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Achieving Climate Targets via the Circular Carbon Economy: The Case of Saudi Arabia

Yousef M. Alshammari [1,2]

[1] College of Engineering, Prince Mohammad Bin Fahd University, Khobar 34754, Saudi Arabia; Yalshammari@pmu.edu.sa

[2] Faculty of Business, Economics and Statistics, University of Vienna, Oskar Morgen Stern Platz 1, 1090 Vienna, Austria

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Abstract: Clean hydrocarbon technologies have a key role to play in achieving the circular carbon economy while meeting climate targets in many countries around the world. The aim of this work is to assess which technology, or combination of technologies, is the most cost-effective in achieving climate targets by 2030 leading to a quick and smooth transition to a low carbon energy system in Saudi Arabia and similar oil-based economies. We find that low carbon policy support by banning crude oil in power generation, leads to accelerated underground oil gasification, in the absence of carbon prices. We also find that setting a policy for carbon reduction targets leads to a more flexible energy system transition enabling more technologies in the mix with an increasing transition period. Our results also show that clean hydrocarbon technologies may be sufficient to achieve new climate targets, as shown by the stabilised emissions in scenario 3 by 2025, without the implementation of renewable sources of energy which most studies do not include. We propose that by investing in clean hydrocarbon technologies over the short term, the transition towards a low carbon economy will be accelerated while developing renewable sources of energy over the long term.

Keywords: CO_2 pricing; thermal splitting; underground gasification; energy transition; CCS

1. Introduction

Meeting climate targets has always been a global necessity. The IPCC emphasises that the Paris Agreement targets must be achieved by 2030 in order to maintain the Earth's temperature rise at less than 1.5 °C. The circular carbon economy, achieved via clean hydrocarbons technologies (CHTs), has a key role to play in achieving this target. The term clean hydrocarbon technologies is a broad term which refers to any technology that converts the energy stored in hydrocarbons into electricity, fuel or useful mechanical work with a minimal carbon footprint. Over the past decade, new hydrocarbon conversion technologies underwent significant breakthroughs to make the future of hydrocarbons more sustainable in a carbon constrained world. New technologies may include not only carbon capture and storage, but also many other new technologies such as direct hydrocarbon fuel cells, conversion of CO_2 into fuels, and underground gasification of hydrocarbons which may achieve the circular carbon economy. Cost-effective implementation of each of the aforementioned technologies will be governed by the economics and their development status. There is a growing need for understanding the role of hydrocarbon conversion technologies in enabling global energy access while realising energy transition that meets climate targets. The following review presents recent breakthroughs in hydrocarbon conversion technologies which could pave the way for their implementation in a circular carbon economy.

2. Literature Review

The concept of the so-called circular carbon economy involves a stepwise closure of the carbon cycle via utilisation or conversion of CO_2 generated from the combustion of fossil fuels leading to significant reduction of carbon emissions [1]. To achieve the circular carbon economy, clean hydrocarbon technologies are needed many of which remain under development. The potential of clean hydrocarbon technologies, shown in Table 1, is demonstrated in a range of previous studies [2–31]. For instance, carbon capture, utilisation and storage (CCUS), which fits within the second segment in Figure 1, is a relatively immature technology and existing research is geared towards improving its capture efficiency and reducing its costs and energy requirements [2–13]. CCUS is a largely debated technology for clean fossil fuels that is expected to achieve a large reduction in CO_2 emissions. Integration of CCUS into existing power plants was estimated to cost households around 10% of their electricity consumption, yet increasing the implementation of CCUS may potentially bring its costs down to $50/tonne in 2050 [2–5]. A significant reduction in CO_2 capture costs was made by the Shidongkou No. 2 Power Plant near Shanghai, China, where CO_2 capture was reported to cost between $30–$35/tonne with a capture efficiency improvement by 11–14% [5]. The commercial success of CCUS has been demonstrated in Norway since 1996 where a carbon tax of $50/tonne was set [5]. Other projects for injection 1 million tonne of CO_2 into saline formation are in operation, two in Norway, and one in Algeria [8]. Despite government support, a few CCUS demonstration projects have existed so far worldwide due to multiple political economy factors that affect decision making processes by policy makers and investors [2–4].

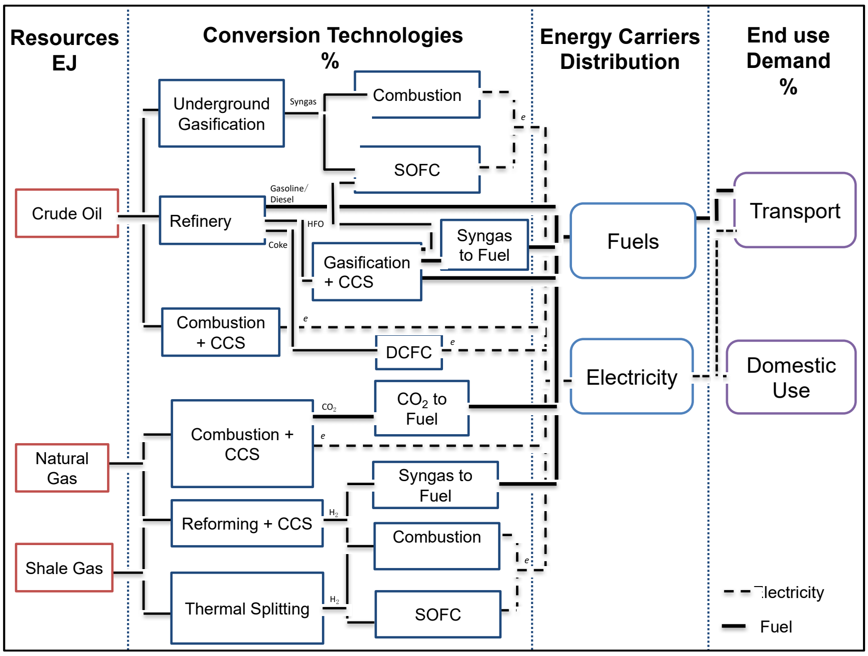

Figure 1. Proposed energy system implemented in our study.

CCUS projects can be carbon positive, carbon neutral, or carbon negative depending on the process of producing and capturing CO_2 used. Numerous small scale CCUS projects have been successfully demonstrated from a technical perspective [6]. Carbon neutral and carbon negative CCUS are required for sustainable utilisation of hydrocarbons within a climate friendly framework. Two carbon neutral CCUS projects, in Kemper County, Mississippi, USA, and Boundary Dam, Canada, which is currently running, both of which obtained government funding of $700 million [7]. Negative CO_2 capture includes capturing CO_2 from biomass combustions or directly from air. The economic viability of CO_2 capture can also be enhanced through its conversion into high value chemical products. For instance, the SK refining complex showed a novel initiative where captured CO_2 is converted into polypropylene carbonate which is used to make accessories such as wallets. For example, the fashion trademark Donna Kanar New York (DKNY), using the Greenpol technology [9], made of polymers to make commercial wallets. Another example is the conversion of CO_2 into methanol using solar thermal energy which was demonstrated by Kim et al. [10]. In their process, a solar reactor is used to convert CO_2 into CO followed by the production of hydrogen, and subsequently methanol. The economic analysis of this process showed that the breakeven price for methanol needs to be $1.2/kg while the system efficiency of solar energy to fuel is 7.1%.

CO_2 capture directly from air is technically possible using adsorbent technologies [11–15]. However, the economic viability of large scale capture of CO_2 from air remains questionable, as no large-scale facility has been built yet [14]. The high cost is largely attributed to the low concentration of CO_2 in air which could at least double the amounts of energy required for CO_2 removal. The carbon pricing policies will play a key role in the economic viability of commercial scale CO_2 capture from air especially at deep emissions targets. A CO_2 price of $50–100/tonne was estimated to be required in order for CO_2 air-capture to be cost-competitive with other mitigation technologies [10,11].

Another promising technology is the gasification of hydrocarbons which has been commercially demonstrated through different large-scale projects in Europe, Asia, and the United States [16]. Gasification enhances the conversion economics by turning heavy low value feedstock into high value gaseous products. One particular area of a special interest is the underground gasification of hydrocarbons which remains under development [17–20]. Furthermore, Underground Coal Gasification (UCG), which was successfully demonstrated in Australia and Uzbekistan [21,22] and many other sites, is being tested and planned around the world including China, India, Russia and the USA. The synthesis gas produced from gasification processes can be fed into fuel cells to generate power. One report showed that underground gasification can be integrated with a solid oxide fuel cell (SOFC) system generating electricity from syngas leading to a net efficiency of 34% which is 4.2% higher than the efficiency for UCG when coupled with steam turbines [22]. SOFCs are the most promising types of fuel cells for clean power generation, especially when coupled with carbon capture systems, and its theoretical efficiency can be as high as 90% [23–25]. Nonetheless, many technical and economic issues remain for its wide implementation including scaling-up, cost, safety, and reliability.

One fuel cell demonstration project is the world's largest fuel cell plant which has been built in South Korea with a capacity of 59 MW, with a planned expansion to 230 MW, which will enable South Korea to diversify its energy mix [25]. Furthermore, GE demonstrated a novel manufacturing method for SOFC with 49% efficiency and an investment cost of $500–550/kW, and that compares well to the investment costs of conventional gas-fired power plants [26]. It should be noted that a SOFC investment below $1700/kW can be considered as optimistic according to the latest figures [23].

Another clean hydrocarbon technology is the thermal splitting of natural gas especially when coupled with carbon-free sources of energy [27–30]. This process competes with other production routes of hydrogen including electrochemical, photo-chemical, photo-biological routes due to the utilisation of solar energy to provide heat, and the higher bulk hydrogen that can be produced from hydrocarbons without CO_2 emissions. Solar heat is provided through concentrated solar radiation which generates the necessary heat for the production process. While produced hydrogen is used to generate electricity through combustion or fuel cells, the produced carbon can be utilised in various industries including rubber and steel manufacturing. The price of carbon has a significant impact on improving the process economics especially when black carbon is sold at a higher price in speciality industries such as the graphite industry. A report on the economic evaluation of the process showed that the required selling prices for both hydrogen and carbon are $9.5/GJ and $0.77/kg, respectively, assuming a plant production capacity of 1 million kg/year hydrogen [30]. The required investments for this process would include solar towers and solar concentrators which generate heat for the thermochemical conversion of methane. With thermal splitting, it is also possible to modify existing conventional facilities without the need to construct new plants as in the case for nuclear, photo-biological or photo-chemical production of hydrogen.

Based on the literature review presented above, this work presents a new energy system model for the power generation and transport sectors in Saudi Arabia based on current and emerging hydrocarbon technologies. The aim of this work is to understand the role and economic benefits of clean hydrocarbon technologies in meeting climate targets, while analysing the interaction between carbon pricing mechanisms and technology policies in meeting climate targets.

Table 1. Summary of emerging clean hydrocarbon technologies.

Technology	Description	Challenges	Projects	Reference
CCUS	Using amine absorption unit to remove CO_2 from flue gas followed by CO_2 separation and transportation to depleted reservoirs	CO_2 transport, capture costs, energy penalty	Sleipner Project Norway	[2–8]
Solar CO_2 Conversion	Photo reduction of CO_2 into CO followed by its conversion to H_2/syngas and later to methanol	Efficiency and costs of production	SK Oil Refinery, Korea	[9,10]
SOFC	Electrochemical conversion of fuel which generates electrons	Catalyst development, and cost of production	GE new SOFC prototype with 6 KW	[22–26]
Underground Gasification	Conversion of heavy oil into hydrogen	Process relatively less understood	Tested for Coal by Cougar Energy, Australia	[16–22]
Solar Splitting	Thermal decomposition of natural gas, using solar energy, to generate hydrogen and carbon	Energy requirement, efficiency and solar intermittency	Under development	[27–30]

3. Methodology

3.1. Model Development

The systems analysis modelling in this study was conducted using the MESSAGE software package. MESSAGE is a linear programming (LP) optimisation model, developed by the International Institute of Applied Systems Analysis (IIASA, Laxenburg, Austria), and it was described in detail in previously published techno-economic analysis studies [32–35]. MESSAGE generates the optimum technology mix that meets the energy demand at the lowest cost under given environmental or economic constraints. MESSAGE can be used to determine the desired energy mix with optimum allocation of resources, enabling diversification of supplies, reduction of foreign imports, while preserving the environment. MESSAGE requires data on energy demand, environmental constraints, conversion efficiency, production costs, and resource capacity. MESSAGE generates the optimum solution to meet the projected energy demand at lowest cost, while meeting the set environmental and economic targets. The following sections describe the data and scenarios used as inputs to the MESSAGE optimization routine.

3.2. Model Data

In order for the model to solve for the lowest cost, it was fed with various data that include energy efficiency, levelised costs of energy production (LCOE), and CO_2 emissions factor for each used technology, as shown in Table 2. Furthermore, the annual energy demand in Saudi Arabia was estimated for domestic electricity, and transport fuels, as shown in Table 3 along with the annual availability of national energy resources estimated as shown in Table 4. The energy demand in this work is based on our previously published work [31,32] which analyses energy transition in electricity and road transport sectors in Saudi Arabia. For the electricity sector, we assume that energy demand will rise in a business as a usual fashion, based on historical data, until 2050. This rise in demand is likely to be reduced by up to 60% in 2025 using newly adopted government energy efficiency measures including insulation, efficient air conditioners and efficient lighting, as discussed in our previously published work [31].

Table 2. Techno-economic Data [17,31,34–37].

Technology Combination	Acronym	Efficiency %	LCOE [$/GJ]	CO_2 Factor [kTonne/PJ]	Notes
Natural Gas Power Plant + Carbon Capture	NGPP + CCS_Elec	0.49	14.46	24	Assuming 80% carbon captured
Natural Gas Power Plant	NGPP_Elec	0.56	7.51	123	Cost is based on current gas prices
Heavy Fuel Oil Power Generation	HFOPP_Elec	0.45	7.62	215	Cost is based on current fuel oil prices
Heavy Fuel Oil Power Plant + Carbon Capture	HFOPP + CCS_Elec	0.37	16.13	53.83	-
Thermal Splitting + PEM Fuel Cell	TS + PEMFC_Elec	0.42	17.26	0	Thermal splitting using energy supplied from solar thermal plant
Steam Reforming of Methane using Solar Thermal Plant + Hydrogen Combustion	SMR + H_2Comb_Elec	0.51	17.26	24	Assuming Solar Thermal for Reforming
Thermal Splitting + Hydrogen Combustion	TS + H_2Comb_Elec	0.42	14.08	24.6	Thermal splitting using energy supplied from solar thermal plant
Refinery Gasoline to Cars	Ref_Gaso_Transport	0.27	1.38	86.07	Efficiency is based on WTW
Refinery Diesel to Cars	Ref_Diesel_Transport	0.41	1.15	86.64	Efficiency is based on WTW
Refinery Coke + DCFC	Ref_Coke_DCFC_Elec	0.54	4.32	0	-
Refinery HFO + Gasification to MeOH	Ref_HFO_Gasi_MeOH_Transport	0.21	10.90	42	With CCS
Refinery HFO + Gasification to DME	Ref_HFO_Gasi_DME_Transport	0.23	12.66	22	With CCS
Underground gasification + SOFC	UOG + SOFC_Elec	0.42	6.17	17.01	Assuming UOG is near commercialisation
HFO Gasification + H_2 combustion	Ref_HFO_Gasi + H_2Com	0.38	7.50	17.01	With CCS

Table 3. Energy Demand Projection [PJ/year].

Sector	2015	2020	2025	2030	2035	2040	2045	2050
Domestic Electricity	1052	1441.65	1974.87	2705.31	3705.90	5076.58	6954.21	9526.32
Domestic Electricity (Assuming 60% efficiency)	768	842	864	789	1082	1482	2030	2781
Diesel–Transport	88.12	126.12	164.12	202.11	240.11	278.11	316.11	354.11
Gasoline–Transport	242.0	346.34	450.68	555.02	659.35	736.69	868.03	972.36

Table 4. Energy Resource Data [PJ/year].

Sector	PJ/Year
Heavy Oil	10,000
Shale Gas	5000
Natural Gas	4000
Crude Oil	2000

On the other hand, the road transport energy demand, in Table 3, assumes continued rise in gasoline and diesel demand from 811 thousand bbl/d in 2015 to 3.26 million bbl/d in 2050 due to increasing number cars from 12 million to 26 million cars, as per the government forecast, which is discussed in our previously published work [32].

Based on the energy system chart shown in Figure 1, a new model was developed which enables analysis of transition from conventional CO_2-emitting technologies to advanced innovative clean hydrocarbon technologies, as discussed in Section 3.1. Initial simulation of the energy system was conducted which yielded reliable results. CO_2 mitigation scenarios were then developed using carbon pricing and technology policy tools as shown in Table 5, and simulation results were obtained for different CO_2 pricing and policy scenarios. This enabled analysing the energy technology mix for different scenarios while understanding the effect of CO_2 pricing mechanisms on reducing CO_2 emissions.

Table 5. Description of CO_2 pricing and technology policy scenarios.

Scenario No.	Scenarios	Description
Ref	BAU	Business as usual scenario, i.e., carry on with existing policies with no price on carbon
Sc.1.	Oil Phase-Out	Ban on crude oil in power generation with no price set on CO_2
Sc.2	Carbon Tax	Globally uniform carbon tax of $7.3/Tonne increasing at 5% annually
Sc.3	Carbon Cap	Capping carbon emissions by 15% (65.7 million Tonne) by 2030 maintained till 2050

Various clean hydrocarbon technologies were considered in this work, as shown in Figure 1 and Table 2. Figure 1 shows innovative potential routes for the conversion of hydrocarbons into energy in the form of electricity, liquid or gaseous fuels. For instance, it is shown that crude oil can either be converted into various conventional fuels through refining processes which can be used to transport fuel demand. Alternatively, crude oil can be combusted directly to generate electricity while capturing CO_2 which can be either sequestered for enhanced oil recovery, or converted into fuels and other chemical products. Another more innovative approach is the conversion of crude oil into hydrogen and syngas directly underground under downhole hydrothermal conditions which minimises the carbon footprint of above-surface processing while enabling combined generation of energy and synthesis gas [1]. The annual increase in CO_2 price in Scenario 2 is shown in Figure A1 in the Appendix A.

4. Results and Discussion

4.1. Energy System

To analyse the technologies used in this work, the energy system in Figure 1 is divided into four segments; (1) resources, (2) conversion technologies, (3) distribution of energy carriers, and (4) the end use demand. This segmentation is crucial in understanding the effects of different parameters within the energy system. For instance, energy resources represent natural resources including crude oil, natural gas, solar light, uranium, wind, etc. According to the second law of thermodynamics, the energy contained in these resources cannot be fully consumed. The efficiency of conversion technologies is, hence, an important parameter to maximise the utilisation of the energy contained in natural resources by converting them to energy carriers for end user application in the form of fuel or electricity (Segment 3). The fourth segment, end use demand, contributes to a low carbon system by reducing inefficiencies associated with energy consumption from an end user standpoint. In this segment, energy is used through domestic technologies including cooking, lighting, air conditioning, heating, and cooling. Proper management of these segments is, thus, an essential aspect for ensuring optimal allocation and utilization of resources while mitigating negative environmental consequences. The technologies used in this energy system are explained in Section 2. Furthermore, the energy demand, in transport and power generation sectors, and energy resources for the system shown in Figure 1, are shown in Tables 3 and 4 based on which the technology transition is analysed based on technology costs and policies in Saudi Arabia.

4.2. Impact of CO_2 Pricing

Based on the energy system shown in Figure 1, the model generated energy mix data that meets energy demand while achieving carbon targets. Figure 2 shows the business as usual (BAU) scenario where energy consumption increases due to rising population and economic growth, while maintaining existing policies of dependence on conventional combustion of hydrocarbons and fuel subsidies. It shows that CO_2 emissions increased almost exponentially to reach 643 million tonne in 2030 and 2156 million tonne in 2050.

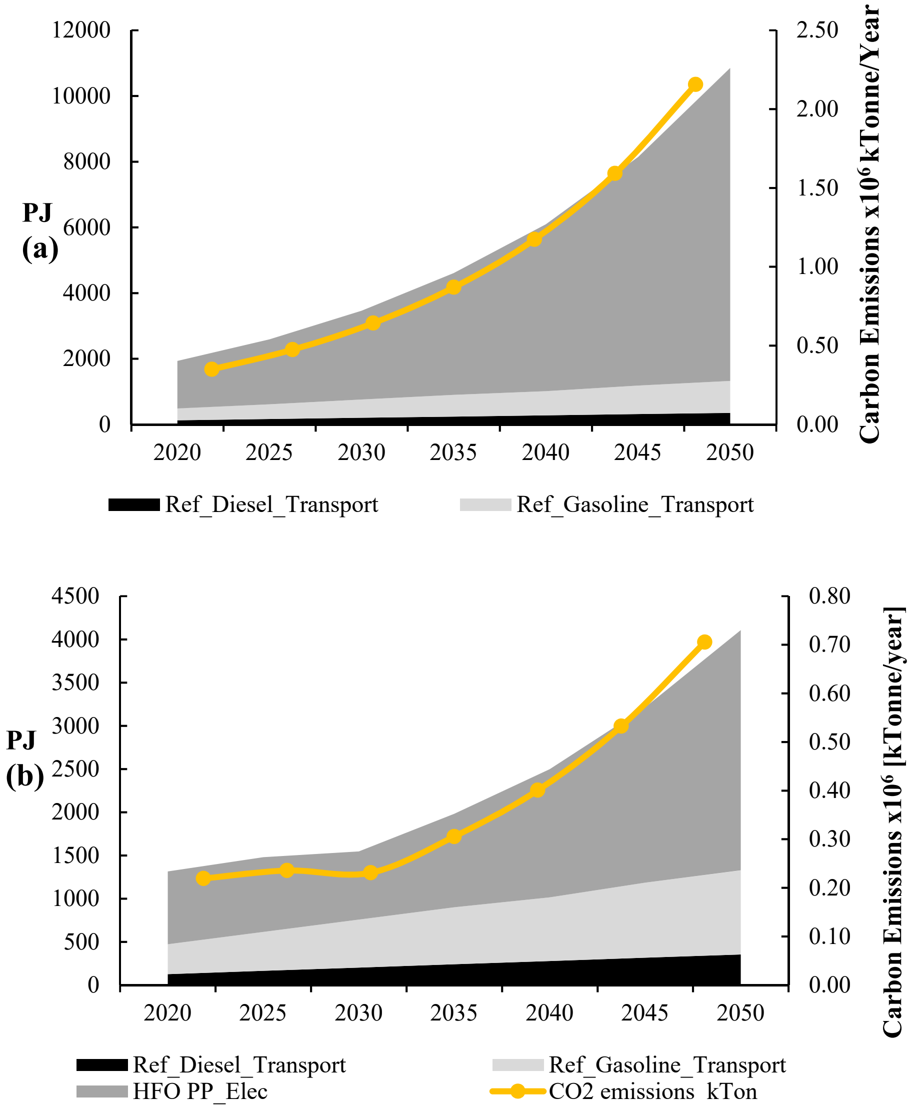

Figure 2. Energy/technology Mix under (**a**) BAU case (**b**) BAU case with 60% energy efficiency targets.

Figure 3 shows the energy mix for Scenario 1, which assumes no CO_2 price is imposed with ban on crude oil combustion in power generation to support low carbon policy. Under this scenario, it is found that all conventional power generation will be replaced by underground gasification of hydrocarbons followed by fuel cells, and coke gasification with fuel cells for the power generation sector. Furthermore, the transport sector continues to rely on conventional hydrocarbons, namely gasoline and diesel. Introducing a carbon price of $7.3/Tonne which rises by 5% annually, as shown in Scenario 2, will lead to a transformation in the power generation sector leading to thermal splitting of methane to generate hydrogen which can be used in fuel cells for power generations, as shown in Figure 4. The generated carbon from this splitting process can be gasified to generate syngas which may be combusted or used in fuel cells as shown in this scenario. The transport sector is also transformed to use synthetic fuels instead of conventional fuels as found in the previous scenario.

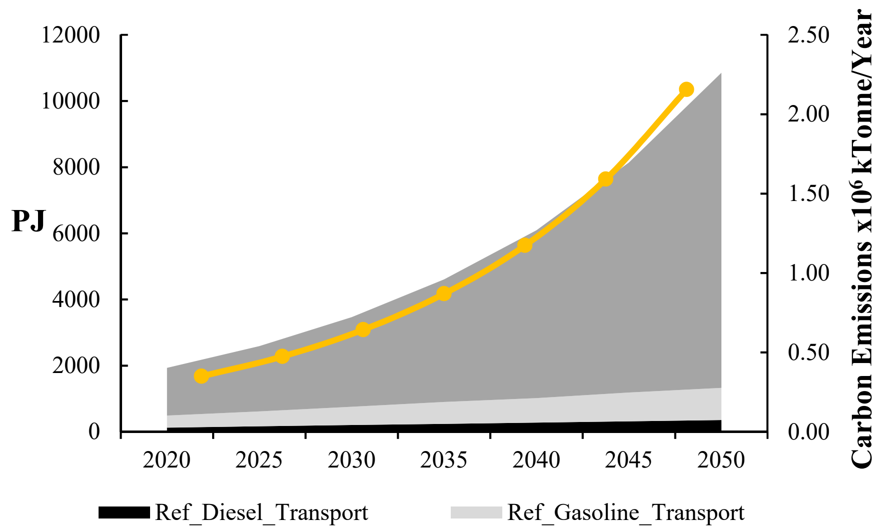

Figure 3. Energy/technology mix for Scenario 1 (no price on CO_2 with a ban on crude oil combustion for power generation in support for low carbon policy).

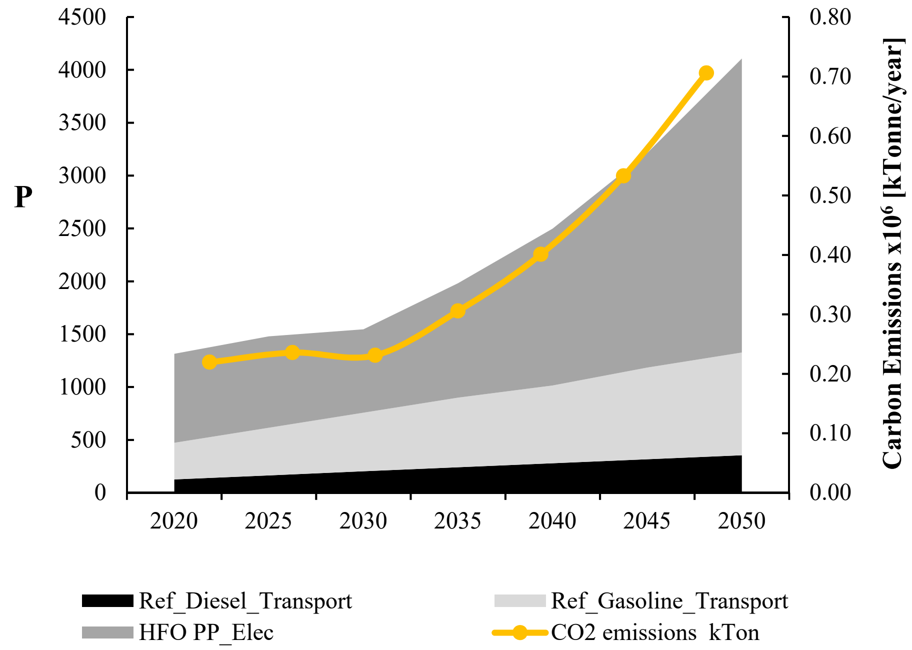

Figure 4. Energy/technology mix for Scenario 2 (CO_2 price $7.3/tonne in 2015 rising at 5% annually with a ban on oil in power generation).

The impact of raising CO_2 prices from $7.3/tonne to $40/tonne, Scenario 2, is shown in Figure 5, which compares the CO_2 emissions levels with and without carbon pricing. We find that that carbon emissions decline by more than 50% when CO_2 prices are introduced. For instance, the CO_2 emissions decrease to 48 million tonne at a CO_2 price of $40/tonne compared with 160 million tonne when no CO_2 price is introduced. The reason for the decline in emissions can be explained by comparing the technology mix in Figure 3 and in Figure 4. When CO_2 pricing is introduced, low carbon technologies are selected, Figure 3, to reduce the costs of high emission technologies in Figure 3. Scenario 2 assumes a CO_2 price of $7.3/tonne that rises by 5% annually to reach around $40/Tonne in 2050, which is shown in Figure 4.

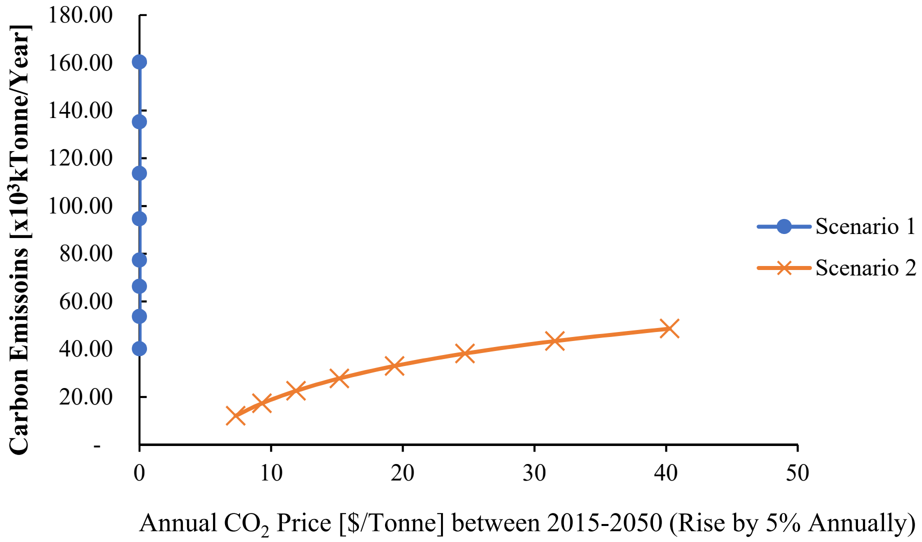

Figure 5. Impact of CO_2 price on carbon emissions.

4.3. *Impact of Capping CO_2*

Figure 6 shows Scenario 3 which shows the impact of capping emissions to achieve a 15% reduction of the emissions in Scenario 1 by 2030 which is maintained until 2050. This will lead to phasing out conventional diesel by 2030 and conventional gasoline by 2045 in the transport sector, which will be replaced by methanol and dimethyl-ether generated from gasification of heavy fuel oil in 2025 and 2030, respectively. The power generation sector shows that underground gasification of hydrocarbons is restored along with coke gasification, both of which are followed by fuel cell power generation starting from the current period until 2030 and 2050. Furthermore, thermal splitting combined with fuel cells emerges in the energy mix in 2040 which accounts for more than 50% of the power generation in 2050.

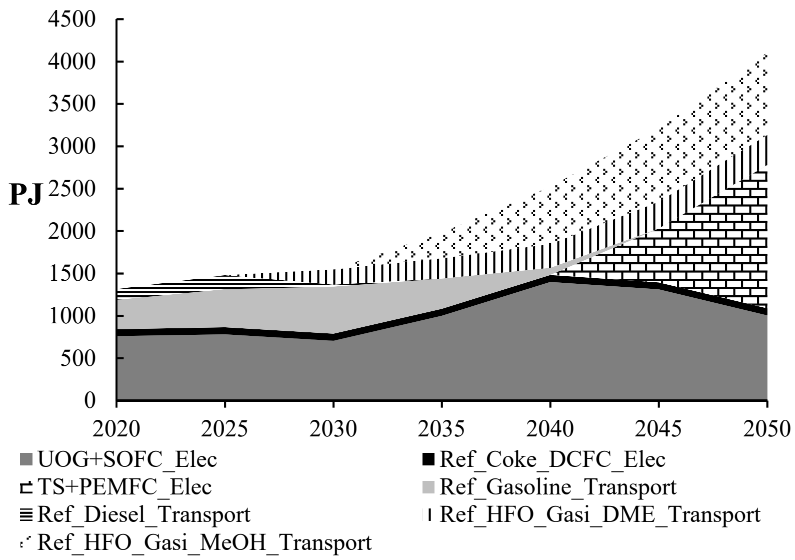

Figure 6. Energy/technology mix for Scenario 3 (CO_2 cap of 65704 (15% reductions of Scenario 1) by 2030 maintained till 2050 and ban on oil combustion for power generation).

The carbon emissions profiles under different scenarios are shown in Figure 7. It is found that Scenario 2, where CO_2 pricing is imposed, leads to the highest reduction in carbon emissions, followed by Scenario 3, and Scenario 1. However, Scenario 3 includes more technologies in the energy mix with more flexibility leading to a fixed emissions level until 2050, while Scenario 1 leads to more than 80% reduction in emissions compared with the BAU scenario.

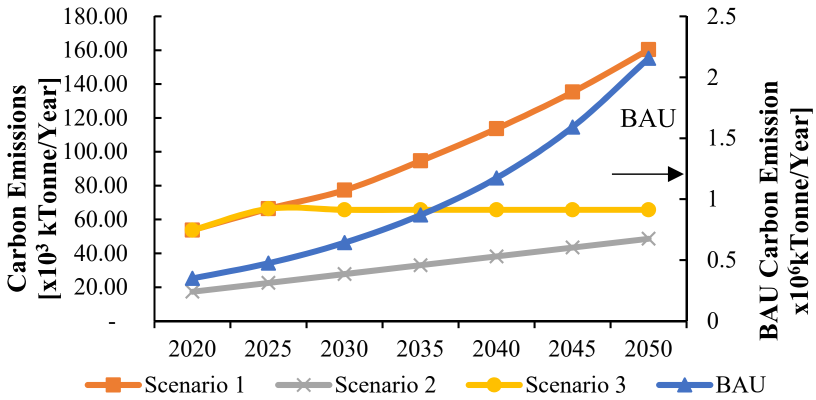

Figure 7. Profiles of carbon emissions under BAU and carbon mitigation scenarios. (Scenario 1: Ban on oil use in power generation, Scenario 2: CO_2 price $7.3/tonne that rises 5% annually, Scenario 3: CO_2 cap by 15% of Scenario 1 by 2030 combined with a ban on oil in power generation).

4.4. Investments Requirements

Figures 8–10 show estimation of the investments requirements for Scenarios 1, 2 & 3. It is found that Scenario 1 offers a cheaper alternative to conventional technologies, Figure 8, as energy demand increases from 2020 to 2050. In this scenario, electricity is assumed to be mainly generated via underground oil gasification combined with solid oxide fuel cell, while the road transport sector remains dependent on conventional gasoline and diesel. On the other hand, the investment requirements for Scenario 2 are significantly higher than the BAU case, Figure 9. It is found that total investments rise from around $20 billion, in 2020, to more than $60 billion, in 2050, in Scenario 2, while the BAU case rises from nearly $7 billion, in 2020, to $22 billion in 2050. This significant increase in the cost observed in Scenario 2 is due to the use of the thermal splitting and PEM fuel cell technology which accounts for at least 75% of total investment requirements. The investment requirements for Scenario 3, Figure 10, are only cheaper at the initial stage of transition between 2020–2030, below $7 billion, but they tend to become at a greater cost compared with conventional technologies as energy demand rises between 2035 and 2050, reaching nearly $30 billion. This is due to the supply of methanol, obtained from fuel oil gasification, in road transport, and the use of thermal splitting with PEM fuel cells in power generation.

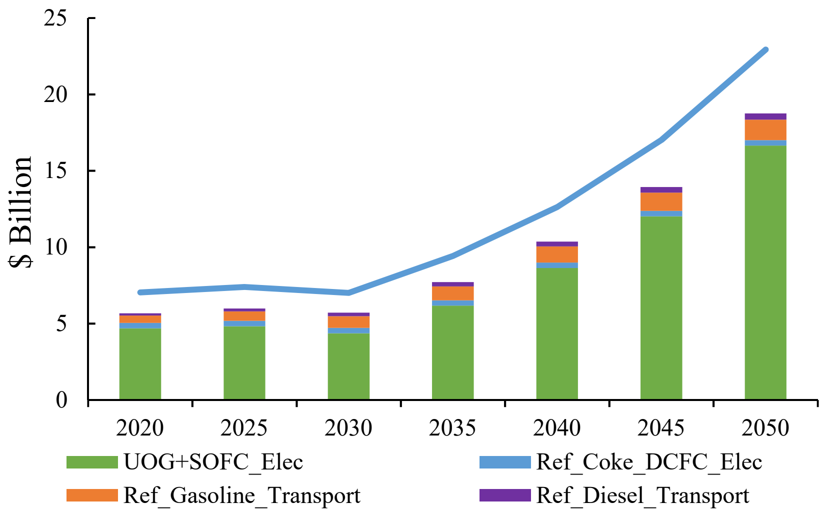

Figure 8. Investment requirements for scenario 1.

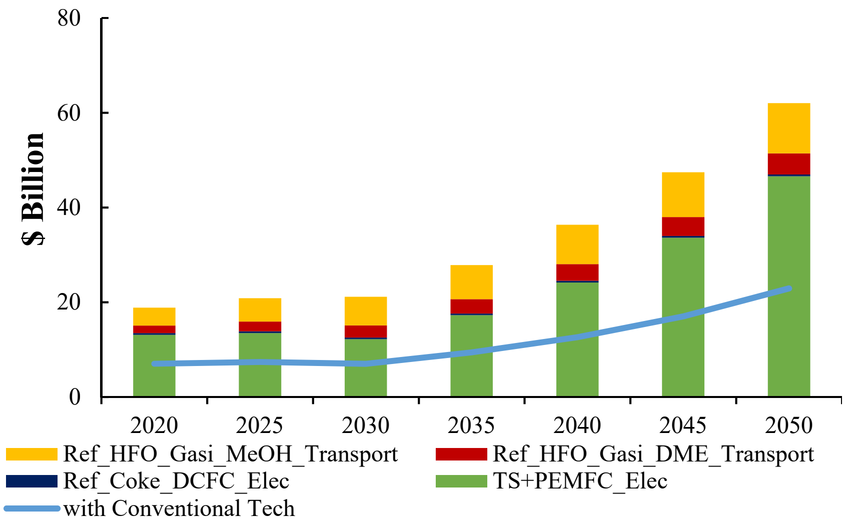

Figure 9. Investment requirements for scenario 2.

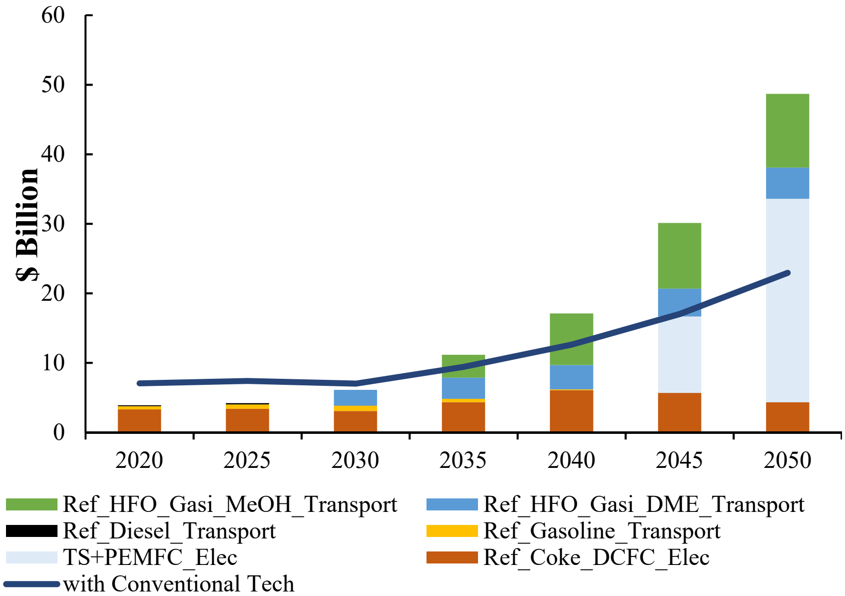

Figure 10. Investment requirements for scenario 3.

It is also found that the total investments required in clean hydrocarbons will amount $121.23 billion, $37.76 billion higher than the investments needed under the BAU scenario.

4.5. Impact of Technology Policy

In this analysis, we find that the economics of technology may not be sufficient to drive its implementation. Supportive policies are necessary for accelerated implementation of new hydrocarbon technologies to drive their maturation at a higher pace. For instance, we also find that low carbon policy support by banning the use of crude oil in the power generation sector, Figure 3, leads to accelerated use of underground oil gasification for hydrogen generation followed by solid oxide fuel cell power generation, in the absence of a carbon price. However, the implementation of such policies will have a higher cost compared with conventional approaches. Imposing a carbon price in Figure 4, on the other hand, leads to accelerated use of thermal splitting for hydrogen generation, instead of UOG, which enables a shift from conventional power generation, using direct combustion of crude oil, to a more innovative approach for exploiting natural gas resources. We also find that setting a policy for a carbon reduction target, 15% reduction by 2030, in Figure 6 leads to a more flexible energy system transition where more technologies appear in the mix with an increasing transition period.

Our results may be compared with previous work [38] which showed that technology policies may lower socio-economic costs by compensating for sub-optimal carbon prices and driving technology development. It was further suggested that technology policies work better when coupled with carbon pricing mechanisms rather than cap-and-trade- mechanisms [38]. In comparison to additional previous studies [38–51], our analysis shows that setting a carbon target policy enables more low carbon technologies to emerge in the energy mix compared with the pricing mechanism, and that leads to a faster transition with less technological options. Hence, we suggest that establishing new clean hydrocarbon technology policies combined with carbon pricing in order to accelerate energy transition based on the clean hydrocarbon technologies considered in our work. Our results also show that clean hydrocarbon technologies may be sufficient to achieve the climate targets, as shown by the stabilised emissions in Scenario 3, Figure 7, by 2025 without implementation of renewable sources of energy which most studies do not include [38–51].

5. Conclusions and Policy Recommendation

The results of this work show that the engineering of energy systems and recombination of clean hydrocarbon technologies is an important consideration for enhancing efficiency while minimising costs. We find that increasing CO_2 prices leads to decreasing carbon emissions by more than 50%, yet having a low carbon policy combined with a carbon reduction target leads to stabilised emissions by 2025, showing that clean hydrocarbon technologies may be sufficient to achieve climate targets. This study shows that clean hydrocarbon technologies may have a major role in achieving climate targets over the next decades. This statement is supported by the facts that the transition to renewables is not fast enough to mitigate climate change, and hydrocarbons will be the cheapest source for hydrogen production until at least 2030, even when coupled with CCS.

Hence, it is imperative to develop the competitiveness and environmental sustainability of emerging clean hydrocarbon conversion technologies which are positioned at the heart of the transition challenge within the short and medium term. CCS is challenged by the CO_2 transport which requires planning of CO_2 network transporting CO_2 from its sources to its storage sites. Investment in such infrastructure can be rewarding in the long term after large scale implementation of CCS has taken place. The significant reduction in CO_2 capture costs in the Shidongkou plant in China shows that it is essential to continue developing the configuration of existing processes in a more cost-effective manner as the Shidongkou process is a conventional amine absorption process.

For hydrocarbons to be within the 1.5 °C scenario, continued R&D in the carbon neutral and carbon negative technologies is required. This is not only exclusive to CCS, but it will also include other clean hydrocarbon conversion technologies including SOFC, thermal splitting, CO_2 conversions, and underground gasification technologies. Although many of these technologies are technically proven, and in fact at the demonstration stage, continued development in their economics, and efficiency is necessary to enable them to compete with conventional combustion of hydrocarbons. On the other hand, new policies and business models are required to fit into the low carbon hydrocarbon economy which will enable higher costs of clean conversion technologies to be cost-effective. Successful demonstration of UCG projects in coal rich countries will open the door for the transfer of technology into oil rich countries. Significant reduction in the costs of solar panels would open greater opportunities for demonstration of solar fuel projects.

Explicit new policies are required for energy transition and, in particular, those policies that would enhance the economic incentives for clean hydrocarbon technologies including CO_2 tax, public funding, and financial incentives. Finally, the integration of the four energy system segments, shown in Figure 1, is necessary in devising new policies that would optimise the use of resources while managing demand and enhancing efficiency. A complete transition to renewables in order to meet the 1.5 °C target will be a global challenge. By investing in clean hydrocarbon technologies over the short term, transition towards a circular carbon economy will be accelerated while developing renewable sources of energy over the long term.

The essential results of this work are highlighted as follows:

- Hydrocarbons can be a part of the national energy mix while meeting climate targets
- Having a low carbon policy combined with a carbon reduction target may stabilise emissions by 2025
- Clean hydrocarbons must be associated with significant measures in energy efficiency
- Total investments required in clean hydrocarbons will amount $121.23 billion, $37.76 billion higher than the investments needed under the BAU scenario

The policy recommendations of this study and its practical applicability can be summarised as follows

- Explicit new policies are needed for incentivising clean hydrocarbon technologies
- Enhancing energy efficiency measures via reforms in fossil fuel subsidies
- Continued R&D in the carbon neutral and carbon negative technologies is needed
- New business models are needed for cost-effective implementation of clean hydrocarbons technologies

The next steps in this work will include development of different scenarios for CO_2 pricing, emissions cap, and technology policies to determine their interaction with energy policies.

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Appendix A

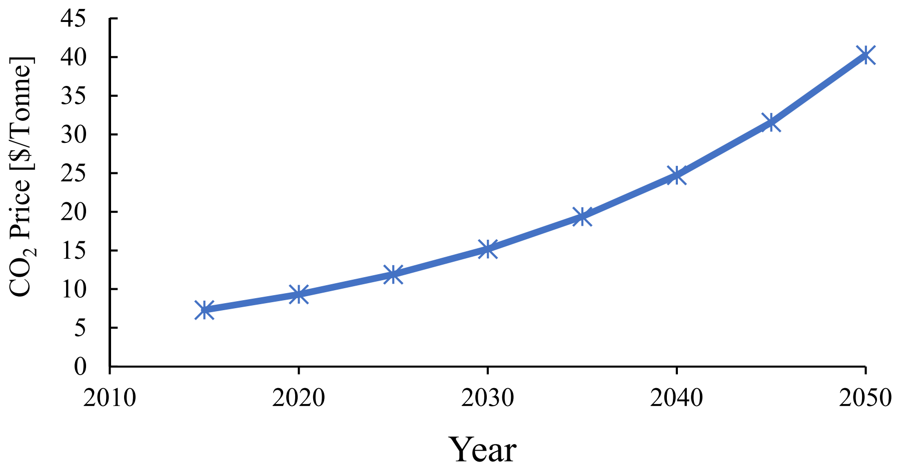

Figure A1. Annual increase in CO_2 price in Scenario 2.

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