CO_2 emissions with different CO_2 emission estimates by different sources is provided. CO_2 emission was chosen for validation as there is vast literature about climate change, especially for the regions in this study. Second, a comparison between the two scenarios is presented to identify which scenario has lower impacts, and to isolate the effects of the policies from the effects resulting from demographic and economic growth.

4.3.1 The method's Validation

Before comparing our results with other estimations, it is essential to keep in mind that substantial differences can be found between CO_2 emissions estimations published by different organizations, agencies, and private companies [18] . Variation in the estimated primary energy use is one of the main reasons behind that; e.g. In 2007, the data from the Energy Information Administration (EIA) differ by about 5% from BP Energy Company, and by only 1% from the International Energy Agency (IEA) [18]. In addition, the studies' boundaries or what emission sources or emission factors they consider might differ. Also, weather land-use is included, and whether it is counted as a 'net' or 'gross' (net emissions account for difference in the CO_2 emissions between the studied year r and base year, while gross accounts for the studied year's CO_2 emissions without comparing it to the base year [19]) can change the results. For this study, the boundaries include the whole economy. The International Energy Agency (IEA) [20], U.S. Energy Information Administration (EIA) [21], BP Energy [22], Earth Policy Institute (EPI) [23] and Global Carbon Atlas (GCA) [24] include the CO_2 equivalent emissions resulting from fossil fuel combustion. The United Nation Framework Convention on Climate Change (UNFCCC) includes emissions from fuel combustion, industrial processes, transportation, solvent and other products use, agriculture, waste and land use change activities [25]. The Emission Database for Global Atmospheric Research (EDGAR), which is the emission baseline for Intergovernmental Panel on Climate Change (IPCC) [26], accounts for CO_2 equivalent emissions from fossil fuels and cement production [27]. Finally, the Carbon Dioxide Information Analysis Center (CDIAC) accounts for CO_2 equivalent emissions from burning fossil fuels, manufacturing cement and flaring gas [28]. Moreover, an analysis done by Z. Liu and co-authors showed that the CO_2 emissions from China might be overestimated by other sources; e.g. in 2008, a difference by

1.1E12 Kg CO_2 equivalent was found in the inventories of the total fossil fuel CO_2 emission in China. By using a special assessed activity and emission factors' specific to China, they found that the applicable emission factor for coal in China is about 40% less on average than the factors reported by the IPCC, which are used by most emissions inventories [26].

Table 4-2 shows estimates of CO_2 equivalent emissions for all the regions from this study and by different sources for the reference year (2011) of the GTAP database or the closest year to that if the estimation from 2011 was not found. As was mentioned, the comparison is not simple, but it could be used to validate this study's methodology and whether its estimation makes sense or not. It could be said that this study's results are higher than most other estimations. This arises from the wider boundary that this study uses. Also, we believe that using the HS system, especially with the energy commodities, gives the study the advantage of having detailed information about the different types of coal, oil and gas and their carbon content. The fact that our results are only slightly higher than most other studies, even with a wider boundaries, suggests that some studies might be overestimating the emission factors of certain fuels type, as Z. Liu's study finds for China [26].

Table 4-2 shows estimates of CO_2 equivalent emissions from this study and by different sources in kg CO_2 eq.

	This Study (2011)	IEA (2011)	EIA (2011)	BP (2011)	EDGAR (2011)	GCA (2011)	EPI (2011)	CDIAC (2011)	UNFCCC (2010)*
China	8.70E+12	8.51E+12	8.12E+12	8.98E+12	9.84E+12	9.73E+12	7.92E+12	9.02E+12	1.13E+13
USA	5.65E+12	5.21E+12	5.48E+12	6.02E+12	5.39 E12	5.57E+12	5.26E+12	5.31E+12	6.21E+12
India	2.29E+12	1.67E+12	1.66E+12	1.80E+12	1.96E+12	1.84E+12	1.98E+12	2.07E+12	1.85E+12
Saudi	5.26E+11	4.35E+11	--	6.02E+11	4.38E+11	5.00E+11	4.32E+11	5.20E+11	5.16E+11
EU	4.77E+12	3.46E+12	--	4.06E+12	3.74E+12	--	--	--	4.47E+12
ROW	1.18E+13	1.20E+13	--	1.25E+13	1.87E+13	--	--	--	--
Total World	3.376E+13	3.13E+13	3.18E+13	3.4E+13	3.5E+13	3.48E+13	--	3.5E+13	--

- For china, UNFCCC year is 2012

4.3.2 Comparison of the scenarios

A comparison between the environmental impacts of the two scenarios for each region's domestic production and the processes that are responsible for the higher impacts are presented in this subsection. That was done by calculating the percentage difference between the environmental impacts of the two scenarios. A negative percentage difference indicates that the K.A.CARE has less environmental impact; positive percentage indicates the opposite. Higher percentage difference of an impact does not necessarily imply that this impact category is the most intense comparing to the other categories in each scenario.

For Saudi Arabia, as shown in Figure 4-2, implementing K.A.CARE is predicted to reduce all the impacts, except fossil depletion, ionizing radiation, ozone depletion and urban land occupation. It is eye-catching that more fossil fuels would be depleted even when the country is utilizing more renewable and nuclear energy. That was because the shocked cheaper oil price in the K.A.CARE scenario compared to BAU incentives the use of oil in the other regions, resulting in increasing Saudi's oil exports. This shows the importance of links between environments and economies, which also explain why K.A.CARE performs better than BAU for most impacts as imports increase and the Saudi industries' outputs decrease, as in detailed in [5]. Climate change and photochemical oxidant formation, and to a lesser extend particulate matter formation and terrestrial acidification, are the environment impacts most reduced by K.A.CARE. On the other hand, the most detrimental impacts are ionising radiation and ozone depletion. For climate change, it is clear that the utilization of renewable and nuclear energy, in the K.A.CARE scenario, is the reason for the reduction of CO_2-eq emissions. Figure 4-3 shows the processes contributed the most for the categories with higher percentage differences. Natural gas, petroleum and petrochemical processes are responsible for most photochemical oxidant formation impact. Electricity generation from oil, agricultural processes like fertilizers production and conversion of forest to arable land are the processes responsible for the greatest particulate matter formation and terrestrial acidification impacts. For ionising radiation, tailings from uranium milling, electricity from nuclear and its radioactive waste are the most impactful processes. On-shore oil and natural gas production and trichloromethane production are the main processes behind most ozone depletion.

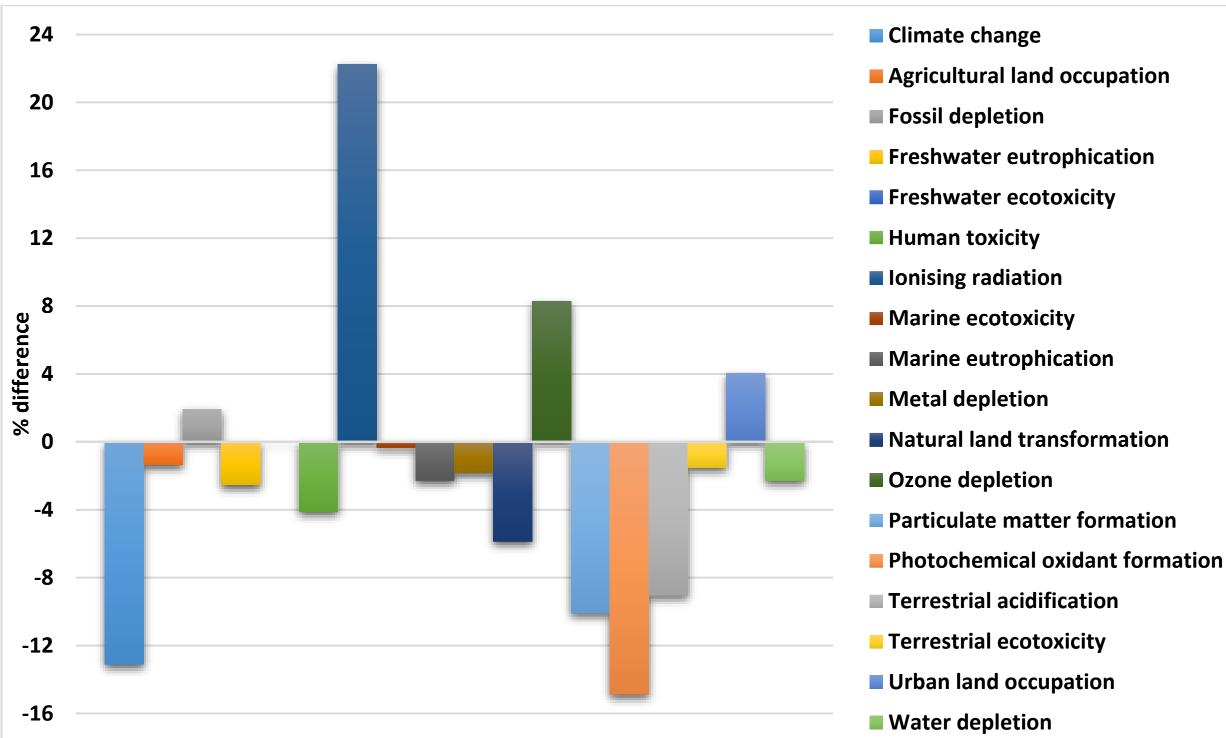

Figure 4-2 Saudi Arabia's environmental impacts' differences between the two scenarios

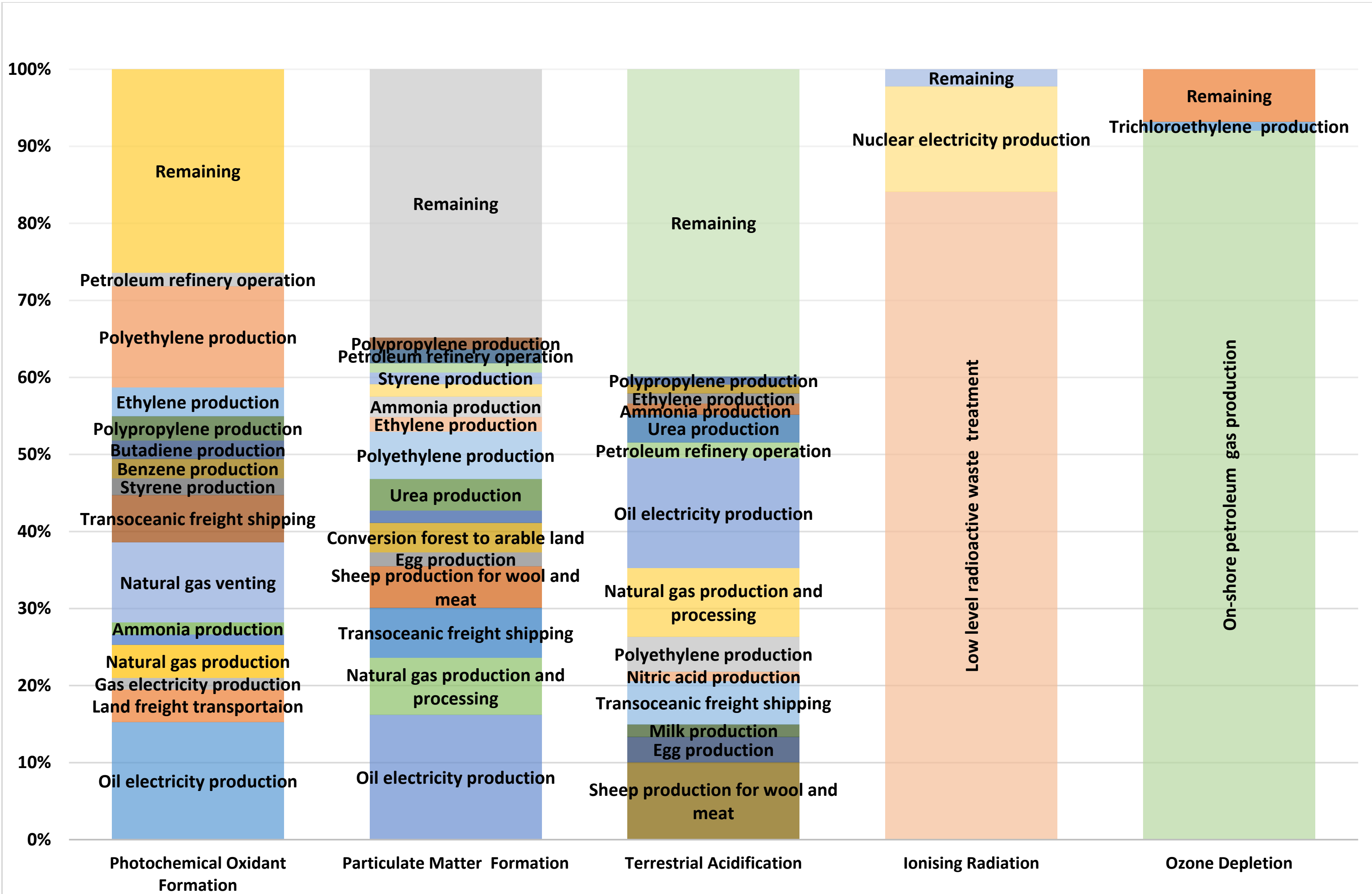

Figure 4-3 the environmental impacts with higher percentage difference between the two scenarios

In China, the results, in Figure 4-4, show a worse environmental performance, although the differences are small, of the K.A.CARE scenario compared to the BAU. That is mainly a consequence of cheaper fossil fuel prices that K.A.CARE causes compared to BAU. Fossil depletion, Climate change, ionising radiation and photochemical oxidant formation are the most affected by the K.A.CARE compared to BAU. The utilization of more fossil fuels, in the K.A.CARE scenario as a result of their cheaper prices, is clearly the reason for fossil depletion. Figure 4-5 shows the processes contributed the most for the other categories. The processes that contribute the most to climate change impact are coal either its mining operation or electricity generated from it. Ionising radiation is impacted the most by these processes: low level radioactive waste treatment and tailings from uranium milling. The processes that impact the photochemical oxidant formation the most are coal either its mining operation or electricity generated from it, and petroleum refinery operation.

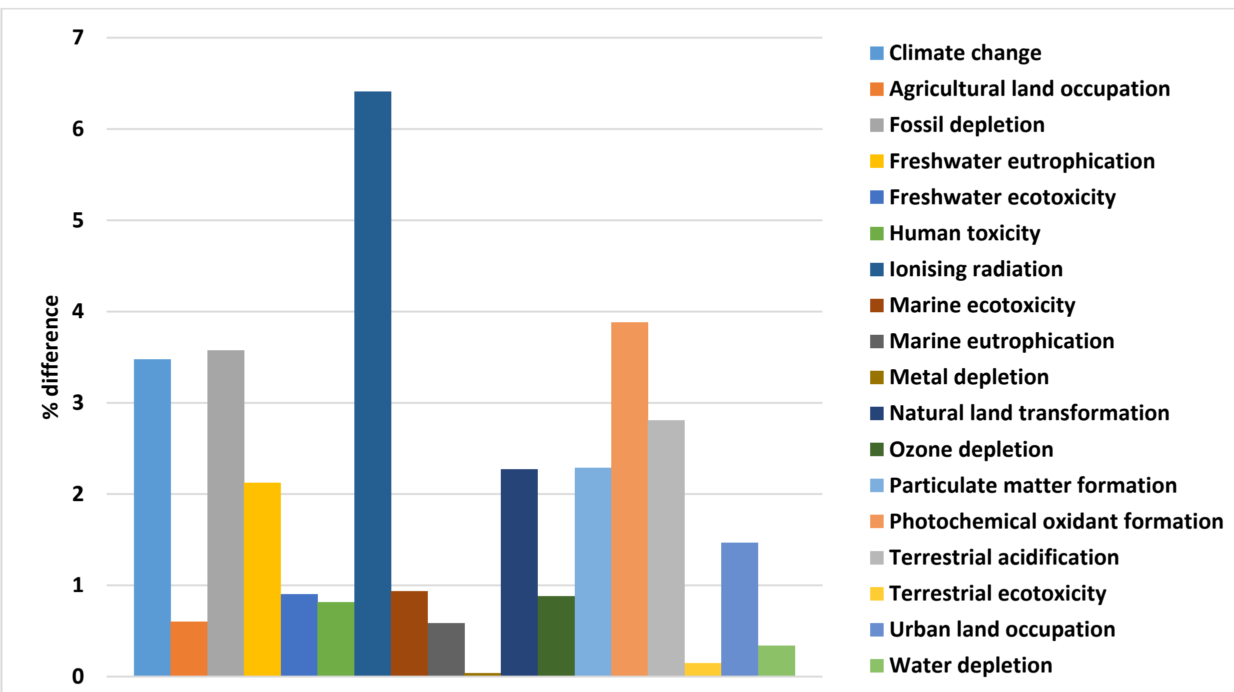

Figure 4-4 China's environmental impacts' differences between the two scenarios

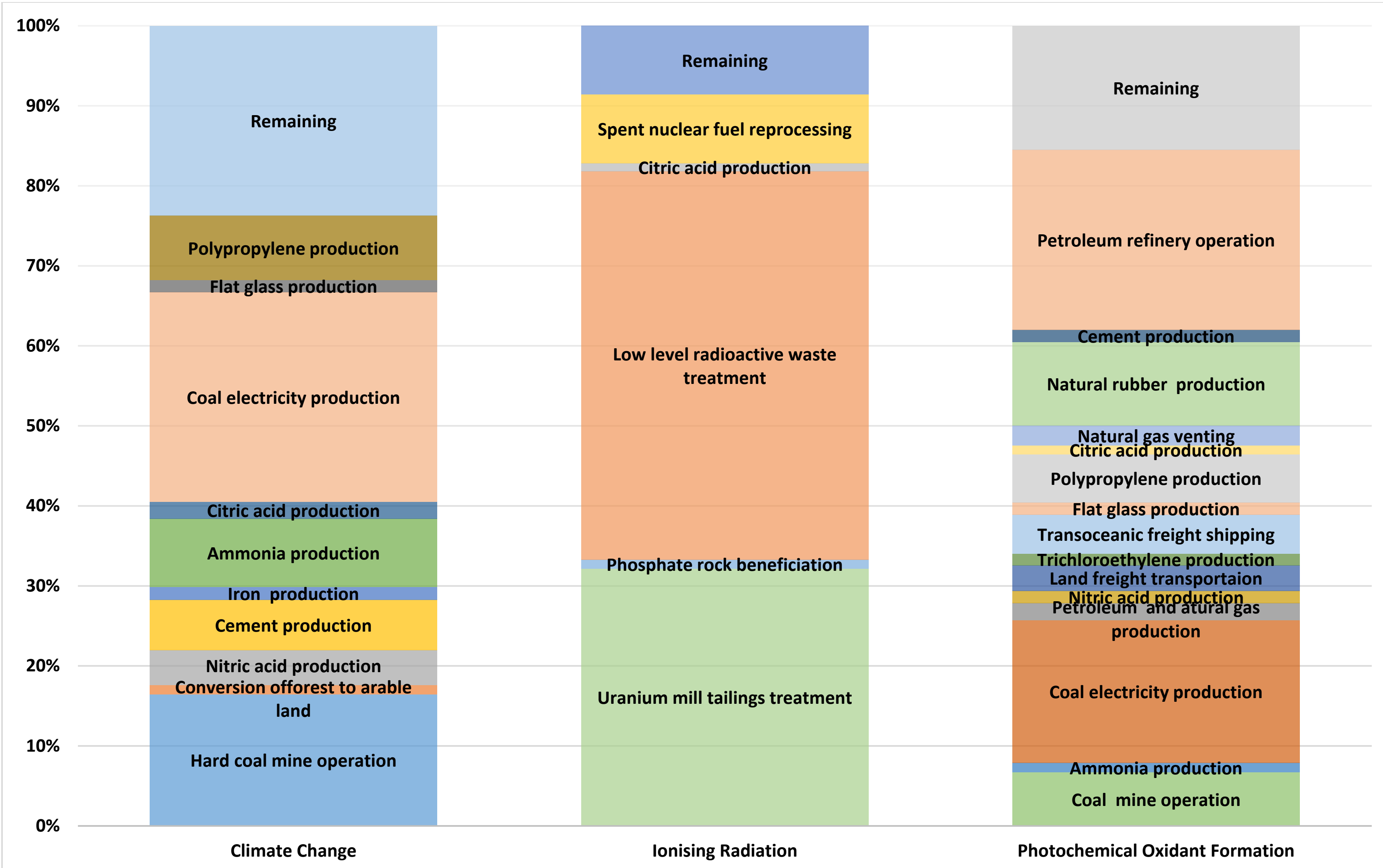

Figure 4-5 The environmental impacts with higher percentage difference between the two scenarios

Europe (EU), Figure 4-6, is predicted to be the most affected region by the K.A.CARE scenario compared to the BAU. Fossil depletion, climate change, natural land transformation, ozone depletion, and photochemical oxidant formation are the most negatively affected categories by the K.A.CARE compared to BAU. Ionising radiation is the only positively affected category. The utilization of more fossil fuels, in the K.A.CARE scenario as a result of their cheaper prices, is clearly the reason for fossil depletion. Figure 4-7 shows the processes contributed the most for the other categories. The processes that affect climate change most are mostly electricity generated from coal, natural gas and oil. The natural land transformation impact is affected the most by onshore well for oil/gas production, and conversion of forest to arable land. The processes most accountable for ozone depletion are onshore petroleum and gas production, trichloroethylene production, and natural gas long distance pipeline transport. In fact, as a result of the pipeline transport of Russian natural gas, ozone depletion impact has been reported in an LCA study of tire nanomaterial in Europe [29]. Photochemical oxidant formation is affected the most by electricity production from coal, natural gas and oil, and petroleum refining. For the only reduced impact, ionising radiation, the processes that contributed the most are tailings from uranium milling, electricity from nuclear and its radioactive waste.

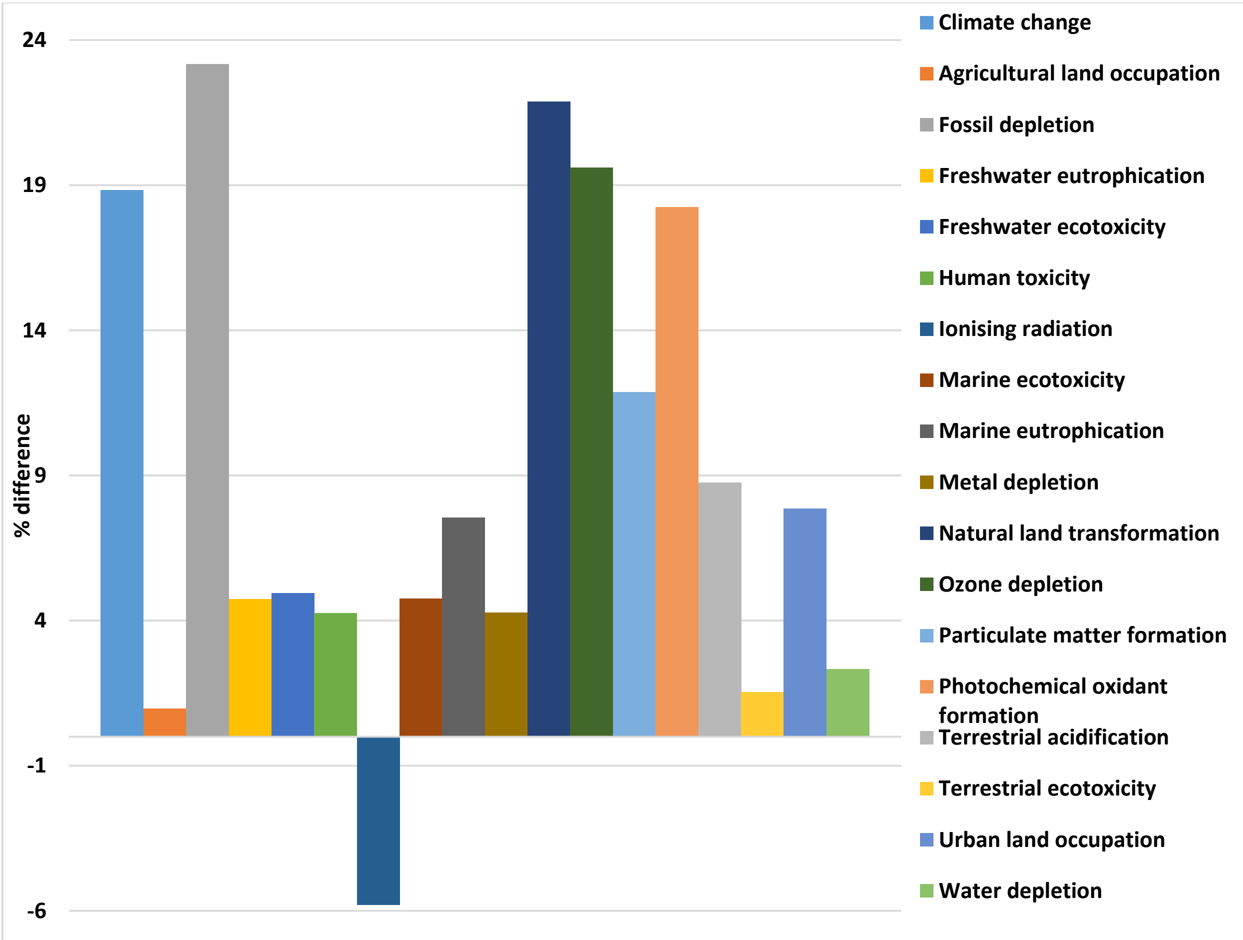

Figure 4-6 EU's Environmental impacts' differences between the two scenarios

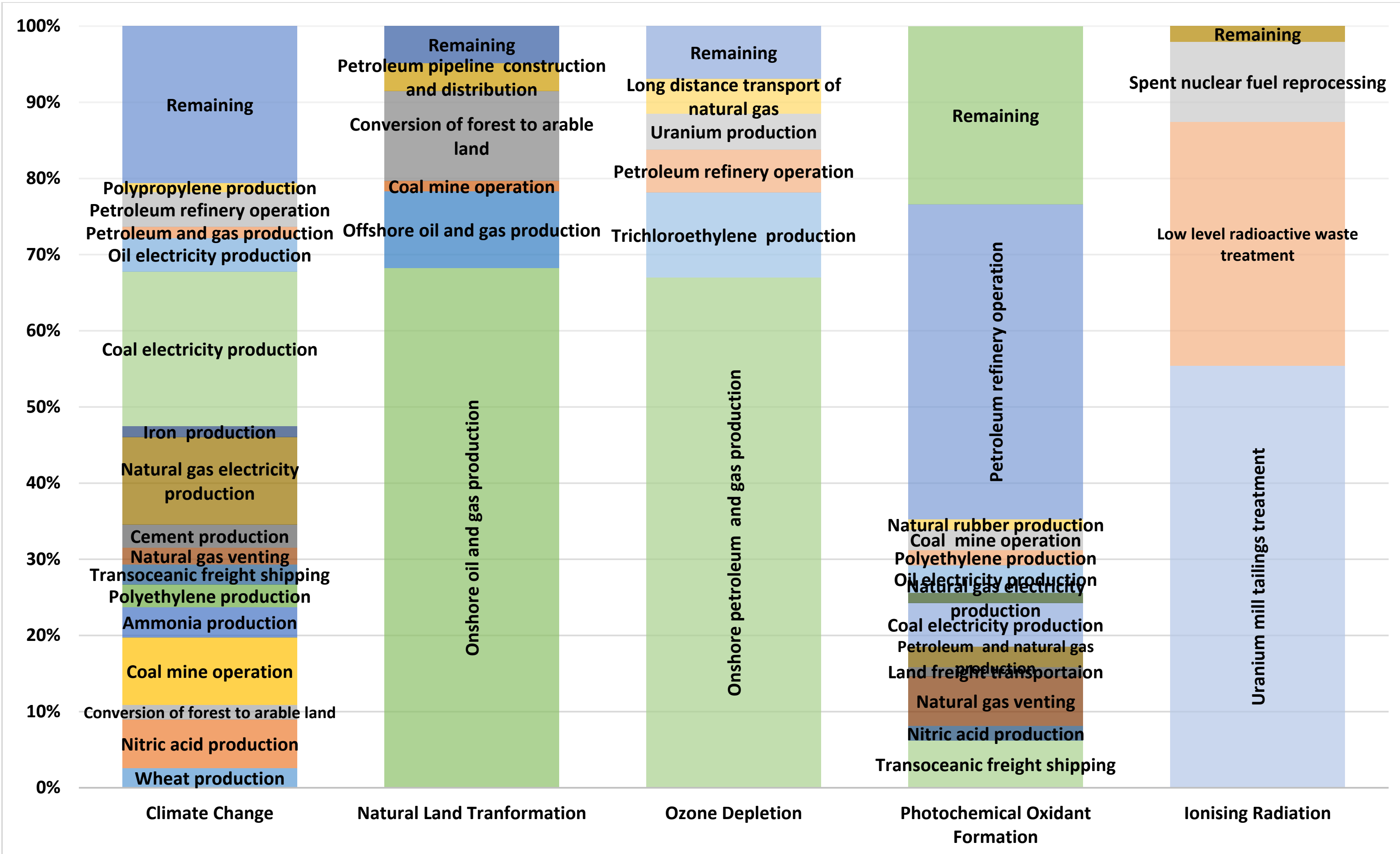

Figure 4-7 the environmental impacts with higher percentage difference between the two scenarios

India, for most the impacts, is predicted to be slightly negatively affected by the K.A.CARE scenario compared to the BAU as shown in Figure 4-8. Fossil depletion, natural land transformation, ozone depletion, and photochemical oxidant formation are the most affected impacts. Particulate matter formation, and water depletion are slightly improved. The utilization of more fossil fuels, in the K.A.CARE scenario, is clearly the reason for fossil depletion. Figure 4-9 shows the processes contributed the most for the other categories. For natural land transformation, the processes that contributed the most are the production of fossil fuels and conversion of forest to arable land. Ozone depletion is affected the most by onshore petroleum and gas production, and trichloroethylene production. The processes that are responsible the most for photochemical oxidant formation impact are petroleum refinery operation, and electricity production from coal. On the other hand, the improved particulate matter formation category is affected the most by electricity production from coal. Finally, the process that impacted the water depletion the most is mainly from the irrigation and hydroelectricity production. They contribute to the water depletion because of the large amount evaporation from the surface area of their reservoirs, which globally sum up to 66E9 m3 per year [30]. That increasingly led to not acknowledge the reservoirs as in-stream water users as there is a removal from the water body [30].

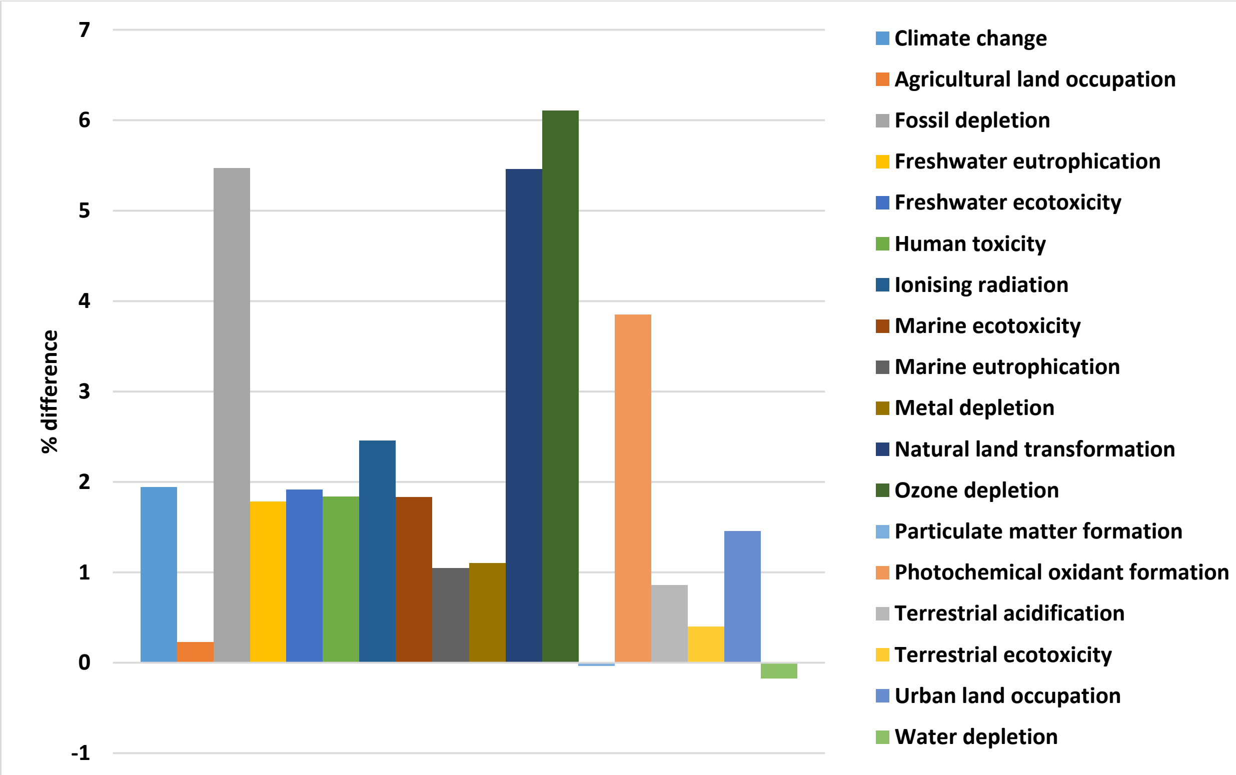

Figure 4-8 India's environmental impacts' differences between the two scenarios

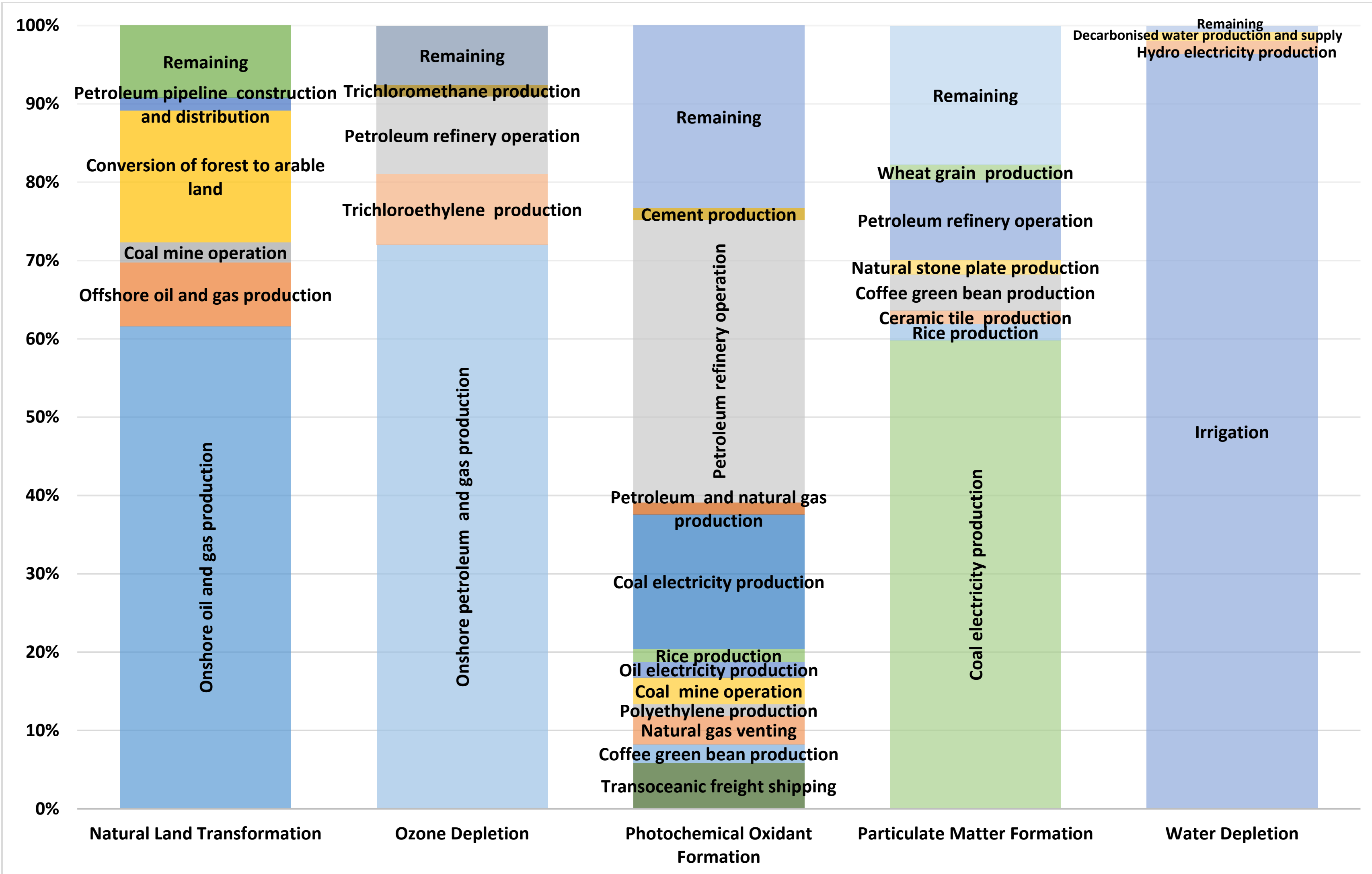

Figure 4-9 The environmental impacts with higher percentage difference between the two scenarios

The United States (USA), as in Figure 4-10, is predicted to be significantly affected by the K.A.CARE scenario compared to the BAU, for some impacts. The impacts that are negatively affected the most are fossil depletion, natural land transformation, ozone depletion, photochemical oxidant formation and urban land occupation. On the other hand, the categories showing improvement are human toxicity, terrestrial acidification and ionising radiation; the first two are significantly benefited. The use of more fossil fuels, in the K.A.CARE scenario, is clearly the reason for fossil depletion. Figure 4-11 shows the processes contributed the most for the other categories. For natural land transformation, the processes mainly responsible are conversion of primary forest to arable land, and onshore oil and gas production. Ozone depletion is affected the most by onshore petroleum and gas production, petroleum refinery operation, and trichloroethylene production. Photochemical oxidant formation is affected the most by petroleum refinery operation, and electricity production from coal. For urban land occupation, the processes most responsible are drying of maize straw processing, drying of bread grain, seed and legumes processing, road and railway track construction and mine operation construction. For the first benefited impact, human toxicity, the processes that contribute the most is coal mining spoil and tailing treatment. Terrestrial acidification is impacted the most by natural gas production, grain production, and electricity production from coal. Finally, the processes accountable the most for ionising radiation are tailings from uranium milling, electricity from nuclear and its radioactive waste.

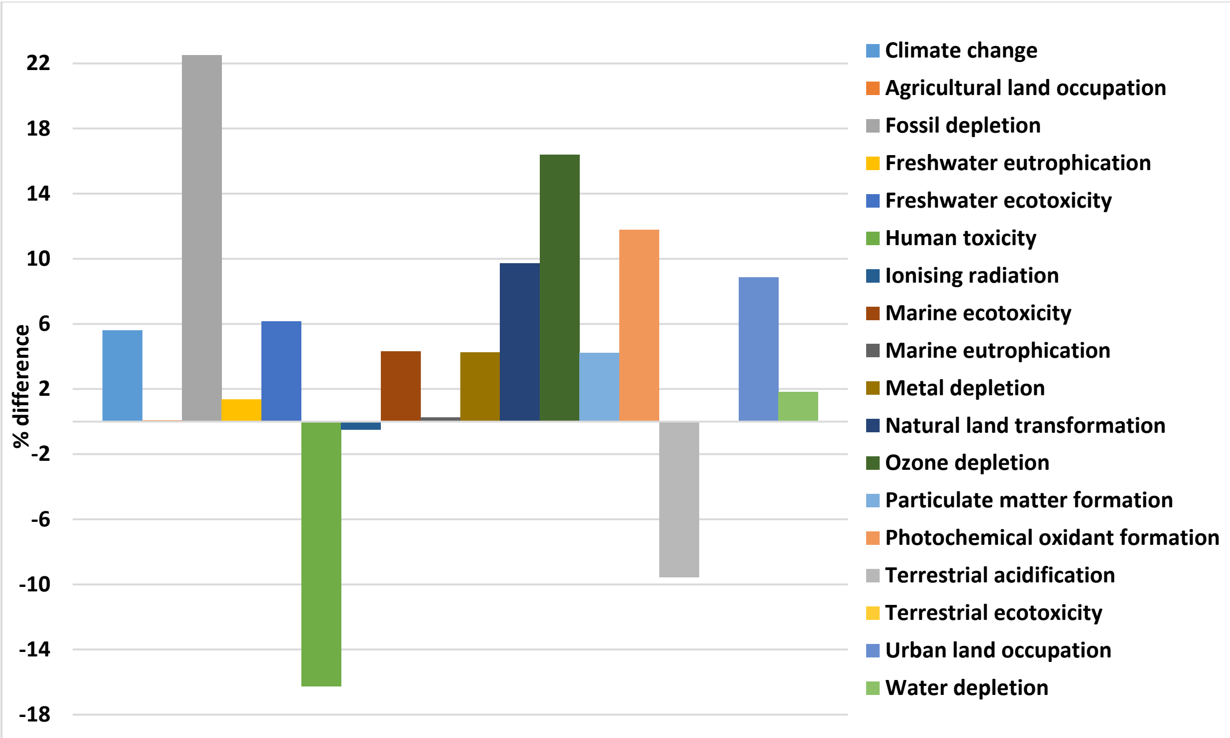

Figure 4-10 USA's environmental impacts' differences between the two scenarios

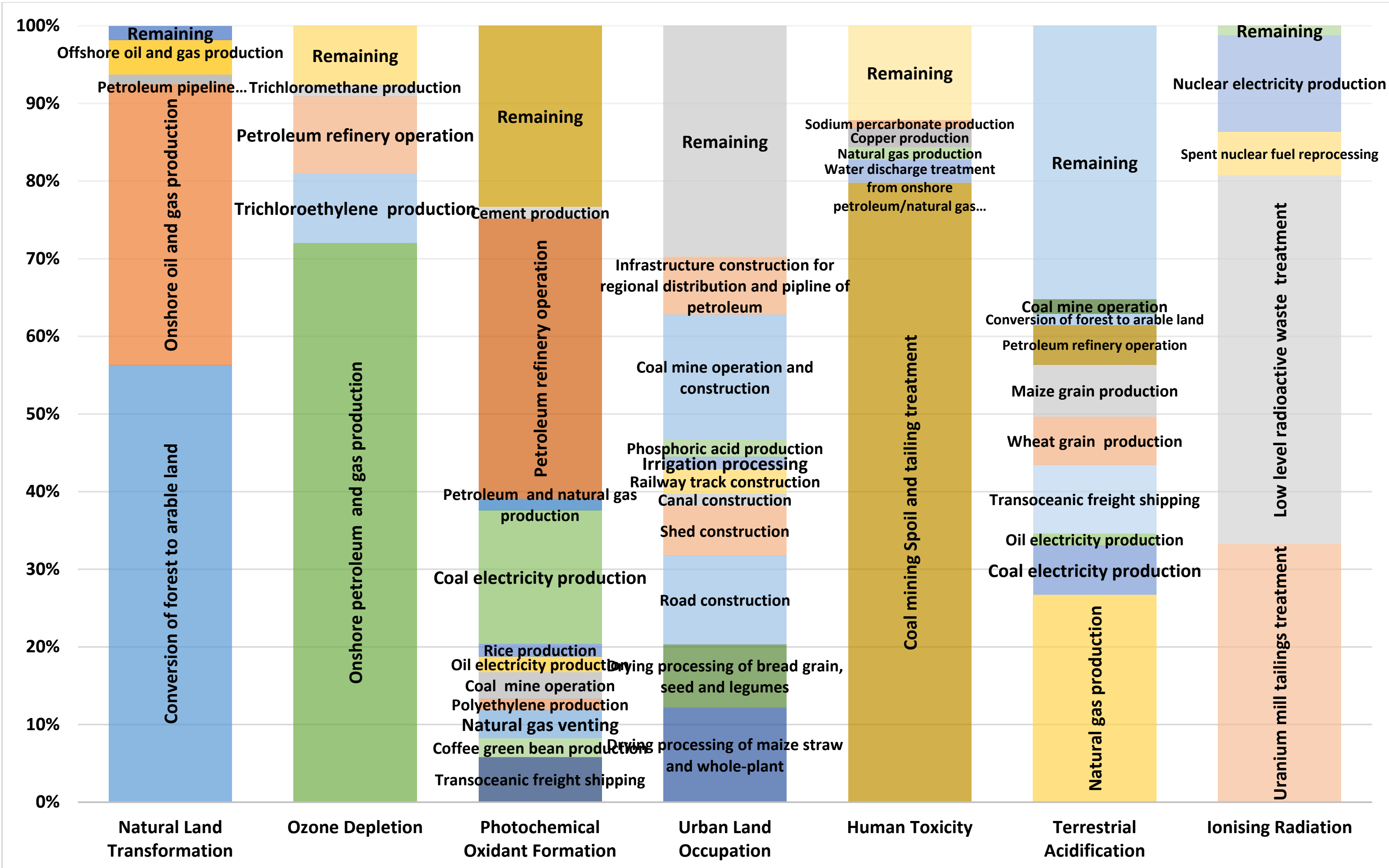

Figure 4-11 the environmental impacts with higher percentage difference between the two scenarios

The Rest of World (ROW) is negatively affected, by the K.A.CARE scenario compared to the BAU, for all the impacts, except agricultural land occupation that is slightly benefited as shown in Figure 4-7. The processes behind the benefited agricultural land occupation impact are: wheat and barley grain production, hardwood and softwood forestry, live cattle production for meat and wool, soybean production, sunflower production, and dried tea production.

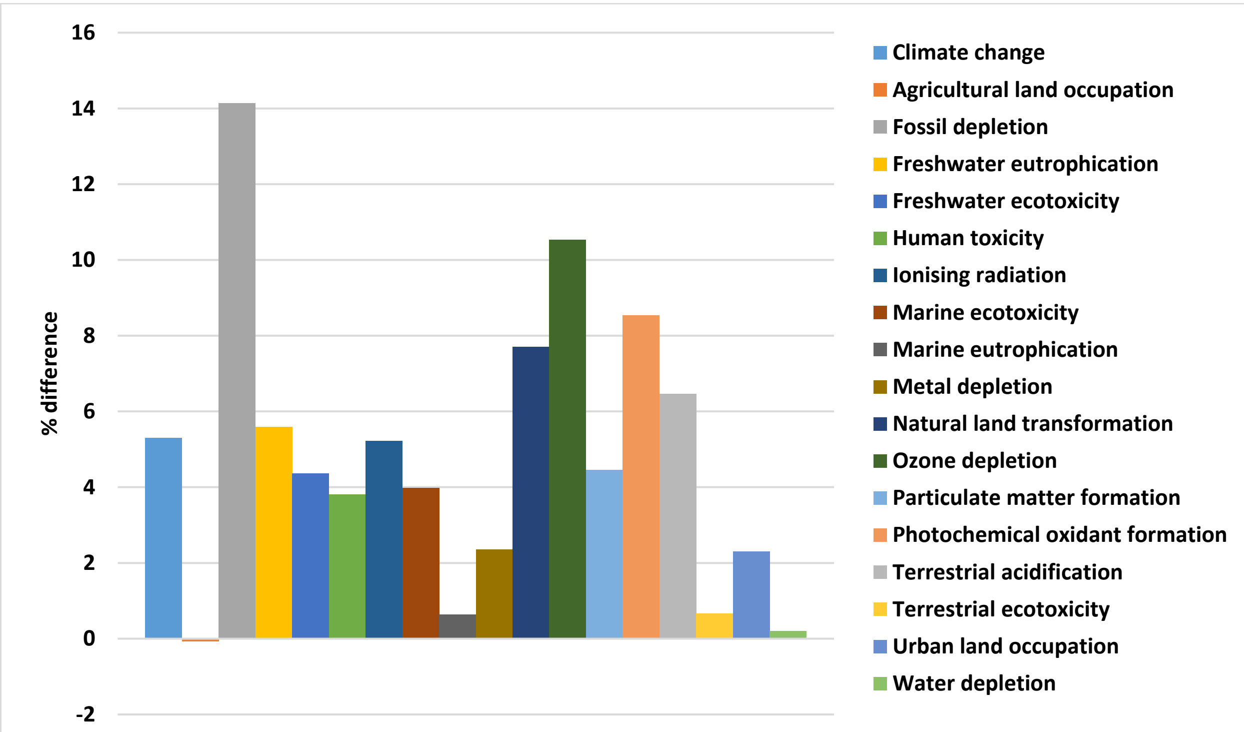

Figure 4-12 environmental impacts’ differences between the two scenarios for ROW

Figure 4-8 shows the greenhouse gas (GHG) emissions of each scenario for all the studied regions. Saudi Arabia is the only region that would be positively affected by the K.C.CARE; the other regions are showing higher GHG emissions. The difference is the highest in EU, and then in USA and ROW. As a total of all regions, 5.09 percent GHG emission increase is resulting from the K.A.CARE implementation compared to the BAU; about 3.17E12 kg CO_2 eq. Based on the

Representative Concentration Pathways (RCP) trajectories, that the Intergovernmental Panel on Climate Change (IPCC) developed in its 5th and most recent assessment report in 2013 [30], both scenarios (62.2 $GtCO_2$ and 65.5 $GtCO_2$ for BAU and K.A.CARE, respectively) follow approximately a similar path of the business as usual trajectory (RCP 8.5). The RCP 8.5 trajectory has an emission between 60 $GtCO_2$ and 72 $GtCO_2$ in 2032. The RCP 8.5 trajectory represents a future with no emissions reduction policies, heavy reliance on fossil fuels, and a lower rate of technology development. With the RCP 8.5 trajectory, the mean of the global average temperature increases 2 ˚C above the pre-industrial levels for the period 2046-2065 and 3.7 ˚C for the period 2081-2100, and a global mean sea level rise of 0.3 and 0.63 m for the same periods [30]. For all other environmental impacts with a global scale effect, as shown in Table 4-1, the total of all regions of each impact indicates that K.A.CARE would have a worse environmental performance.

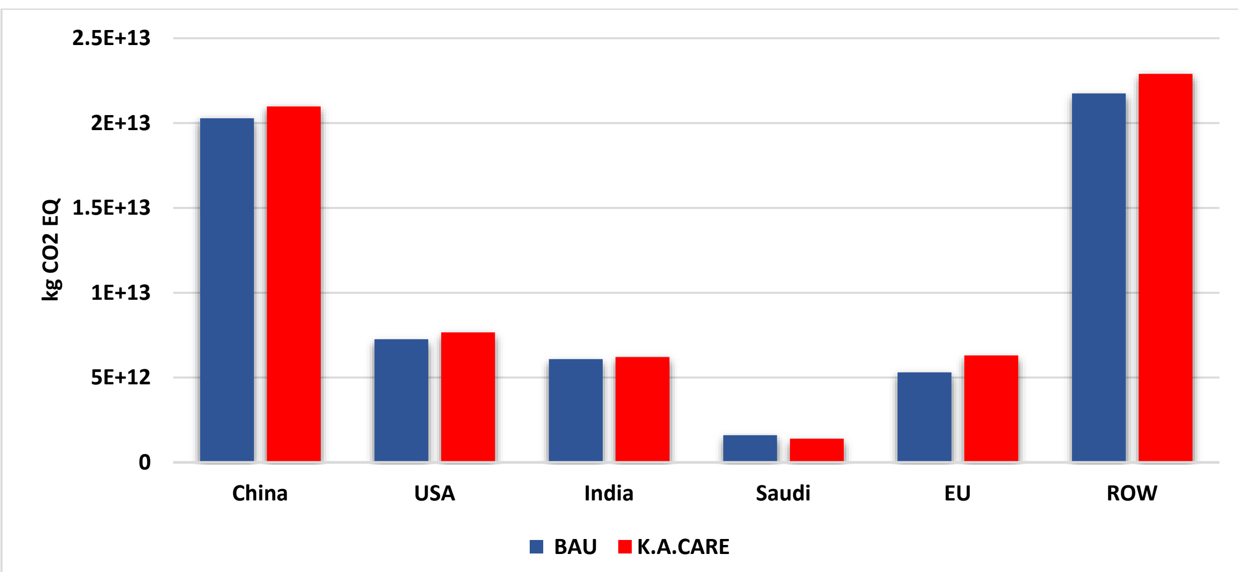

Figure 4-13 the greenhouse gas (GHG) emissions of each scenario for all the studied regions

4.4 Conclusions

This study assessed the potential environmental impacts of implementing the Saudi K.A.CARE energy plan, where half of the electricity generation will be met by renewable and nuclear sources. A combination of a consequential LCA (CLCA) perspective and a computable general equilibrium (CGE) economic model was used to quantify all direct and induced relevant emissions and consumed resources. The United Nations (UN) Comtrade database was used to convert traded commodities' monetary values (US dollar) to physical units (in kg); the use of the Harmonized System (HS) commodities' classification gives the study an advantage of having detailed information about the types of those products for each region. Business as usual (baseline) and K.A.CARE scenarios were developed to account for market conditions up to 2032. To find the scenario with lower environmental impacts and distinguish between the impacts that are generated by the studied policy from the ones resulting from the demographic and economic growth, a comparison between the two scenarios was made. The legitimacy of the methodology used was validated by comparing its estimates of the CO_2 emissions, for the base year, with CO_2 emission estimates by different sources. Saudi Arabia showed an environmental advantage for all the impacts, except fossil depletion, ionizing radiation, ozone depletion and urban land occupation. For other regions, side effects were shown for most impacts. For the total greenhouse gas (GHG) emissions of all regions, 5.09 percent GHG emission increase is resulting from the K.A.CARE compared to the BAU. For all other environmental impacts with a global scale effect, the all regions' total of each impact indicates that K.A.CARE would have a worse environmental performance. That bring our attention to "the green paradox" phenomenon where a policy intended to stimulate the green technologies in a region leads to more environmental damage, in other regions, by bringing more fossil fuels into use, and that calls for the need of global coordinated efforts to protect the environment.

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4.6 Appendix

Table A.1: Aggregations of GTAP-E regions

GTAP-E region	Member Countries
KSA	Saudi Arabia
USA	United States
EUROPE	Austria, Belgium, Cyprus, Czech Republic, Denmark, Estonia, Finland, France, Germany, Greece, Hungary, Ireland, Italy, Latvia, Lithuania, Luxembourg, Malta, Netherlands, Poland, Portugal, Slovakia, Slovenia, Spain, Sweden, United Kingdom, Switzerland, Norway, Rest of EFTA, Albania, Bulgaria, Belarus, Croatia, Romania, Russian Federation, Ukraine, Rest of Eastern Europe, Rest of Europe
CHINA	China
INDIA	India
ROW	Australia, New Zealand, Rest of Oceania, Hong Kong, Japan, Korea Republic, Mongolia, Taiwan, Rest of East Asia, Brunei Darussalam, Cambodia, Indonesia, Lao People's Democratic Republic, Malaysia, Philippines, Singapore, Thailand, Viet Nam, Rest of Southeast Asia, Bangladesh, Nepal, Pakistan, Sri Lanka, Rest of South Asia, Canada, Mexico, Rest of North America, Argentina, Bolivia, Brazil, Chile, Colombia, Ecuador, Paraguay, Peru, Uruguay, Venezuela, Rest of South America, Costa Rica, Guatemala, Honduras, Nicaragua, Panama, El Salvador, Rest of Central America, Dominican Republic, Jamaica, Puerto Rico, Trinidad and Tobago, Caribbean, Kazakhstan, Kyrgyzstan, Rest of Former Soviet Union, Armenia, Azerbaijan, Georgia, Bahrain, Iran, Israel, Jordan, Kuwait, Oman, Qatar, Turkey, United Arab Emirates, Rest of Western Asia, Egypt, Morocco, Tunisia, Rest of North Africa, Benin, Burkina Faso, Cameroon, Cote d'Ivoire, Ghana, Guinea, Nigeria, Senegal, Togo, Rest of Western Africa, Central Africa, South Central Africa, Ethiopia, Kenya, Madagascar, Malawi, Mauritius, Mozambique, Rwanda, Tanzania, Uganda, Zambia, Zimbabwe, Rest of Eastern Africa, Botswana, Namibia, South Africa, Rest of South African Customs Union, Rest of the World

Table A.2: Aggregations of GTAP-E sectors

GTAP-E Sector	Description	Comprising
AgriFood	Agriculture,forestry,& fishing	Paddy rice, Wheat, Cereal grains nec, Vegetables, fruit, nuts, Oil seeds, Sugar cane, sugar beet, Plant-based fibers, Crops nec, Bovine cattle, sheep and goats, horses, Animal products nec, Raw milk, Wool, silk-worm cocoons, Forestry, Fishing
Coal	Coal mining	Coal
Oil	Oil extraction	Oil
gas	Gas extraction & distribution	Gas, Gas manufacture, distribution
oil_pcts	Petroleum, coal products	Petroleum, coal products
En_Int_ind	Energy intensive industries	Minerals nec, Chemical, rubber, plastic products, Mineral products nec, Ferrous metals, Metals nec
other_ind	other industries	Bovine meat products, Meat products nec, Vegetable oils and fats, Dairy products, Processed rice, Sugar, Food products nec, Beverages and tobacco products, Textiles, Wearing apparel, Leather products, Wood products, Paper products, publishing, Metal products, Motor vehicles and parts, Transport equipment nec, Electronic equipment, Machinery and equipment nec, Manufactures nec
water_Cons	water and Construction	Water, Construction
Transcomm	Transport and Communication	Trade, Transport nec, Water transport, Air transport, Communication
OthServices	Other Services	Financial services nec, Insurance, Business services nec, Recreational and other services, Public Administration, Defense, Education, Health, Dwellings
TandD	transmission & distrubuition	Electricity transmission & distrubuition
elygas	Electricity from gas	Gas base and peak load
elyoil	Electricity from oil	Oil base and peak load
elycoal	Electricity from coal	Coal base load
nuclear	Electricity from nuclear	Nuclear base load
wind	Electricity from wind	Wind base load
hydro	Hydroelectric	Hydro base and peak load
solar	Electricity from solar	Solar peak load
elyother	Electricity from others	Other base load

5 Ex-ante Analysis of Economic, Social and Environmental Impacts of Large-scale Renewable and Nuclear Energy Targets for Global Electricity Generation by 2030

5.1 Abstract

This study assesses the economic, social and environmental impacts of renewable and nuclear energy targets for global electricity generation by 2030. It examines different regions, as they might experience different impacts depending on the structures of their economies and their local natural resources, to understand the impact of these targets on their economics and well-being of their people. These regions are: Saudi Arabia, the United States (US), China, India, Europe and Rest of World (ROW). A well-known Computable general equilibrium (CGE) model, the Global Trade Analysis Project (GTAP), is modified and used to predict global economic shifts that would be triggered by two scenarios. The business as usual (BAU) scenario assumes that the current electricity mix remains unchanged until 2030. The renewable and nuclear energy (RNE) scenario is based on the International Energy Outlook (IEO) 2016 prediction. The analysis shows that the GDP of all regions, except India, is affected negatively. The study shows a loss of 4.45 million jobs worldwide in the RNE compared to the BAU. Finally, the implementation of planned renewable and nuclear energy slightly benefits the environment but not enough to mitigate rise in global temperature.

5.2 Introduction

Achieving a sustainable development target involves many factors. A sustainable supply of energy resources is one of the crucial factors. As electricity's growth is the fastest among the end-use energy forms worldwide [1], a transition to renewable power is crucial for achieving sustainability. Many countries are committed to using renewable and nuclear energy to reduce their dependence on foreign petroleum and mitigate their greenhouse gas emissions [2]. The subsequent economic stimulus, environmental preservation, and improvement to social system are pillars of sustainability. Several studies have assessed the renewable energy targets for specific regions separately, e.g. the USA [3], China [4], India [5], Malaysia [6,7], Taiwan [8], Germany [9], Turkey [10,11], Netherlands [12] and Spain [13,14], or multi-countries, e.g. the gulf cooperation council (GCC) countries [15], South Asian Association for Regional Cooperation (SSARC) countries [16], BRICS countries [17], and European Union (EU) [18]. Because country targets might have strong spillover effects into other regions, it is vital to study renewable energy targets on global scale. The shift to renewable and nuclear energy will impact countries' trade (exports and imports) of raw material, intermediate and final products. The world's most traded commodities such as oil and natural gas will be affected by this transition to renewable and nuclear energy, which results in sectorial shifts in domestic economies and their interactions through international trade [12].

Different regions might experience different effects regarding the sustainability pillars depending on the structures of their economies and their local natural resources [3]. This study examines the impact of renewable electricity generation targets in Saudi Arabia, the United States (US), China, India, Europe, and rest of the world (ROW) on their economic welfare and the environment. The rationale for choosing these regions is explained in the following paragraphs.

Saudi Arabia is the world's largest exporter of petroleum and possesses 18 % of the world's proven petroleum reserves. Saudi Arabia's oil and gas sectors account for about 50% of its gross domestic product (GDP), and for 85 % of its total export earnings. It exports seven million barrels per day (MBD) of crude oil, which represents 32% of production of the Organization of the production of the Petroleum Exporting Countries (OPEC), which in turn is responsible for 60% of the total international traded petroleum [19]. The country has a plan for the deployment of renewable and nuclear energy called the King Abdullah City for Atomic and Renewable Energy (K.A.CARE). This plan is driven by the anticipated large growth in electricity demand, which is projected to increase from 69 GW in 2015 [20] to 120 GW by 2032 [21]. Projected population and industrial growth drives this continuing increase in demand, and Saudi Arabia meets its current demand through burning fossil fuels [22]. K.A.CARE's goal is to source more than half of its generated electricity from non-fossil fuel resources by 2032. The suggested mix is: 45.6 % from hydrocarbons, 31.16% from solar, 13.37% from nuclear, 6.84% from wind, 2.28% from waste, and 0.76% from geothermal [21]. It is important to mention that the recent announcement of the Saudi 2030 vision does not mean the abandonment of the K.A.CARE plan. The K.A.CARE program is still a current plan; but it has been managed by the Ministry of Energy, Industry and Mineral Resources (MEIM). (M. Al-Abdalla, personal communication, July 4, 2017)

The United States (US) is the largest producer of petroleum products in the world [19]; however, it is a net importer of petroleum products as a result of its high petroleum consumption [23]. Electricity generation accounts for 40 % of total energy consumption in the US [24]. In 2012, about 36% and 30% of electricity was produced from coal and natural gas, respectively [1]. Low gas prices as a result of the expansion in production brought by the shale gas revolution, led to this high share of gas-fired power generation [25]. The US is the second largest emitter of greenhouse gases (GHG) in the world after China [26]. An increase in renewable energy use is a measure the US policy-makers take in response to the challenges of climate change and energy security. In the "New Energy for America Plan," the share of renewable sources used to generate electricity should reach 25% in 2025. The role of renewable source in electricity generation in 2012 was about 12%, hydro and wind were responsible for 7% and 3.5% respectively [1]. Solar power is a promising alternative energy source in the US, as its average annual growth reach 11.7% [27]. Nuclear energy plays a big role in electricity generation, representing 19% of the electricity mix in 2012 [1], and proposal is being introduced to build new nuclear plants [28].

China, with its rapid economy's growth, and as the largest energy consumer in the world [25], has become the largest emitter of greenhouse gases (GHG) in the world since surpassing the US in 2007 [29]. In the Paris Accord, China pledged to reduce its emissions and increase its use of renewable resources [30]. Although China relies on coal to generate about 75% of its electricity [1], the country has recently invested in nuclear and renewable sources including hydro, wind, and solar [31]. In addition, demand for coal is projected to slow in the future [32,33]. Due to ambitious government efforts, China has become the world's leader in both hydro and wind energy [34]. China is the largest generator of hydropower worldwide, providing about a quarter of the world's total generated hydropower [34], which represents about 18% of the Chinese generated electricity [1]. The wind capacity has increased over a hundredfold in the last decade, making China the world's fastest-growing wind energy market [34]. The country is also the largest manufacturer of photovoltaic cells in the world [34]. Despite the phase-out policy that a number of countries have adopted after the Fukushima nuclear accident, China remains committed to nuclear power expansion. The country has reached self-sufficiency in nuclear reactor engineering [34].

India is the second fastest growing economy after China [35], the fourth largest oil and petroleum consumer, and the fourth largest oil importer in the world [36]. Thus, in India there is a huge demand for energy, which is currently met by coal and imported oil and gas. India is the sixth largest and second fastest GHG emitter in the world driven by a growth in coal consumption. Among the 10 most polluted cities in the world, three are in India [37]. The country is fortunate to have a variety of renewable energy resources, and has plans to implement the world's largest renewable energy program [35]. In 2012, renewable energy supplied 18% of India's needed electricity, mostly coming from hydropower that represented 12% of the generated electricity [1]. The contribution of wind power was about 3 % [1], and the country occupies the 5th place in global wind power generation [35]. Most regions in India receive between 4-7 kWh per square meter per day of solar radiation, which creates an incentive for the country to invest in solar energy [38]. Regarding nuclear power, India has a modest level of installed nuclear energy (2.85 % of its electricity mix in 2012 [1]) and Indian policy-makers have shown an interest in the role the nuclear energy could play in further boosting India's economic growth [39].

Among the global total installed capacity of renewable energy in 2012 (1440 GW), about 22 % was located in the European Union (EU) [40]. This is a response to EU's fuel taxes, which are the highest worldwide [41]. In 2012, the shares of renewable and nuclear electricity in the EU were 25% and 21.74%, respectively. Among renewables, the share of hydropower was the largest at 16%, followed by wind (4.15 %) [1,40]. The EU set a target in 2014 to increase its share of renewable energy to at least 27 % by 2030 [42]. Nuclear energy is declining as an electricity source in Europe [42]; its share will decrease as some countries intend to phase this source out, but it will not be totally eliminated [43].

The EU's leadership in renewable energy has raised concerns in Europe about whether it would lead to green growth or erode the European competiveness in the global economy [44,45]. Thus, to measure the economic effects of implementing renewable energy, a global computable general equilibrium (CGE) model GTAP-E was used in this study. As the power sector is crucial for mitigating climate change, we model the planned electricity mix, including its renewable energy targets for 2030, and compare them to a business-as-usual model, where the current electricity composition is used to meet the growing demand until 2030. The aim of this work is to understand the long-term economic, social and environmental impacts of the projected global implementation of renewable energy. The remainder of this paper is organized as follows: Section 2 provides a description of the model and database, and the simulation scenarios; section 3 presents the economic, social and environmental results; and the final section presents a discussion of the main results and conclusions.

5.3 Methodology and scenario design

5.3.1 GTAP-E model

We use the GTAP-E model [46], an energy-environmental version of the CGE GTAP Model [47], to assess the impact of the implementation of the projected renewable and nuclear energy plans in selected countries/regions. The model specifies the behavior of government and private household in each region as rational agents maximizing utilities. All the regional income is collected by a regional household and exhausted in government, private household and saving expenditures according to a Cobb-Douglas utility function. The sources of income for the regional household includes taxes and returns to factors of production (labor, capital, land, and natural resources). A combination of the factors of production and intermediate inputs is used by firms to produce a final good. The profit maximization objective, subject to a constraining production function, governs the behavior of firms. A Cobb-Douglas function determines the demands of the government, while a constant difference of elasticity function[4] governs the demands of private households. Bilateral trade is specified following Armington [48]; it differentiates the goods by their origin, which allows for their export and import ratios to change. See Hertel [47] for more details.

GTAP-E is an extension of the GTAP model that incorporates a more detailed specification of the energy sector and, therefore, is well suited to assess changes in energy markets [46,49]. This study uses the GTAP 9 database, in which the global economy in year 2011 is represented for 140 countries and 57 GTAP commodity sectors [50]. The database has all renewable and nuclear energy technologies aggregated in one sector (electricity). Disaggregated electricity technologies were imported from the GTAP-POWER database [51]. Then, as shown in appendices A.1 and A.2, the database was aggregated into 6 countries/regions and 19 commodities. In addition, since the share of renewable and nuclear energy for Saudi Arabia was zero in the database, small shares were artificially introduced as recommended by The General Equilibrium Model for Economy-Energy-Environment (GEM-E3) [52]. That allows us to exogenously increase their contribution until the Saudi Arabia's goal in 2030 is met. For the model, the factors of production and intermediate inputs are used by firms to produce final goods according to nested constant elasticity of substitution functions (Figure 5-1). The non-coal energy sources (crude oil, gas and petroleum products) were bundled in one nest to allow substitution between them according to a substitution elasticity of $\sigma_{ELFNCOAL}$, as shown at the bottom of Figure 5-1. The non-electricity energy nest is

[4] Constant difference of elasticity is nonhomotheteic, which means the consumers change their spending share on luxury goods vs. necessities as their income changes. This is based on the income elasticity for each good [77].

made from the non-coal energy nest bundled with coal according to the substitution elasticity of $\sigma_{ELFNELY}$. With a substitution elasticity of σ_{ELFENY}, the energy nest consists of a bundle of the non-electricity nest and the aggregated electricity sector. The capital-energy nest is made by a combination of energy nest and capital with substitution elasticity of σ_{ELFKEN}. In addition, the capital-energy nest is bundled with the other endowments with substitution elasticity of $\sigma_{ELFVEAN}$ to make the endowment-energy nest. According to a Leontief technology (zero substitution), the endowment-energy nest and the non-energy inputs are combined to form the firm output. An important modification for the GTAP-E model, the addition of two new nests, was made to enable the use of renewable and nuclear technologies as shown in Figure 5-2. The first nest consists of the electricity technologies (Technologies) and the distribution and transmission sector (TandD) with a substitution elasticity of zero, as suggested in the literature [52–54]. The Technologies nest, with a substitution elasticity of 5 as suggested by the OECD ENV-Linkages Model Version 3 [55], includes eight new electricity producing technologies (elyoil, elygas, elycoal, wind, nuclear, solar, hydro, and elyother).

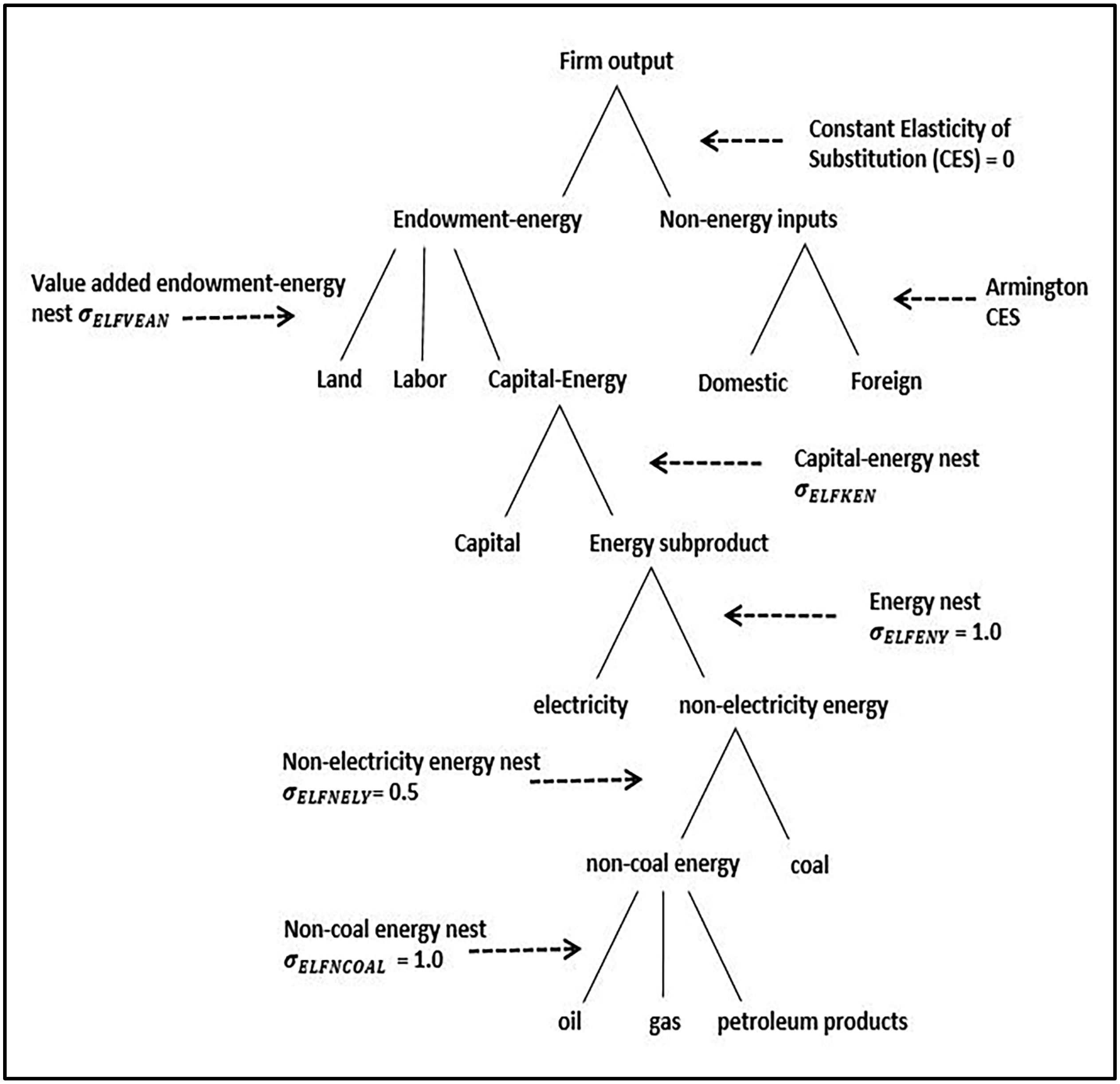

Figure 5-1 Original GTAP-E production structure [56].

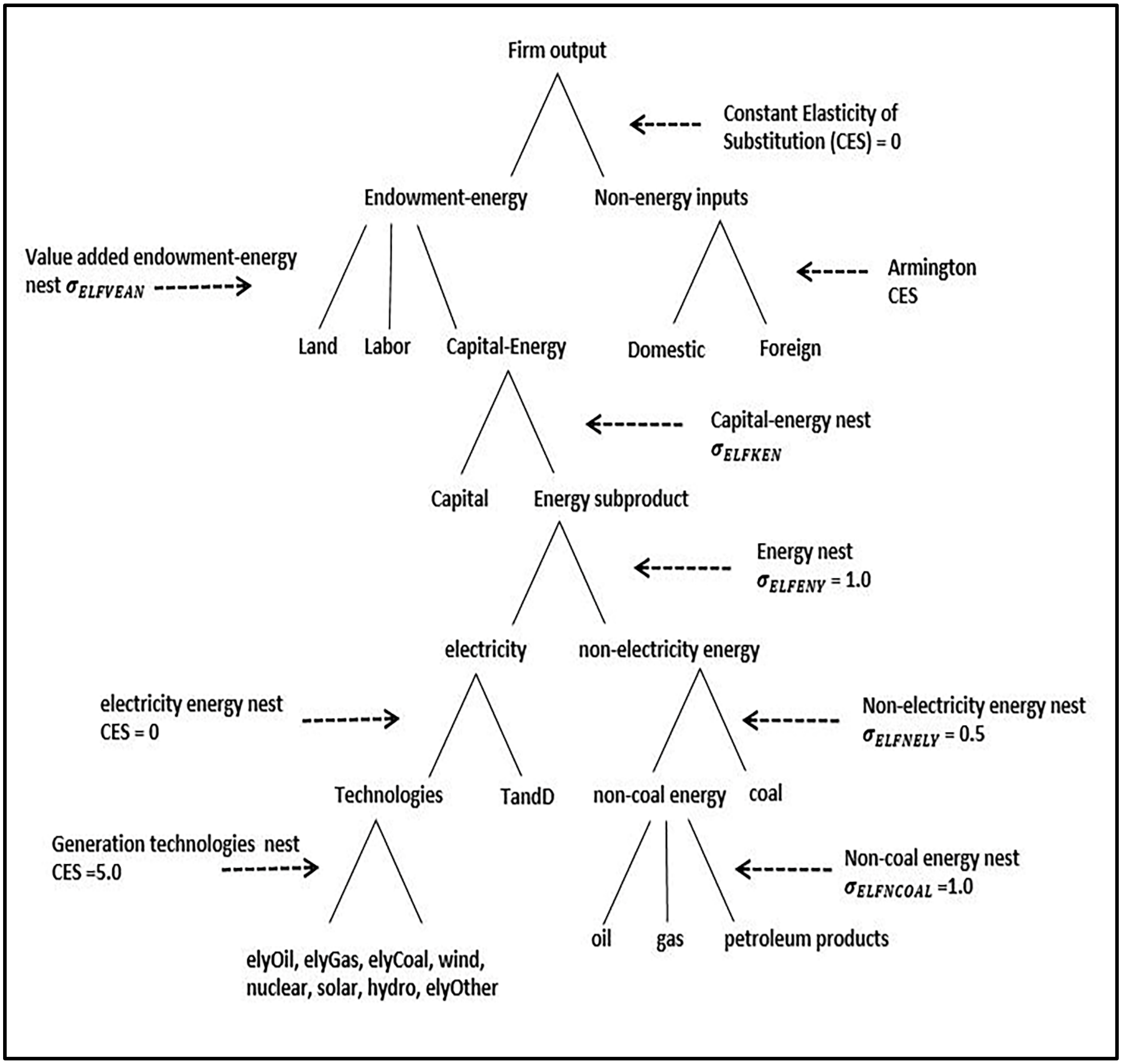

Figure 5-2 Modified GTAP-E production structure

5.3.2 Technological improvement

In addition to the fuels' availability and costs [57], the energy technologies' development plays a vital role in the future energy systems [58]. Technological improvement was taken into account as an input for the GTAP-E model for each type of electricity technology. To simulate this, the model accounts for the reduction of the input requirements to produce a given commodity (electricity in our case); the cost of production for each electricity technology thereby decreases. One of the most common methods to inform energy planning and policy analysis regarding the potential effects the technical changes have in the large scale energy-economic models is the learning rate method [59]. It predicts how the cost of technology declines with cumulative production [59–61]. For mature and prevalent technologies like fossil fuels and nuclear power plants, the rate of technological improvement is not high [59,61]. Literature shows that the solar and wind energy sectors have the highest costs reduction as they are the fastest growing energy subsectors worldwide [59,61]. For hydropower plants and as a result of nature conservation compensating measures, the learning rate is negative, indicating increasing in cost [61]. For this study, the projected learning rates of the electricity technologies for 2030 were obtained from literature and shown in appendix A.3 [58,60–62].

5.3.3 Scenario description

Two scenarios were developed: the business as usual scenario (BAU) assumes that the current electricity mix remains unchanged until 2030, and the renewable and nuclear energy scenario (RNE), which incorporates many of the IEO2016 predictions and updated renewable energy and CO_2 mitigation targets [1]. To estimate the state of the global economy in 2030, projected changes in selected exogenous variable were obtained from different sources. The estimation of global population growth comes from the U.S. Census Bureau [63]. Estimates from the literature [63,64] were used to obtain the projected growth of the gross domestic product (GDP) and capital. Estimates of labor growth projections come from the International Labor Organization (ILO) [65]. Three factors were considered by the US Energy Information Administration (IEA) in their IEO2016 prediction. The first is data on the countries and their previous successes in meeting what they had planned; the second is indicators about each country's financial capabilities in meeting their targets; and the third is market pricing assessment to support renewable energy. The developed BAU and RNE electricity mix scenarios for each region are shown in Figure 5-3 (the absolute values of electricity production mix are shown in appendix A.4). Figure 5-4 shows the shares of world electricity generation in both of the BAU and RNE scenarios. Electricity generated from oil is 61% lower; its share of total generation is 4.64% in the BAU scenario, and 1.78% in the RNE scenario. For natural gas electricity generation, it is higher by 17.77% in the RNE scenario compared to the BAU; its share of total electricity generation is 19.93% in the BAU, and 23.48% in the RNE. That calls attention to the complementary relationship between renewable energy (mainly wind and solar) and the gas generation technologies, which are considered as fast-reacting fossil technologies. This relationship helps to overcome the supply variability problem of renewable energy resulting from its intermittency and non-dispatchability, especially with the current lack of cheap storage options. A recent study published by the National Bureau of Economic Research looked at the growing of renewable energy plants in 26 countries for more than two decades; it reports that for a long run a 1 % increase in the share of fast-reacting fossil technologies with each 0.88 % increase in the share of renewable energy [66]. The share of world coal electricity generation is 43.11% in the BAU, and 33.07% in the RNE; it is lower by about 23.29%. Nuclear power is higher by 33.59%; while the hydropower is lower by 9.64% in the RNE compared to the BAU. Wind, solar and others power generation are higher by 165.74%, 413.48% and 90.7%, respectively. According to the learning rate method, the technological improvements are higher in the RNE than the BAU scenario. Table 5-1 summarizes the two scenarios.

Table 5-1 Scenarios analyzed:

Scenario	**Description**
1. Business As Usual (BAU)	1- Account for the evolution of the global economy until 2030. 2- Current electricity mix remains unchanged until 2030. 3- Consider the technological improvements.
2. Renewable and Nuclear Energy (RNE)	1- Account for the evolution of the global economy until 2030. 2- Electricity mix that incorporates the 2030 renewable and nuclear energy targets based on IEO2016 predictions. 3- Consider the technological improvements.

The social impact is considered through accounting the employment effects of the two scenarios. The study considers both direct and indirect employment. Direct jobs are those created in the electricity technologies sectors. To calculate the direct jobs for each technology, the employment factors (the number of jobs per unit of electricity capacity for each type of electricity production technology) estimated by Institute for Sustainable Futures are used. These are taken from a report about a methodology for calculating global energy sector jobs [67]. Indirect jobs are the ones induced by the changes in the electricity sectors and created in other sectors. They are calculated by dividing the labor endowment payment of each sector in the database by the average salary of each region for the available sectors to estimate the number of laborers. Then, the number of laborers is multiplied by the simulation's predicted fractional change in the labor quantity to predict the number of laborers in future. Different sources were used to provide estimates for each region's average salaries [68–74].

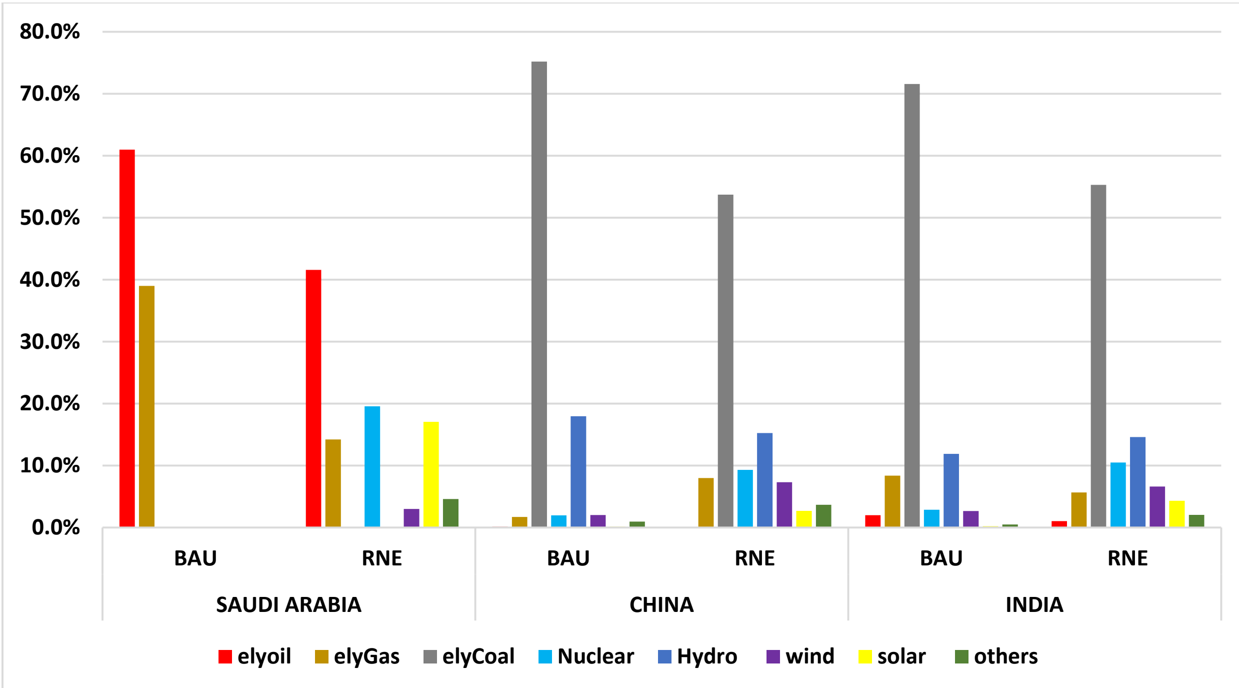

Figure 5-3 the electricity mix in 2030 for the business as usual (BAU) and renewable and nuclear energy (RNE) scenarios

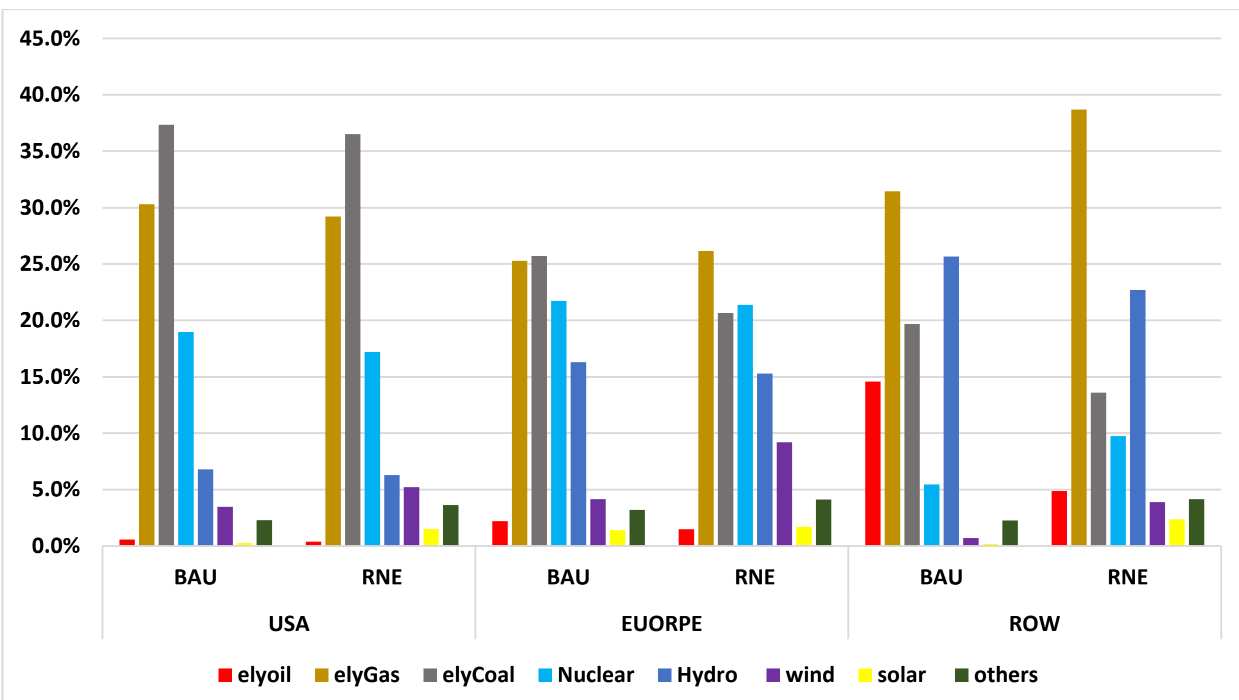

Figure 5-4 the electricity mix in 2030 for the business as usual (BAU) and renewable and nuclear energy (RNE) scenarios.

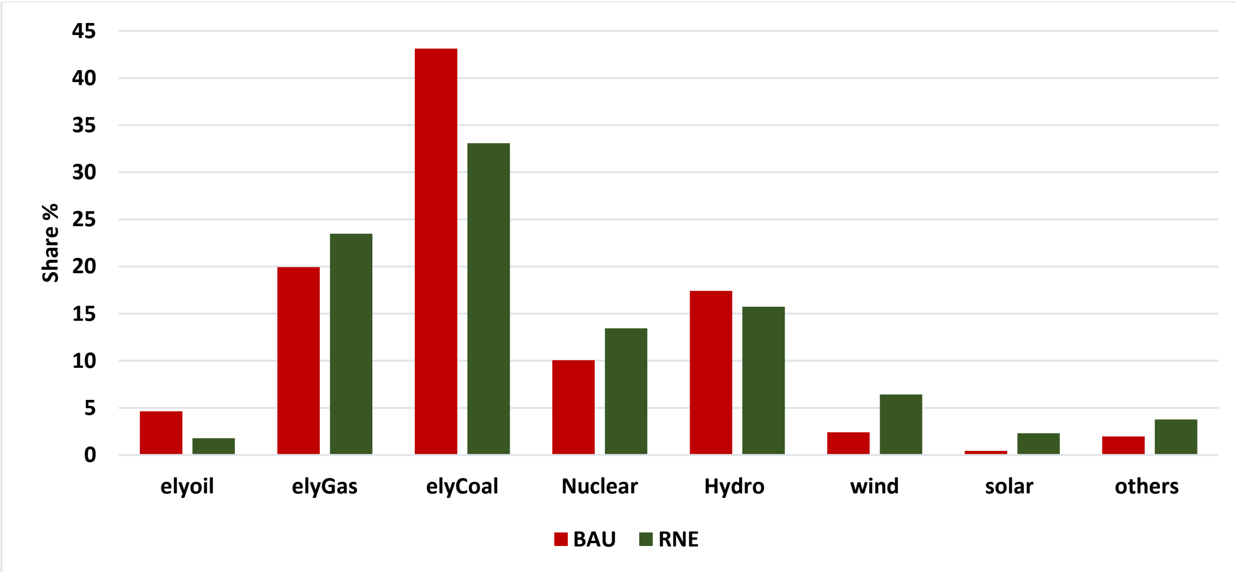

Figure 5-5 the shares of electricity mix worldwide in 2030 for the business as usual (BAU) and renewable and nuclear energy (RNE) scenarios

5.4 Results

The simulated economic, social and CO_2 emission impacts of implementing the renewable and nuclear energy (RNE) scenario for each region are presented in this section. Unless specified otherwise, the results are expressed as the difference between the RNE and BAU scenarios.

Table 5-2 presents the percentage change in GDP's components and total GDP in the RNE compared to BAU scenario. It is no surprise that economies that are heavily reliant on oil, like Saudi Arabia's economy, are affected the most as a result of the utilization of more renewable and nuclear energy, which leads to lower oil prices. Compared to the BAU, Saudi spending on investment in the RNE is reduced by about 27%, which reflects the current situation in Saudi Arabia, where some projects have been postponed or cancelled as a result of the recent global decline in oil prices. European investment and government spending are the second most affected. This is because the EU's tax on oil is the highest, and lower oil prices mean less revenue for the government, which affects investment. For the USA, India and the ROW, exports, in the RNE compared to the BAU, fall because of reduced demand for their top exports, e.g. petroleum products (oil_pcts), and energy intensive industries (En_Int_ind). China's imports decrease as a result of a decline of the price of its oil imports, which represents about 10% of its imports. Regarding consumption, the regions with higher shares of electricity technologies (especially renewable) in their consumption structure are affected the most. India shows positive consumption as electricity occupies a small share of the country's consumption structure.

Table 5-2 Percentage change in GDP's components and total GDP in the RNE compared to BAU scenario

	consumption	investment	government	export	import	Total
KSA	-5	-27.28	-5.06	-0.55	-13.4	-3.52
USA	-1.58	-0.54	-1.57	-4.97	-2.37	-1.58
EUROPE	-2.89	-7.73	-2.88	-1.42	-4.76	-2.81
CHINA	-0.41	1.88	-0.23	-2.39	0.77	-0.31
INDIA	0.02	-0.21	0.13	-4.24	-3.61	0.03
ROW	-1.02	0.12	-0.99	-4.98	-2.95	-1

Figure 5-10 show the difference between the two scenarios (RNE compared to the BAU) for each region in regard to sectoral output, commodity prices, direct and indirect jobs. In the USA, for the sectorial output, coal mining and oil extraction are unsurprisingly the most affected sectors; their outputs are 5.89% and 5.43% lower, respectively. The second most affected sectors are the energy intensive industries, and refined petroleum products (oil_pcts), which are lower by 3.32% and 1.57%, respectively. Conversely, the water_Cons sector, which includes the construction industry, shows a positive impact, as there is a large increase in wind, solar and other electricity technologies; and their requirement for the construction sector is the highest among the other required intermediate inputs. Capital goods (CGDS) are mainly affected by construction and investment; the increase in construction overcomes the small decrease in investment (Table 5-2).

The other industry, which include electronic and machinery equipment, is affected positively as it includes upstream renewable energy industries. For the commodity prices, the decline in the prices of energy commodities pushes down the energy costs of other sectors, which leads to a reduction in their prices. The RNE scenario creates more jobs for the USA than the BAU by about 10000 direct jobs and 144000 indirect jobs.

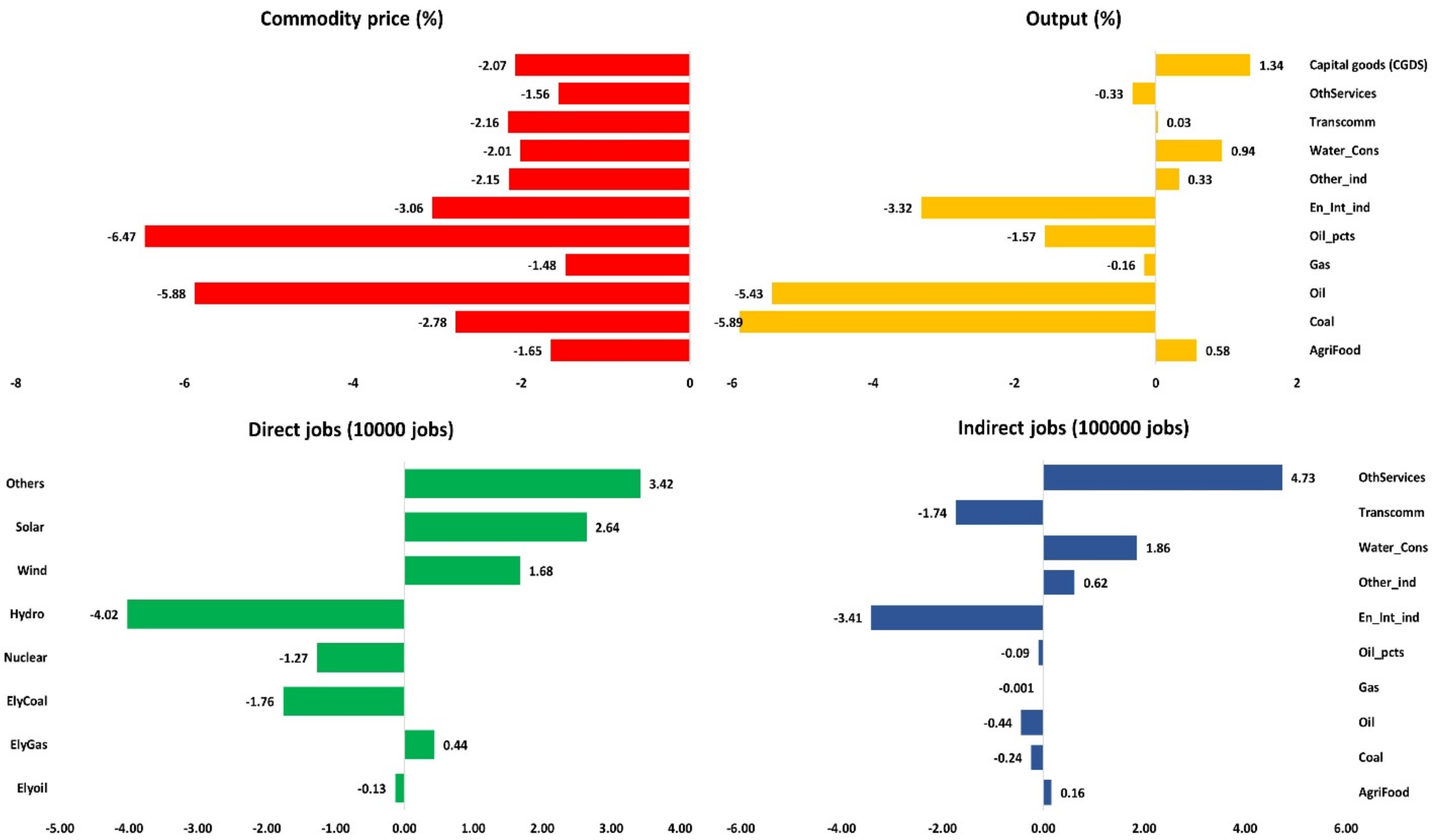

Figure 5-6 Impacts on sectoral output, commodities price, direct and indirect jobs in USA (RNE compared to BAU)

In Saudi Arabia, the GDP decrease is a result of a decrease in investment, consumption, and government spending, which leads to output reduction in most sectors. It is eye-catching that the output of the oil sector is increasing even with the declining use of oil to generate electricity in Saudi Arabia and other regions, and the decline of most sectors' output in Saudi Arabia. The reason is that the Saudi oil exports increase by 5.5% as a result of large declines in other regions' oil production. Similarly, the gas sector and its export increase as a result of higher demand for gas worldwide. The coal output shows a relatively large decrease, but the base value is small since Saudi Arabia is not known for coal use making small absolute changes appear as a large percent change. The large decrease in investment (Table 5-2) leads to a decline in the construction sector output, and subsequently a decline in capital goods (CGDC). This finding is consistent with "The Impact of Decreasing Oil Prices on the GCC RHC Market" report [75], which says that the slumping oil prices have affected the Gulf Cooperation Council (GCC) countries through lowering government revenue, which in turn has affected spending plans and construction. The other industry (other_ind), which includes electronics and machinery, shows some gain as it includes upstream renewable energy industries. For the commodity prices, as in USA and other regions, the cheaper energy commodities push down the production costs of other sectors and their prices. About 27,000 direct jobs are created and 100,000 indirect jobs are lost in the RNE scenario compared to BAU.

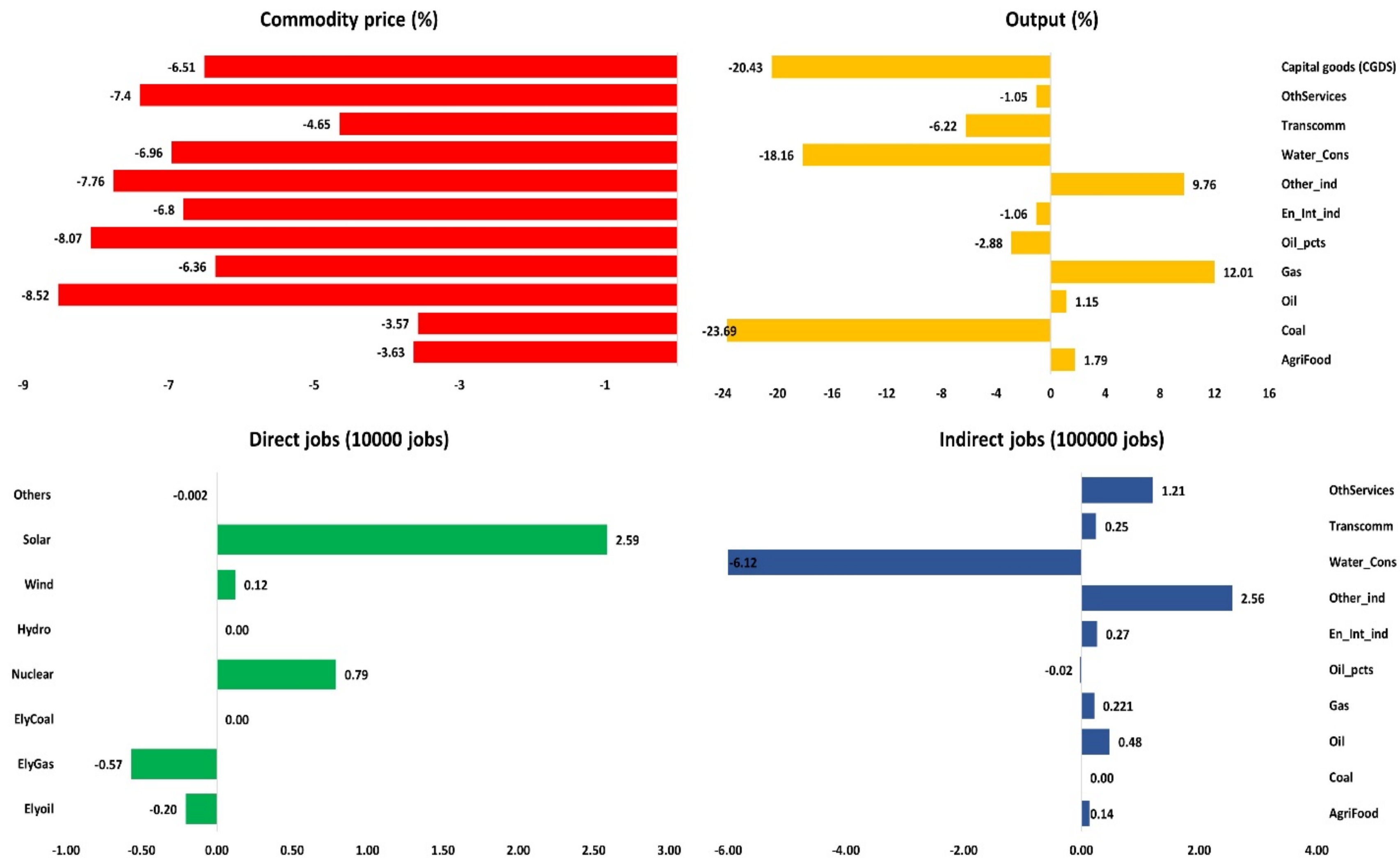

Figure 5-7 Impacts on sectoral output, commodities price, direct and indirect jobs in Saudi Arabia (RNE compared to BAU)

Regarding Europe, as in Saudi Arabia, the GDP decrease led to output decreases in most sectors, and the decline in capital goods (CGDC) results from a decline in construction caused by the relatively large decrease in investment (Table 5-2). The rise of the gas sector output is a result of an increase in the electricity generated from gas. The large decrease of the generated electricity from coal and oil leads to a large reduction of their outputs. As Europe is a net exporter of the outputs from energy intensive industries (En_Int_ind) and other industries (other_ind), cheaper energy prices increase its exports of these commodities; in addition, the increased use of renewable energy increases the output of other_ind. Commodity prices go down as a result of cheaper energy. Finally, employment is affected as the RNE scenario causes a loss of about 55,000 direct jobs and 477,000 indirect jobs compared to the BAU.

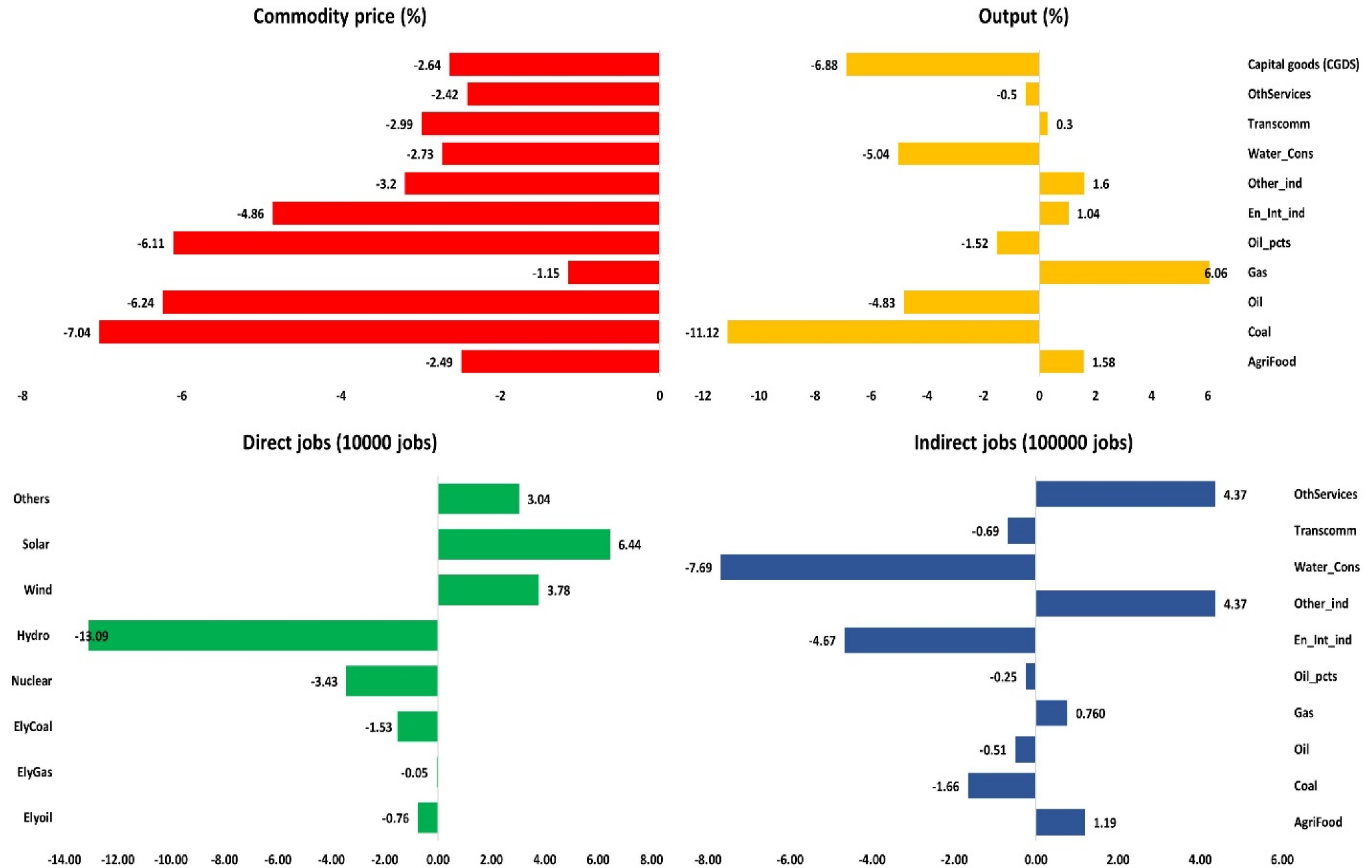

Figure 5-8 Impacts on sectoral output, commodities price, direct and indirect jobs in Europe (RNE compared to BAU)

In China, the increase of investment (Table 5-2) leads to an increase in construction and capital goods (CGDS). The small reduction of GDP in the RNE compared to the BAU results from the large reduction of coal mining and electricity generation from coal, especially considering that China is the biggest producer and consumer of coal worldwide. But in general there are increases in all sectors' outputs except coal and oil. Gas rises the most, as there are large increases in electricity generated from gas, and energy intensive industries (En_Int_ind), including in the petrochemical industry. This matches a study about the impact of falling oil prices on the major oil producing and consuming countries [76]. As China's oil imports increase by 13%, the output of the petroleum products sector (oil_pcts) increases by 6.63%. For the commodity prices, cheaper energy reduces the prices in all sectors, except for services (othservices) and communication (transcomm) as they are capital and labor intensive, and the prices of these two endowments increase in China and India. Finally, China loses about 6200 direct jobs and 1,165,000 indirect jobs, as a result of the RNE scenario compared to BAU. Most of the employment loss is in the energy intensive industries (En_Int_ind), coal, and other industries (other_ind) sectors. It is clear that the decreasing use of coal to generate electricity is behind the loss in employment in the coal sector. For energy intensive industries (En_Int_ind) and other industries (other_ind) sectors, the substitution of capital for labor explains the reduction of employment even with higher outputs. In general, China, India and, to a lesser extent, ROW have higher endowment substitution parameters than other regions. The prices of labor and capital rise and fall, respectively, as a result of low population growth and high capital growth. This leads to the substitution of capital for labor, which is shown clearly in those sectors as they have the highest endowment substitution parameters.

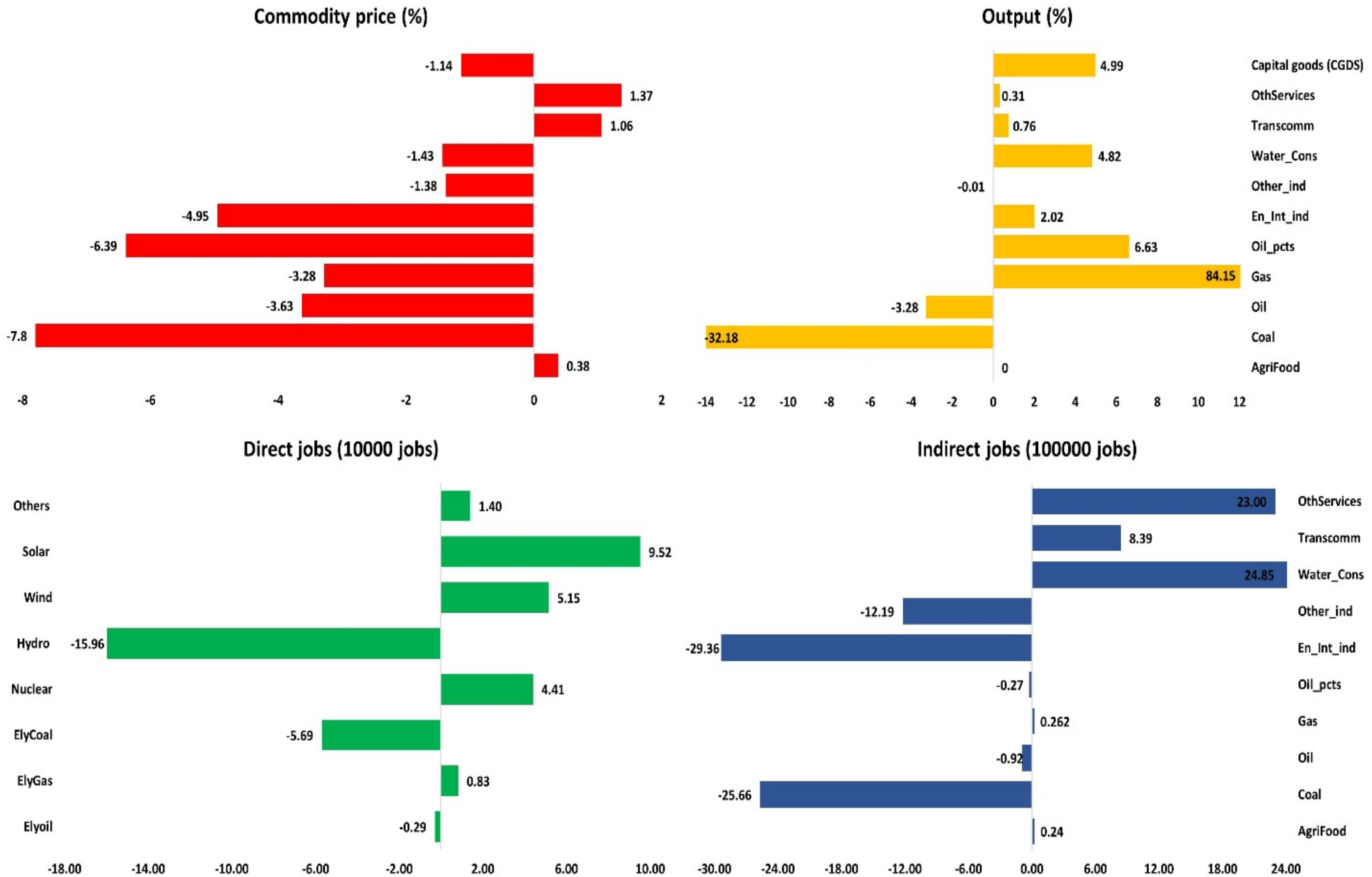

Figure 5-9 Impacts on sectoral output, commodities price, direct and indirect jobs in China (RNE compared to BAU)

For India, there is a small increase of GDP as a result of increased consumption and government spending, as well as the increase use of renewable and nuclear sources to generate electricity. In addition, the reduced use of fossil fuels to generate electricity leads to a decrease in the output of their extraction sectors. All of this leads to a small increase in construction and capital goods (CGDS). The outputs of energy intensive industries (En_Int_ind) and other industries (other_ind) sectors decrease for two reasons. The first is the large reduction in the fossil fuel sectors and associated electricity generated. The second is the increase of their imports, especially in the energy intensive industries (En_Int_ind), other industries (other_ind), which have the highest Armington parameters in comparison to the other sectors in India. For the commodity prices, as in China, the prices of all sectors are reduced by cheaper energy, except for services (othservices) and communication (transcomm), as they are capital and labor intensive. Finally, employment is affected, as India will lose about 30900 direct jobs and 942,000 indirect jobs in the RNE compared to the BAU.

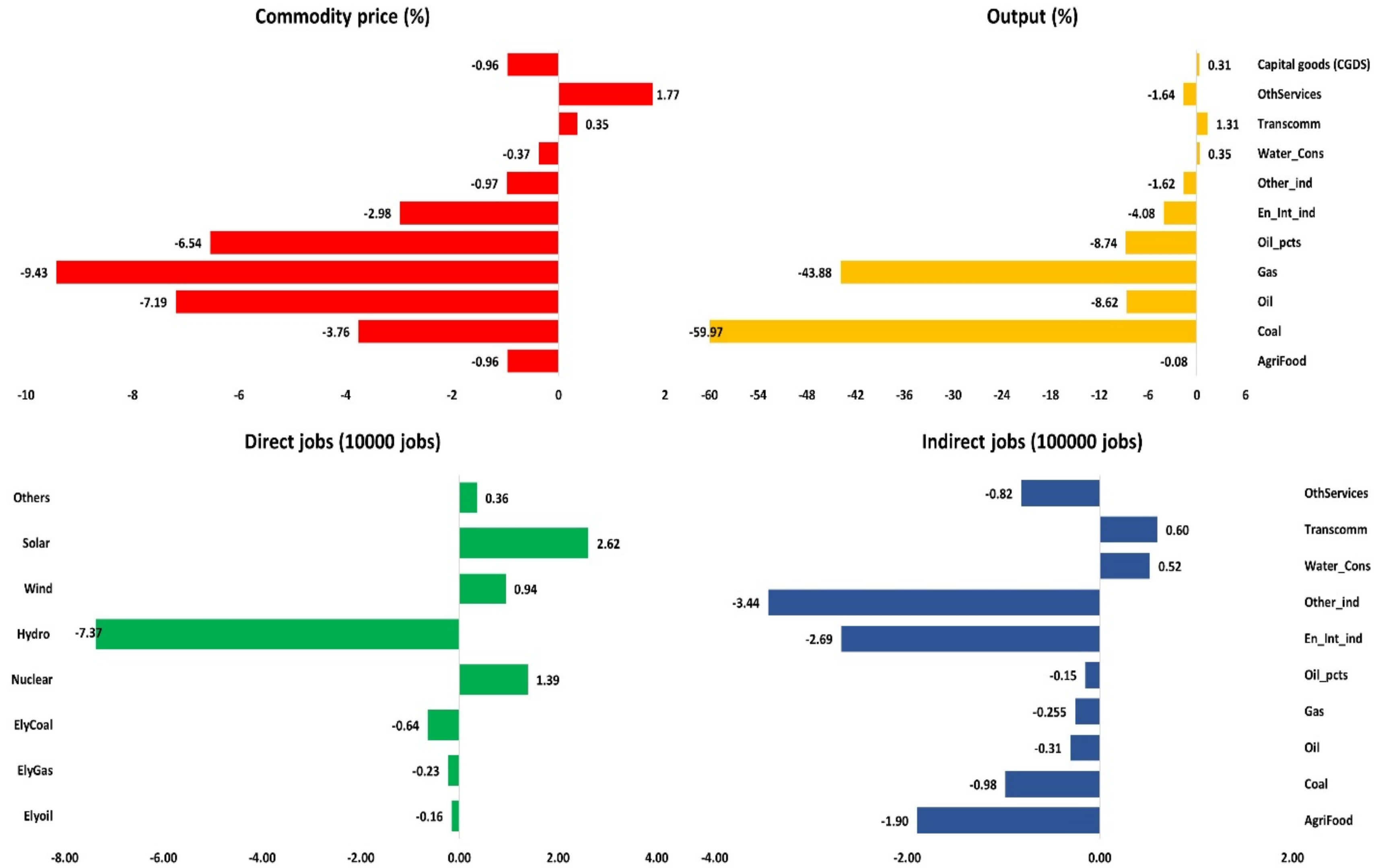

Figure 5-10 Impacts on sectoral output, commodities price, direct and indirect jobs in India (RNE compared to BAU)

Regarding ROW, the increase of construction and capital goods (CGDS) is a result of the small investment increase (Table 5-2). The reduction of the electricity generated from coal and oil impacts their extraction's sectors. Despite the increase in electricity generated from gas, its output decreases because ROW increases their imports of gas by 21% in the RNE scenario compared to the BAU as the Armington parameter for the gas sector is the largest. For the commodity prices, all sectors' prices are reduced as a result of cheaper energy, except for gas, whose price increases as demand rises. Finally, ROW loses about 106,000 direct jobs and 1,748,000 indirect jobs in the RNE compared to the BAU.

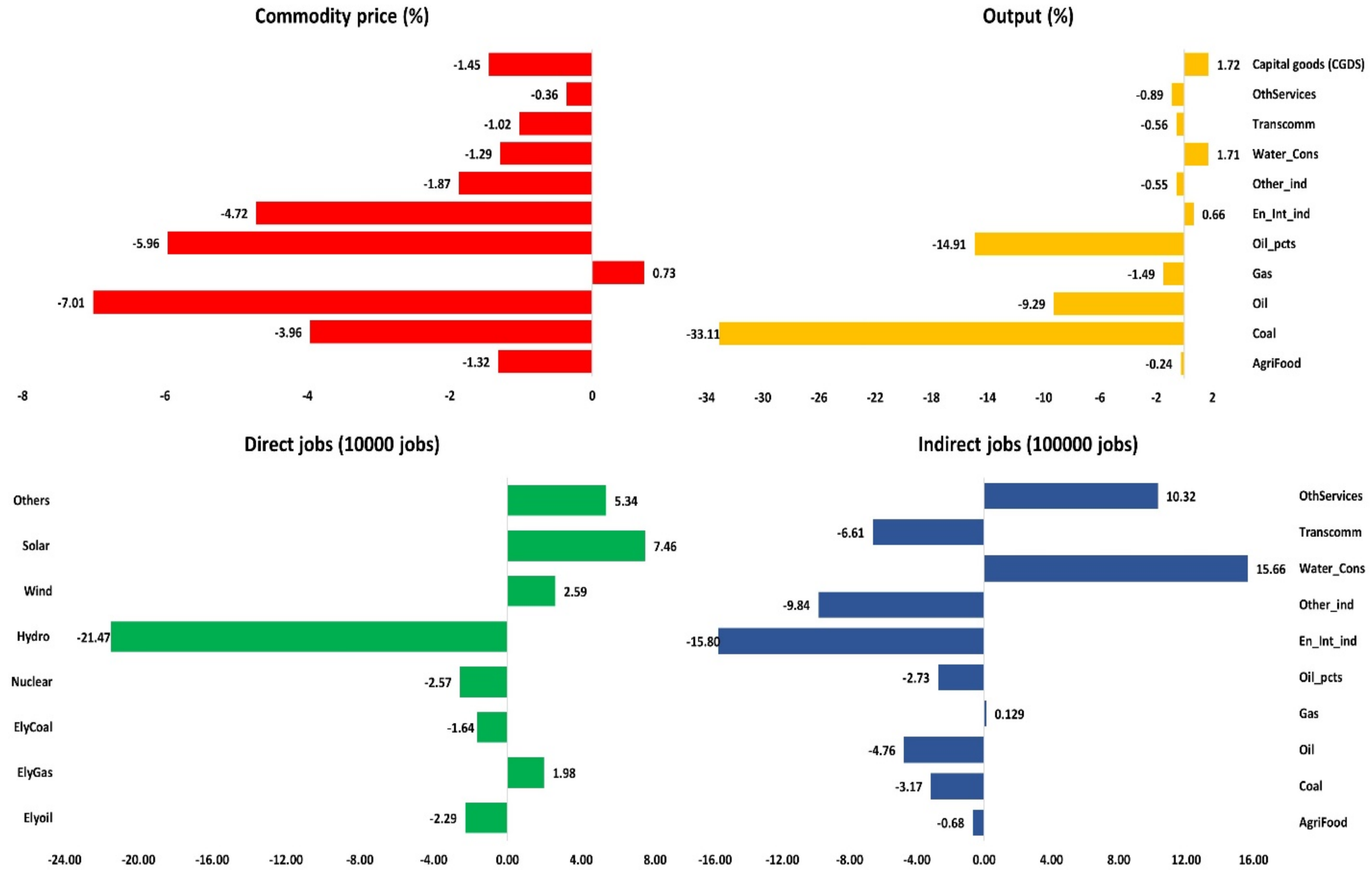

Figure 5-11 Impacts on sectoral output, commodities price, direct and indirect jobs in ROW (RNE compared to BAU)

Economic welfare, measured in GTAP by equivalent variation, summarizes the overall effects of changes in trade on the well-being of the regions. As welfare is related to trade, the changes in export and import have a big effect on welfare. The best measure of these changes is "terms of trade", which is defined as the purchasing power of the country's exports for imports [77]. In other words, an improvement in terms of trade means that the country can buy more imports for each unit it sells of exports. Table 5-3 summarizes the results of welfare and terms of trade for all the regions. Economic welfare worsens in Saudi Arabia as its export earnings are reduced by the fall in the price of oil, which represents about 85 % of its total export earnings; this in turn lowers its terms of trade. The USA's welfare and terms of trade improve because the price reduction of its main exports (energy intensive industries [En_Int_ind], other industries [other_ind], and services [othservices]) is less than the price reduction of its main imports (other industries [other_ind], energy intensive industries [En_Int_ind], and Oil), when we compare the RNE to BAU scenario. European welfare and terms of trade are worsened by the larger price reduction of its main exports compared to its imports, when we compare the two scenarios. The main European exports are energy intensive industries (En_Int_ind), other industries (other_ind), and services (othservices); and their price changes are -4.86%, -3.2%, and -2.42%, respectively. These commodities are also the main imports, and their price changes are -4.62%, -2.7%, and -1.79%, respectively. For China, its welfare and terms of trade improve because the price reduction of its main export, other industries (other_ind), is less than the import prices. Other industries (other_ind) represents about 76% of China's exports and about 42.4% of its imports. Its welfare and terms of trade improve because the price reduction of other industries (other_ind) (-1.38%) is less than in its imports (-2.22 %); this is in addition to the reduction of the price of oil, which is one of the main imports for

China. The situation in India is similar to China; where the exports prices are affected by less than in its imports.

Table 5-3 Equivalent variation ($ US millions), and terms of trade (% difference) (RNE compared to BAU scenario)

Region	Equivalent Variation	Terms of Trade
KSA	-32965.25	-5.64
USA	18869	0.57
EUROPE	-31885	-0.36
CHINA	21788	1.57
INDIA	14437	2.61
ROW	-8560	-0.01

Regarding the CO_2 emissions, all regions show a reduction as they reduce their use of coal and oil to generate electricity (Table 5-4). Saudi Arabia shows a relatively large decrease (considering the size of its economy to other regions) in its emissions, this is caused by the reduced use of oil to generate electricity, in addition to the smaller increase in most sectors' outputs in the RNE scenario. For USA and Europe, a smaller decrease is seen as their reduction of fossil fuels to generate electricity is less than others. The larger reduction of coal to generate electricity drives the large reduction in CO_2 emission in China and India.

Table 5-4 CO_2 emission (percentage difference), and CO_2 differences (RNE compared to BAU scenario)

Region	Change in CO_2	Million Tonne-CO_2
KSA	-16.85	-61.51
USA	-1.89	-96.48
EUROPE	-5.21	-297.85
CHINA	-29.72	-2152.68
INDIA	-49.78	-881.71
ROW	-13.04	-1123.7

The BAU scenario is responsible for the addition of approximately 15.98 GtC (CO_2 emissions). This follows the A1FI scenario based on the earlier projections that were developed by the Intergovernmental Panel on Climate Change (IPCC) in its 4th assessment report in 2007 [78], and higher than the business as usual RCP 8.5 scenario (13.79 GtC) of the 5th and most recent IPCC's assessment report in 2013 [79]. The RCP 8.5 is comparable to the A2 scenario of IPCC 2007 [80]. The A1FI describes the fossil fuel intensive future world, where the economic growth is a very rapid, population peaks in the mid-century and more efficient technologies are introduced rapidly [78]. According to the A1FI scenario, the CO_2 concentration reaches 448.6 ppm and global average temperature increases by 0.85 ˚C. On other hand, the RNE scenario is responsible for the addition of approximately 14.73 GtC, which follows a level between the A1FI and A1B of the 2007 IPCC's predicted scenario. The A1B describes a similar future world for A1FI but without the intensive fossil fuel sources, instead a balance between all energy sources. According to that, the CO_2 concentration reaches 448 ppm and global average temperature increases by the same amount 0.85 ˚C [79].

5.5 Conclusions

This study assessed the economic, social and CO_2 emission impacts of implementing the planned renewable and nuclear power in 2030 based on IEO prediction. Depending on the structures of their economies and their local natural resources, regions react differently. Thus, different regions with different economic structures were examined. These regions are: Saudi Arabia, the United States (US), China, India, Europe and ROW. The analysis shows that the GDP value of all regions, except India, is negatively affected; especially for Saudi Arabia because oil prices decrease as a result of the expansion of renewable energies. Regarding sectorial outputs, the upstream industries for the coal and oil electricity technologies, like coal mining and oil extraction, are the most negatively affected sectors. Conversely, the upstream industries of the renewable and nuclear power are positively affected. There is, in general, a reduction in commodity prices, resulting from declines in the energy prices; except for services (othservices) and communication (transcomm) in China and India, as they are capital and labor intensive. Regarding employment, the study shows a loss of 4.45 million jobs worldwide in the RNE compared to the BAU. Economic welfare worsens most in Saudi Arabia as its exports earnings are reduced by the lower price of oil. In Europe and ROW, a deterioration in economic welfare is shown. An improvement of economic welfare is shown in the other regions. The implementation of planned renewable and nuclear energy slightly benefits the environment but not enough to mitigate rise in global temperature. We believe that the results of this work could be used by policy makers as a justification to introduce a certain fiscal policy. Finally, it is important to mention that using a dynamic models, e.g. dynamic GTAP, would be more appropriate for this study as they are a path dependent with respect to wealth accumulation, the partial adjustment treatment of the capital stock, and the adaptive expectations treatment of the expected rate of return and the normal growth rate [81]. However, in this study we do not analyze the path of the economy primarily because GTAP-E is not built dynamically and introducing this feature entail massive modifications to the modeling framework that were beyond the scope of this study. Thus, our results implicitly assume a proportional accumulation of wealth and behavior of capital stocks across all regions and time. That a pitfall of this study and planned future area of research.

5.6 References

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5.7 Appendixes

Table A.1: Aggregations of GTAP-E regions

GTAP-E region	Member Countries
KSA	Saudi Arabia
USA	United States
EUROPE	Austria, Belgium, Cyprus, Czech Republic, Denmark, Estonia, Finland, France, Germany, Greece, Hungary, Ireland, Italy, Latvia, Lithuania, Luxembourg, Malta, Netherlands, Poland, Portugal, Slovakia, Slovenia, Spain, Sweden, United Kingdom, Switzerland, Norway, Rest of EFTA, Albania, Bulgaria, Belarus, Croatia, Romania, Russian Federation, Ukraine, Rest of Eastern Europe, Rest of Europe
CHINA	China
INDIA	India
ROW	Australia, New Zealand, Rest of Oceania, Hong Kong, Japan, Korea Republic, Mongolia, Taiwan, Rest of East Asia, Brunei Darussalam, Cambodia, Indonesia, Lao People's Democratic Republic, Malaysia, Philippines, Singapore, Thailand, Viet Nam, Rest of Southeast Asia, Bangladesh, Nepal, Pakistan, Sri Lanka, Rest of South Asia, Canada, Mexico, Rest of North America, Argentina, Bolivia, Brazil, Chile, Colombia, Ecuador, Paraguay, Peru, Uruguay, Venezuela, Rest of South America, Costa Rica, Guatemala, Honduras, Nicaragua, Panama, El Salvador, Rest of Central America, Dominican Republic, Jamaica, Puerto Rico, Trinidad and Tobago, Caribbean, Kazakhstan, Kyrgyzstan, Rest of Former Soviet Union, Armenia, Azerbaijan, Georgia, Bahrain, Iran, Israel, Jordan, Kuwait, Oman, Qatar, Turkey, United Arab Emirates, Rest of Western Asia, Egypt, Morocco, Tunisia, Rest of North Africa, Benin, Burkina Faso, Cameroon, Cote d'Ivoire, Ghana, Guinea, Nigeria, Senegal, Togo, Rest of Western Africa, Central Africa, South Central Africa, Ethiopia, Kenya, Madagascar, Malawi, Mauritius, Mozambique, Rwanda, Tanzania, Uganda, Zambia, Zimbabwe, Rest of Eastern Africa, Botswana, Namibia, South Africa, Rest of South African Customs Union, Rest of the World

Table A.2: Aggregations of GTAP-E sectors

GTAP-E Sector	Description	Comprising
AgriFood	Agriculture,forestry,& fishing	Paddy rice, Wheat, Cereal grains nec, Vegetables, fruit, nuts, Oil seeds, Sugar cane, sugar beet, Plant-based fibers, Crops nec, Bovine cattle, sheep and goats, horses, Animal products nec, Raw milk, Wool, silk-worm cocoons, Forestry, Fishing
Coal	Coal mining	Coal
Oil	Oil extraction	Oil
gas	Gas extraction & distribution	Gas, Gas manufacture, distribution
oil_pcts	Petroleum, coal products	Petroleum, coal products
En_Int_ind	Energy intensive industries	Minerals nec, Chemical, rubber, plastic products, Mineral products nec, Ferrous metals, Metals nec
other_ind	other industries	Bovine meat products, Meat products nec, Vegetable oils and fats, Dairy products, Processed rice, Sugar, Food products nec, Beverages and tobacco products, Textiles, Wearing apparel, Leather products, Wood products, Paper products, publishing, Metal products, Motor vehicles and parts, Transport equipment nec, Electronic equipment, Machinery and equipment nec, Manufactures nec
water_Cons	water and Construction	Water, Construction
Transcomm	Transport and Communication	Trade, Transport nec, Water transport, Air transport, Communication
OthServices	Other Services	Financial services nec, Insurance, Business services nec, Recreational and other services, Public Administration, Defense, Education, Health, Dwellings
TandD	transmission & distrubuition	Electricity transmission & distrubuition
elygas	Electricity from gas	Gas base and peak load
elyoil	Electricity from oil	Oil base and peak load
elycoal	Electricity from coal	Coal base load
nuclear	Electricity from nuclear	Nuclear base load
wind	Electricity from wind	Wind base load
hydro	Hydroelectric	Hydro base and peak load
solar	Electricity from solar	Solar peak load
elyother	Electricity from others	Other base load

Table A.3: Projected learning rates of the electricity technologies for 2030

Electricity Technology	Learning Rate
Solar	11
Wind	6
Nuclear	5.8
Hydro	-10
Others	13.67

- Learning rate of 0.1 means a cost fall by 10 % when the cumulative production doubles

Table A.4: The absolute values of electricity production mix in 2030

	billion kwh					
	SAUDI ARABIA		CHINA		INDIA	
	BAU	RNE	BAU	RNE	BAU	RNE
elyoil	257.9	175.8	10	6	39	20
elyGas	164.9	60.0	138	647	164	111
elyCoal	0.0	0.0	6092	4353	1407	1087
nuclear	0.0	82.7	158	754	56	206
hydro	0.0	0.0	1454	1234	234	287
wind	0.0	12.7	163	592	52	130
solar	0.0	72.1	10	218	4	85
others	0.0	19.4	76	297	9	40
	USA		EUORPE		ROW	
	BAU	RNE	BAU	RNE	BAU	RNE
elyoil	27	18	138	93	1119	375
elyGas	1421	1371	1585	1639	2412	2969
elyCoal	1752	1713	1611	1295	1510	1043
nuclear	890	808	1363	1341	419	746
hydro	318	295	1021	958	1969	1740
wind	163	245	260	576	54	299
solar	13	71	88	107	14	181
others	108	171	201	258	174	318

6 Conclusion

Evaluating the global environmental impacts of the current and future energy policies in Saudi Arabia using Life cycle assessment (LCA) method was the main objective of this dissertation. Additionally, the subsequent economic stimulus of those planned polices and their potential effects on multiple social systems were studied. For that, using a holistic method that can account for the large-scale direct and induced environmental and economic consequences is mandatory. The study showed the magnitude of the environmental impacts, based on the ALCA analysis, is influenced by the type of primary fuel used for electricity generation. In addition, the emergence of renewable and nuclear energy is mainly driven by fossil fuel energy prices and ease of substitution for the fossil fuel electricity technologies. Thus, fostering the shift to renewable and nuclear technologies might require implementing a policy that raises fossil fuel energy prices, e.g. a carbon tax. However, the lack of wide and comprehensive convention of a carbon tax might lead to carbon leakage associated with moving the production of carbon-intensive goods to regions that do not adopt a similar tax. Finally, an ex-ante analysis was done to study the economic, social and environmental impacts of large-scale global electricity generation targets to utilize renewable and nuclear energy by 2030. The study showed a deteriorated GDP in most regions. In addition, the world would face a loss of 4.45 million jobs. Economic welfare worsens most in the oil-based economies as their exports earnings are reduced by the lower price of oil. The environment benefits of the targeted renewable and nuclear energy would be slight and not enough to mitigate the global temperature rise. Thus, as some well-intentioned policies design to promote green technologies might have unintended side effects that increase fossil fuel use and CO_2 emissions and have negative effects on some local economies, global coordinated efforts are needed. We believe that the results of this work could be used by policy makers as a justification to introduce a certain fiscal policy. Finally, it is important to mention that using a dynamic models, e.g. dynamic GTAP, would be more appropriate for this study. That a pitfall of this study and planned future area of research.