A ROADMAP FOR DECARBONIZATION OF SINGAPORE AND ITS IMPLICATIONS FOR ASEAN

Opportunities for 4IR Technologies and Sustainable Development

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Abstract

This article presents a roadmap to decarbonize Singapore's energy consumption sectors. Central to this roadmap is a carbon capture and storage (CCS) project involving centralized post-combustion carbon capture, CO_2 transportation by existing pipelines or tankers, establishing a regional CCS corridor, and hydrogen production with CCS. Applications of fourth industrial revolution technologies will be important for the success of this project. They include efficient carbon capture using nanotechnology, autonomous vessels for CO_2 shipment, digital twin and additive manufacturing for pipeline maintenance and repairs, and characterization of reservoirs for CO_2 storage using big data, artificial intelligence, and machine learning, among others. Potential benefits of this project to ASEAN will include shared financing, cost reduction by leveraging economy of scale, preserving regional oil and gas industries, a quicker energy transition, and creation of new growth industries such as CCS and hydrogen. Engineers and scientists in ASEAN need to be prepared for this challenge.

Nexus between decarbonization, sustainable development, and 4IR technologies

Climate change is an existential problem facing humanity. At least eight of the 17 sustainable development goals (SDG) set by the United Nations have to do with combating climate change (Ramakrishna, 2021). They include SDG6 (clean water), SDG7 (clean energy), SDG11 (sustainable cities), SDG12 (responsible consumption and production), SDG13 (climate action), SDG14 (life below water), SDG15 (life on land), and SDG17 (partnership). Consequently, global decarbonization to combat climate change is one of the biggest engineering efforts ever in human history. In general, there are four switches to transition from an unsustainable high-carbon-intensity economy to a sustainable low-carbon-intensity economy. They are renewable energies, CCS, hydrogen, and adoption of a circular economy (Lau et al., 2021). In each of these four areas, 4IR technologies will play a key role. In this article we will focus on the use of 4IR technologies for CCS and its benefits to ASEAN countries.

Singapore's CO_2 emission profile

In 2017, Singapore emitted 52 million tons of CO_2 which was 0.1% of global emission (NCCS, 2021a). Singapore ranks 27th out of 142 nations in terms of per capita CO_2 emission and 126th in terms of CO_2 emission per dollar GDP. As a signatory to the Paris Agreement, Singapore has pledged to achieve peak CO_2 emission of less than 65 million tons by 2030, half it by 2050 and reduce it to zero before 2100 (NCCS, 2021b). Out of Singapore's total CO_2 emission, 46% comes from industry, 39% from power generation, 13% from transport, and 2% from buildings and other sectors. Ongoing measures to reduce CO_2 emission include improving energy efficiency, increased use of solar photovoltaic energy, zero-emission buildings, electrification of transport, sustainable urban farming, adoption of a circular economy, and reforestation. Possible future measures will include importing green hydrogen, importing renewable electricity via regional power grid, and carbon capture and utilization.

One unique feature of Singapore's CO_2 emission is that it is heavily concentrated in Jurong Island, a small island in the southwest of Singapore (Wikipedia, 2021). About 71% of Singapore's power plants, 69% of refineries and practically all chemical plants are located in Jurong Island which has an area of only 32 km^2. Jurong Island is home to some of the largest refineries and petrochemical complexes in Southeast Asia. Its refineries process 1.5 million barrels of crude oil per day turning crude oil into gasoline, kerosene, and jet fuel sold domestically and abroad. Jurong Island's chemical plants rank among the top 10 in the world and produce lubricants, resins, polymers, plastics, and fuel additives. In 2015, Jurong Island contributed to S$81 billions or one-third of Singapore's total manufacturing output (EDB, 2021). Due to this concentration of industries, 54% of Singapore's total CO_2 emission, or 27 million tons per year, come from Jurong Island. This creates an unique opportunity for centralized carbon capture and processing.

Centralized post-combustion carbon capture and processing

Due to a high concentration of large CO_2 emitters in Jurong Island, it is possible to direct flue gas from multiple industrial plants to a central location for carbon capture and compression. Post-combustion carbon capture technology can be used to capture CO_2 from several flue gas streams with varying CO_2 concentration. Flue gas from power plants has a CO_2 concentration of 10-20% whereas that from petrochemical plants can be as high as 80% or more. These streams can be fed into a absorber column where CO_2 will be absorbed by liquid solvents such as amines, NaOH, KOH, or ammonia. The solvent can be regenerated by stripping the CO_2 out of the liquid by steam, allowing it to be recycled to the absorber column while producing a concentrated CO_2 stream. In addition to chemical solvents, solid absorbents, membrane, or a combination of them may also be used for post-combustion CO_2 capture. After being captured, CO_2 can be compressed and cooled to liquid or supercritical form. Although post-combustion carbon capture can be retrofitted into existing industrial plants, it is cheaper to build a single centralized plant to capture CO_2 from multiple sources. Our roadmap calls for building a plant that has the capacity of capturing 5 Mtpa of CO_2 which is on par with the largest post-combustion carbon capture plants in the world (Global CCS Institute, 2020). By integrating CO_2 capture, liquefaction, and temporary storage into a single centralized plant, more reduction in capital investment can be achieved. Centralized post-combustion carbon capture is only possible due to Singapore's unique CO_2 emission profile. A centralized post-combustion CO_2 capture plant in Jurong Island capable of processing several million tons of CO_2 per year will a first of its kind in the world.

A Regional CCS Corridor

An important part of Singapore's decarbonization roadmap is a detailed CO_2 source-sink mapping exercise to identify large industrial CO_2 sources and subsurface reservoirs for permanent CO_2 storage (Li et al., 2021). Initially, such a source-sink mapping exercise should identify CO_2 sources and sinks within a 1,000-km radius from Singapore. Besides Jurong Island in Singapore, large stationary CO_2 sources within this area include power plants, refineries, and factories in Sumatra Island of Indonesia and Peninsula Malaysia. It is interesting to note that four (North Sumatra, Riau, Lampung, South Sumatra) of the top provinces for CO_2 emission in Indonesia are located in the Sumatra Island.

Major CO_2 sinks are subsurface layers of porous media (reservoirs) which include saline aquifers as well as depleted or partially depleted oil and gas reservoirs (Lau et al., 2021). They are formed by the deposition of eroded materials (sediment) and precipitation of chemicals and organic debris within a water environment. Over geological time, continuous sedimentation will produce stacked reservoirs in the basin. For CO_2 storage, three types of reservoirs are particularly important. They are saline aquifers, oil reservoirs, and gas reservoirs. For oil and gas reservoirs to exist, five factors must be present. They are the existence of a porous layer to provide the pore space for water, oil or gas to accumulate, an impermeable caprock (seal) to prevent leakage of hydrocarbon to a shallower layer, a structural or stratigraphic trap to prevent lateral migration of hydrocarbon, a source rock for the conversion of organic matter into hydrocarbon, and a migration path from the source rock to the reservoir. Three factors must be present for the existence of an aquifer. They are the presence of a porous layer to provide the pore space for water to accumulate, the presence of an impermeability base layer (underburden) preventing water to flow into deeper strata, and the presence of trap to prevent lateral migration of water. Aquifers are further classified into two types: confined and unconfined. A confined aquifer has an impermeable caprock (seal) to prevent upward migration of water. An unconfined aquifer has no such caprock. The existence oil and gas reservoirs in a sedimentary basin are usually well studied by oil companies in their exploration and production of oil and gas. However, the existence of aquifers is generally poorly studied. It has been estimated that there is ample pore space in subsurface reservoirs in the world's sedimentary basins to store more than two and a half centuries of anthropogenic CO_2 emissions (Lau et al., 2021).

There are eight major sedimentary basins within a 1,000-km radius from Singapore (Figure 1). They are the North Sumatra, Central Sumatra, South Sumatra, Northwest Java, East Natuna, West Natuna, Penyu, and Malay basins. The first six basins are in Indonesia whereas the last two are in Malaysia. There are many oil and gas reservoirs of varying degree of depletion in these eight sedimentary basins. Our preliminary estimates show that the total CO_2 storage capacity in these seven basins exceeds 100 Gt of which 90% resides in saline aquifers and the remaining in oil and gas reservoirs (ADB, 2013; Hedriana et al., 2017). It should be noted that injection of CO_2 into an oil or gas reservoir may lead to production of incremental oil or gas by processes known as enhanced oil recovery (EOR) or enhanced gas recovery (EGR) due to total or partial miscibility of the CO_2 with the oil or gas condensate in the reservoir (Li et al., 2021). This makes the economics of CO_2 EOR or EGR more attractive than pure geological storage of CO_2 in a saline aquifer.

A detailed regional source-sink mapping will involve ranking by CO_2 emission sources by amount and CO_2 concentration. Likewise, CO_2 sinks are ranked by storage capacity, reservoir type, and readiness for CO_2 storage. Mapping of potential sources to potential sinks is done based on factors such as distance, capacity, and readiness (Li et al., 2021).

CO_2 transportation via pipeline or marine vessel

CO_2 is usually transported either in supercritical form by pipelines or in liquid form by marine vessels (Al Baroudi et al., 2021). In pipeline transport, the pipeline is usu-

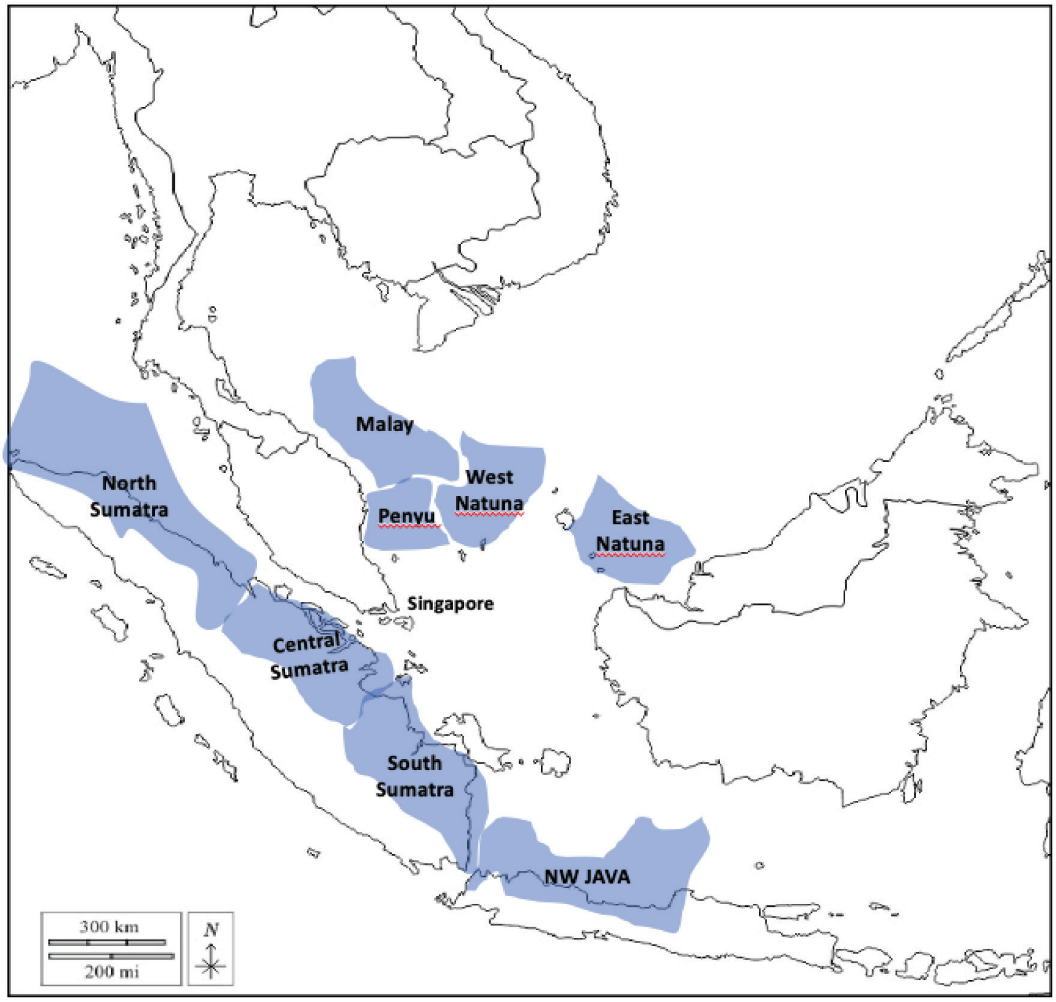

Figure1: Major sedimentary basins with 1,000 km distance from Singapore to be considered for permanent storage of CO_2

ally pressurized to above 10.3 MPa to ensure CO_2 is in supercritical form with a density close to 800 kg/m^3. There are two existing pipelines supplying natural gas to Singapore from Indonesia. One of them is a 654-km-long West Natuna-Singapore pipeline that supplies natural gas from the Indonesia's West Natuna gas field to Jurong Island. The gas delivery contract for this pipeline will end in 2022 and it is not certain whether it will be renewed. The second is the 470-km-long South Sumatra-Singapore pipeline that supplies natural gas from Indonesia's Suban gas field in South Sumatra to Singapore. This pipeline will cease to operate by 2023 when the existing gas contract ends. Indonesia plans to use the gas for domestic consumption. If one or both of these pipelines cease to be used for natural gas delivery, they may be used instead for shipping CO_2 from Singapore to subsurface reservoirs in either the South Sumatra or West Natuna Basin for permanent CO_2 storage. In addition, Singapore's gas transmission network is connected to Petronas' Peninsula Gas Utilization Pipeline. This network was used to supply natural gas from Malaysia to Singapore. These existing natural gas pipelines may be used to transport industrial CO_2 from Singapore to Indonesian or Malaysian subsurface reservoirs for permanent storage. In such a scenario, shipment of CO_2 from Singapore will be relatively inexpensive as no or limited new pipeline needs to be constructed. For transportation of CO_2 over long distances where existing pipelines are unavailable, marine shipment can be used. Currently, small quantities (capacity of 1,000 m^3) of liquefied CO_2 are being transported by ships by the food and beverage, and chemical industries. Marine shipment of large quantities of CO_2 can be done by LPG tankers with capacity of 100,000 m3 (80,000 tons) of liquid CO_2. The existing LNG terminal in Jurong Island may be modified to handle offloading of liquid CO_2. As Singapore is a hub for ship building, modifying LPG tankers or building new tankers for liquid CO_2 shipment in Singapore's shipyards is feasible.

CCS as an enabler of a hydrogen economy

The fourth step of the roadmap is to use CCS as an enabler of a hydrogen economy

(Lau, 2021a, 2021b). It is to build a steam methane reforming (SMR) plant in Jurong Island to produce hydrogen from natural gas (Lau and Ramakrishna, 2021). This is done by mixing steam with natural gas to a high temperature in the presence of a catalyst. This process converts natural gas into hydrogen and CO_2. The hydrogen may be sold as a clean energy carrier for use in hydrogen fuel cell vehicles, as well as heating and as feedstock for industrial use. The produced CO_2 can be removed by CCS. This process will allow Singapore to be a producer of hydrogen for domestic consumption and export. Already, countries like Japan and South Korea are planning to import hydrogen from overseas and include it in the future energy mix. It is estimated that the global market for industrial hydrogen will increase from the current 87 million tons to over 200 million tons in 2030. There is much for Singapore to benefit if it can become a regional hub for exporting hydrogen. CCS will be a key enabling technology for this to happen. New industries such as CCS and hydrogen may well become one of the new growth engines for the Singapore economy.

Decarbonization timeline

Table 1 gives the decarbonization timeline based on our roadmap. The CO_2 emission rate in 2019 was historical whereas those in 2050 and 2100 are projected. The assumptions are Singapore will half its 2017 CO_2 emission by 2050 and reduce it to only 10% of its 2019 value by 2100 or sooner. Total elimination of CO_2 emission is probably too expensive. Consequently, we use 10% of current emission as the goal.

Also shown in Table 1 are the ways to achieve CO_2 mitigation in various sectors of the economy.

In the power sector, the chief migration method is by post-combustion carbon capture. Secondary methods will include importing electricity from the regional power grid and increased use of solar photovoltaic (PV).

In the road transport sector, the chief method is to replace internal combustion engine (ICE) passenger cars by electric vehicles (EV) and long-haul ICE vehicles by hydrogen fuel cell vehicles (HFCV). For the marine transport sector, the migration method is to replace fossil-fuel based fuels by hydrogen or biofuels. For the aviation transport sector, the mitigation method is to replace current fossil-fuel based jet fuel with biofuels. Singapore already has one of the biggest biofuel refineries in the world with a capacity of 1.3 Mtpa (The Chemical Engineer, 2019).

The refining sector is the heaviest emitter of CO_2 in Singapore. The chief CO_2 mitigation method is to reduce the output of Singapore's refineries. Shell has recently announced cutting the capacity of its Bukom refinery from 500,000 bbl/d to 300,000 bbl/d by July 2021 (Argusmedia, 2021). On the other hand, ExxonMobil has plans to expand the capacity of its largest refinery in Jurong Island from 592,000 bbl/d by another 48,000 bbl/d (The Straits Times, 2020). The overall reduction in refinery capacity in Singapore will reduce CO_2 emission in this sector. Post-combustion carbon capture will still be the mainstay of CO_2 mitigation for refineries. Another suggestion is to gradually replace crude oil refining by hydrogen production using SMR of natural gas and using CCS to remove the emitted CO_2. This will require a structural change in the overall refining industry in Jurong Island. However, it will align with the overall goal of transitioning from a fossil fuel based economy to a low-carbon-intensity economy.

Post-combustion carbon capture will continue to be the main CO_2 mitigation method for the petrochemical business in Jurong Island. As for the building and other sectors, the introduction of low or zero-emission building, of which Singapore already has one, and adoption of a circular economy to reduce demand for high-carbon-intensity material will be important CO_2 mitigation methods.

If we make the assumption that CO_2 emission in Singapore has already peaked at around 53 Mtpa today, then achieving 90% reduction in CO_2 emission will require a reduction of 48 Mtpa. One possible scenario for achieving this is given in Figure 2 wherein 59% of the reduction will be achieved by CCS, 24% by reducing refinery output and industry restructuring,

Table 1: Current and projected CO_2 emission from Singapore based on roadmap

Sector	CO_2 emission (Mtpa)			CO_2 mitigation methods
	2017	2050	2100 or sooner	
Power	19.16	9.58	1.92	(1) post-combustion CCS, (2) import electricity from regional grid, (3) more solar photovoltaic
Refinery	22.32	11.16	2.23	(2) reduced refinery capacity, (3) post-combustion CCS, (3) substituting crude refining by hydrogen production with CCS
Petrochemical	2.91	1.46	0.29	(1) post-combustion CCS
Transport	6.71	3.35	0.67	(1) Less internal combustion engine vehicles, (2) electric vehicles, (3) hydrogen fuel cell vehicles, (4) biofuels for aviation, (5) hydrogen and biofuel for marine vessels
Building & others	0.99	0.49	0.10	(1) zero-emission buildings, (2) adoption of circular economy
Total	52.09	26.04	5.21	

and 12% by fueling transport by electricity, hydrogen, and biofuels. Achieving this will require ramping up CCS from zero to 28 Mtpa between now and 2100 or sooner. This is feasible if a ASEAN open access CCS corridor is established in the next decade. Other scenarios, for example using CO_2 to produce building materials and chemicals, are possible. However, regardless of which scenario is chosen, CCS will be the major contributor to Singapore's decarbonization.

"Southern Lights" project

In this roadmap we propose a "Southern Lights" project wherein industrial CO_2 from Singapore will be transported to a nearby country for permanent storage in a subsurface reservoir through the establishment of a ASEAN CCS corridor (Lau and Ramakrishna, 2021). Figure 3 illustrates the concept behind the project. Industrial CO_2 from Singapore is transported by marine vessels or pipelines to a host country. This CO_2 together with CO_2 from the host country will be temporarily stored in an onshore facility. CO_2 from this facility will be piped to either an onshore or offshore reservoir for geological storage in a saline aquifer, EOR in an oil reservoir or EGR in a gas reservoir. The choice of the target reservoir will be the result of a detailed CO_2 source-sink mapping exercise. This project will be the first cross-border CCS project in ASEAN and will involve multiple companies and governments.

The name "Southern Lights" is inspired by a similar "Northern Lights" CCS project sanctioned by the Norwegian government in

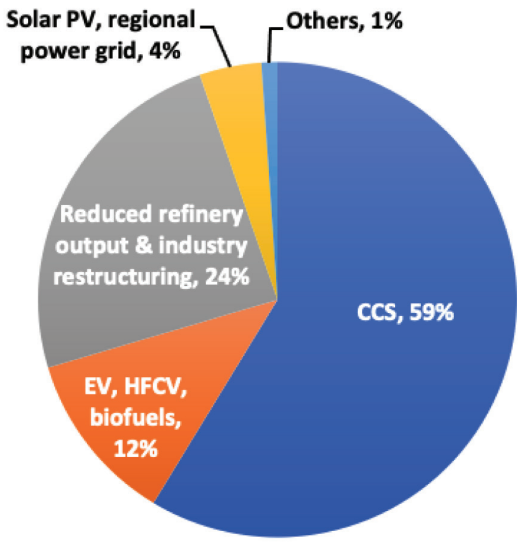

Figure 2: Relative contributions to 90% reduction in Singapore's CO_2 emission from 2019 level

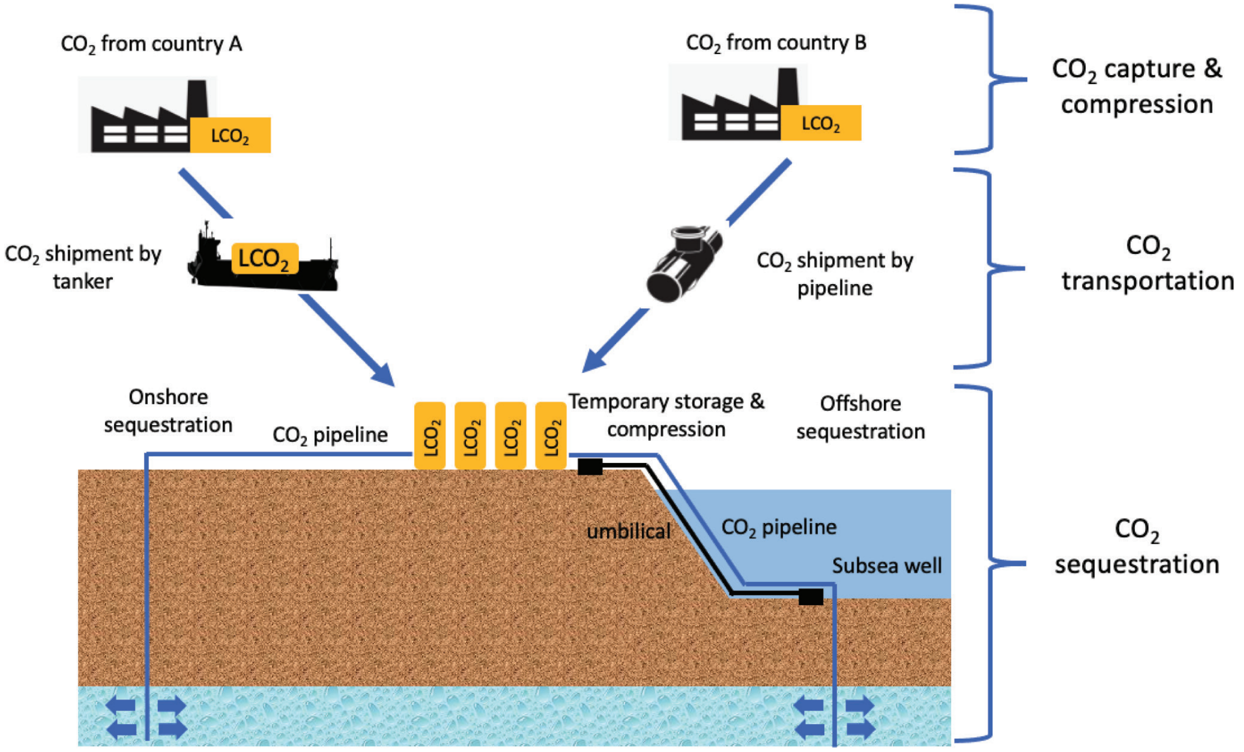

Figure 3: Southern Lights: A cross-border ASEAN CCS project

Table 2: Work for different phases of Southern Light project

Project component	Identify Phase	Feasibility Phase	Select Phase	Define Phase	Execute Phase	Operate Phase
CO_2 capture	Identify suitable CO_2 sources in Singapore for post-combustion carbon capture	Identify CO_2 capture technologies, plant locations, capture volume over time.	Select CO_2 capture technology and location for carbon capture plant in Singapore and host country	Perform detailed design of carbon capture plant in Singapore and host country.	Construct carbon capture plant in Singapore and host country.	Operate carbon capture plant as designed.
CO_2 transport	Determine CO_2 transport options from Singapore and host country.	Assess local and international regulations controlling movement of CO_2 across borders. Determine showstopper.	Select mode of CO_2 transport from Singapore and host country to target reservoir.	Detailed design of CO_2 storage facility in host country. Define specification of CO_2 tankers or pipelines.	Build CO_2 tankers and/or pipelines	Deliver CO_2 through pipelines or tankers as planned.
CO_2 storage	Perform regional CO_2 source-sink mapping within 1,000-km radius from Singapore	Assess storage capacity of target reservoirs by numerical simulations. Assess injectivity and number of wells needed. Investigate risk of CO_2 leakage.	Select the best target reservoir for CO_2 storage.	Perform detailed design of drilling, construction, and operation of wells.	Construct and test CO_2 injection wells. Install CO_2 monitoring equipment.	Operate CO_2 injection wells and optimize injectivity based on well and reservoir data.

September 2020 (Equinor, 2019). Costing 2.7 billion dollars, the Northern Lights project will capture 0.8 million tons per year of CO_2 from a cement factory and a waste-to-energy power plant in the southwest of Norway. The captured CO_2 will be shipped by tankers over approximately 1,000 km to the west coast of Norway for temporary storage. From there, the CO_2 will be piped to one or two subsea wells where it will be injected into a saline aquifer for permanent storage. The project will be operational by 2024 and will expand to 5 million tons of CO_2 per year. There are also plans to accept CO_2 from other European countries in future.

Table 2 illustrates the major technical work components in the different phases of the project. Commercial, financial, social, and governmental aspects of the project are not included. Many learnings from the Northern Lights project in Norway should be captured to shorten the learning curve. Following the best practice used by petroleum industry, the Southern Lights project will be divided into six phases: identify, feasibility, select, define, execute, and operate (Lau, 2008). In the Identify Phase, data are assessed to determine if the project is worth pursuing. If the answer is positive, then the project goes into the Feasibility Phase where all available options to pursue the project will be identified and evaluated. In the Select Phase, the optimal project concept is selected for detailed design. In the Define Phase, detailed engineering design of the project will be performed to provide the basis of design for the project. Also final investment decision will be made at the end of this phase. In the Execute Phase, construction begins and the assets are installed. In the Operate Phase the assets are operated to achieve permanent CO_2 storage as planned.

Benefits to ASEAN

The following are some potential benefits of the Southern Lights project to participating ASEAN countries. It is expected this project will cost several billion dollars and the project will last two to three decades. As the project will involve at least Singapore and a host country for CO_2 storage, its cost will be shared by both governments. Initially, construction of the carbon capture plants will be capital expensive. However, part of the cost of these plants can come from a carbon tax. At present, Singapore has a carbon tax of S$5/ton which may be increased to S$10 to $15/ton by 2030. This revenue can be used to partially finance the construction of the carbon capture plant in Singapore. Other countries may also use a carbon tax to raise finances for CCS projects. In addition, financing through international agencies such as the Asian Development Bank or the Asian Infrastructure Investment Bank may be worth considering.

Another benefit of the Southern Lights project is to reduce CCS cost by the estab-

Table 3: Nexus between decarbonization and 4IR technologies

Decarbonization technology	Technology subcategory	Examples of 41R technology	Reference
Post-combustion carbon capture	Chemical solvent	Materials informatics to identify new solvents	Rajan (2013)
	Solid sorbent	Solid sorbet using nanotechnology	Fryxell and Cao (2017)
	Membrane	New membrane using nanotechnology	Mueller et al. (2012)
	Absorber and stripper	Smart sensors to improve efficiency	Fryxell and Cao (2017)
CO_2 transport	CO_2 pipeline	Smart sensors to monitor flowrate, corrosion and leakage with real-time data transmission using IoT	Algarni and Zwawi (2019)
		Digital twin to schedule maintenance	Xue and Gai (2020)
		Additive manufacturing for repair and applying coating	Pathak and Saha (2017)
		Weather and metocean prediction using big data, AI, machine learning	Liu et al. (2020)
	Liquid CO_2 tanker	Zero-emission vessel using hydrogen or biofuels	de-Troya et al. (2016)
		Digital twin of key equipment in tanker	Bondarenko and Fukuda (2020)
		Autonomous tanker	Bassam et al. (2019)
CO_2 storage	Characterization of subsurface reservoir	AI and big data for seismic data processing	Pandey et al. (2020)
		Data analytics for seismic data interpretation	
		AI and data analytics for well log interpretation	
	Reservoir engineering	Quantum computing for geophysics	Moradi et al. (2018)
		Quantum computing for reservoir simulation	Ottaviani et al. (2019)
		Nanotechnology for wettability alteration of reservoir	Li et al. (2019)
		Nanotechnology for increasing heat transfer for geothermal heat mining by CO_2	Yang et al. (2005)
	Field operation	Intelligent wells to control CO_2 injection and production of water and hydrocarbon	Lau (2008)
		Smart field technologies (4D seismic, intelligent wells) with real time history matching using quantum computing	Engberg et al. (2014)
		Smart sensor to detect downhole seismic activity	van Dok et al. (2016)
	Post-injection CO_2 plume monitoring	Smart sensor to monitor CO_2 plume movement	Bathellier and Czernichow (1997)
Hydrogen production	Catalyst	Improved catalyst for SMR using nanotechnology	Rodriguez et al. (2004)
	Membrane reactor	Improved membrane using nanotechnology	Mueller et al. (2012)
	Plant efficiency	Smart sensors to enhance plant efficiency	Mukhopadhyay and Gupta (2008)

lishment of a regional CCS corridor. This corridor has a shared CO_2 collection and transportation network which will reduce CO_2 transportation cost for participating countries. If existing natural gas pipelines and oilfield infrastructure such as storage facilities and wells are used, further cost reduction can be achieved. Many ASEAN countries have substantial oilfield infrastructure which may be usable for future CCS projects. In addition, the large-scale removal of CO_2 by CCS will play an important role in preserving many industries in ASEAN countries, such as oil and gas, coal mining, marine, and offshore. This is important for sustaining the economies of ASEAN in the post pandemic era.

Another purpose of the Southern Lights project is to accelerate the transition to a hydrogen economy in participating countries. As a clean energy carrier, hydrogen is one of four important levers of the ongoing energy transition (Lau et al., 2021). If CCS on a large scale in ASEAN is proven by the Southern Lights project, it can be the basis for the production of hydrogen from either natural gas or coal. By using coal gasification or SMR, coal and natural gas can be converted to hydrogen and CO_2. If the emitted CO_2 is removed by CCS, then ASEAN countries can produce "blue" hydrogen for both domestic consumption and export. Already, countries including Japan and South Korea have announced their intention to import hydrogen and include it in their future energy mix. By upgrading coal and natural gas to hydrogen and getting rid of the emitted CO_2 by CCS, ASEAN countries like Singapore, Indonesia, and Malaysia may transition to a hydrogen economy much faster than buying hydrogen from other countries. There is much to gain for ASEAN countries to become exporters of this valuable commodity. A key part of the Southern Lights project is for Singapore to build a hydrogen plant next to its post-combustion carbon capture plant in Jurong Island. This will be a demonstration project for combining hydrogen production with CCS in ASEAN.

As ASEAN countries recover from the COVID-19 pandemic, they need new growth engines. This is especially important because of the decline of the oil and gas, and marine and offshore industries caused by the collapse of oil price since 2014. A successful CCS demonstration project like Southern Lights will revive not only these industries but also provide impetus for new growth industries such as CCS and hydrogen.

Challenges to the project

According to the Global CCS Institute there are only 28 large-scale CCS in operation in 2020 (Global CCS Institute, 2020). Together they store 41 Mtpa of CO_2 and 38 more are being planned with a capacity of 76 Mtpa. However, even countries that implement CCS project only store less than 1% of their emitted CO_2. This slow pace of CCS implementation is concerning and is due to many reasons (Lau et al., 2021). First is the lack of carbon pricing. Outside of northern Europe and U.S.A., most countries have low or no carbon tax or credit. Within ASEAN, Singapore is the only country with an established carbon tax although Malaysia is considering imposing one. Consequently, there is little incentive for companies to conduct CO_2 geological storage projects. A high enough carbon tax will create a strong incentive for CCS. However, the level of carbon tax is sensitive to energy price and cost of capital which varies from country to country. In addition, a consistent and predictable national energy policy will go a long way toward encouraging companies to invest in CCS. Subsidy for low carbon technologies, such as CCS, electric or hydrogen fuel cell vehicles, is beneficial to investment in these technologies. Lack of CCS regulations is also a potential challenge. Cross-border CO_2 movement is controlled by the London Protocol and Basel Convention (Dixon et al., 2015). However, ASEAN countries are not signatories to them. Therefore, both national and international laws need to be passed to govern the movement of CO_2 in ASEAN, its disposal and monitoring in subsurface reservoirs. Long-term liability of CO_2 disposal and whether it can be transferred from the operator to the state after a certain period of time also needs to be addressed. Permitting of CO_2 disposal also needs to be streamlined to avoid long delay. In additional, public awareness of CCS is low in ASEAN. Support for CCS can be increased if economic benefits, such as creation of new industries and new employment opportunities, are clearly articulated. Public engagement by trusted experts is needed to raise awareness on the benefits of CCS. Trusted experts should include those from institutes of higher learning, technology practitioners, and government officials. In addition, a lack of local expertise can be a barrier to a large-scale CCS project. Therefore, transfer of knowledge from foreign technology providers to local companies should be an important element of a CCS project. In addition, research collaboration between institutes of higher learnings and local and foreign technology providers will facilitate technology transfer and creation of local expertise in ASEAN. Implementation of a large-scale CCS project can be facilitated by a public-private partnership (PPP) which brings multiple industries, government agencies, and investors together. A stable, cooperative framework that lasts for two to three decades will be needed for a project like Southern Lights. This framework should encourage sharing of risks and rewards, and protection from political risks of governments changing their minds. A PPP may be a better vehicle to achieve this than a purely commercial partnership.

Decarbonization and fourth industrial revolution technologies

As one of the biggest engineering challenges ever for humanity, global decarbonization is an sustainable development issue which has a strong connection to many 4IR technologies. Table 3 gives an incomplete list of 4IR technologies that will likely be used in the decarbonization of Singapore.

Post-combustion carbon capture will likely utilize 4IR technologies such as materials informatics, nanotechnology, and smart sensors for improved plant efficiency. Nanotechnology is one of the 4IR technologies which has captured worldwide attention and has found many applications (Lau et al., 2017). CO_2 transport through pipelines will likely utilize smart sensors with internet of things (IoT), digital twin and additive manufacturing. CO_2 transport by tankers will likely involve big data, artificial intelligence (AI), machine learning, and quantum computing for weather and metocean prediction. In addition, digital twin can be used to monitor ship equipment for preventive maintenance. Other 4IR technologies may include zero-emission and autonomous ships. Subsurface CO_2 storage will likely use big data, AI, machine learning, and quantum computing for seismic and well log data processing and interpretation and numerical reservoir simulations. Hydrogen production will likely use nanotechnology for new catalysts and reactor design and smart sensors for improved plant efficiency. Indeed the list will go on and on.

Research and development on some of these 4IR technologies have already been conducted in Singapore. Singapore's government-supported Advanced Remanufacturing Technology Centre (ARTC) has been conducting research in additive manufacturing since its establishment in 2017. The Technology Centre for Offshore and Marine Singapore (TCOMS) was launched jointly by Singapore's Agency for Science, Technology and Research (A*STAR) and the National University of Singapore (NUS) in 2016 to conduct advanced research in marine technologies including the use of digital twin and autonomous vessels. Since 2016 NUS researchers, supported by the Petroleum Engineering Professorship programme of Singapore's Economic Development Board (EDB), have been conducting research on the use of nanotechnology for enhanced oil recovery and new stainless steel-carbon nanotube composites for downhole tools. Other research areas include use of AI, machine learning, big data and data analytics in the processing and interpretation of seismic data for reservoir characterization.

Conclusions

Herein, we have presented a roadmap for decarbonization of Singapore which will allow the country to half its current CO_2 emission by 2050 and reduce it to only 10% or less before the end of the century. The chief elements of this roadmap include decarbonizing Singapore's power and petrochemical sectors by post-combustion carbon capture, decarbonizing the transport sector by switching to electric and hydrogen fuel cell vehicles, using hydrogen fuel for marine vessels and biofuels for aviation. In the industrial sector, both reduction in Singapore's refining output and restructuring of the refining industry to hydrogen production are suggested. In addition, adoption of a circular economy will reduce demand for energy and high-carbon-content materials.

It is proposed that the majority of CO_2 mitigation (about 60%) will be provided by post-combustion CCS technologies. To this end, implementation of a Southern Lights CCS project is proposed. This project will include centralized post-combustion carbon capture in Singapore, establishing a regional CCS corridor, shipment of CO_2 from Singapore and other regional sources via existing natural gas pipelines or liquid CO_2 tankers to a target location for permanent storage, and building a SMR hydrogen plant in Singapore and removing the emitted CO_2 by CCS. This project will be ASEAN's first cross-border CCS project. Potential benefits will include shared financing, reduced cost of decarbonization by leveraging economy of scale, preserving regional oil and gas industries, enabling a quicker transition to a hydrogen economy, and creation of regional growth industries such as CCS and hydrogen.

Many challenges to the implementation of this CCS project exist. Solutions to them will include public engagement on CCS, establishing a PPP for project financing, management, and execution, formulating consistent energy policies by participating governments and international cooperation for transfer of knowledge to local entities.

A number of 4IR technologies will also play a key role in the success of this project. Research and development on some of them have already being conducted in Singapore. Working together, ASEAN countries can benefit from harnessing many 4IR technologies to implement a regional CCS project which may become the catalyst for sustainable development in the region.

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Centre for the Fourth Industrial Revolution of the World Economic Forum

The Centre for the Fourth Industrial Revolution of World Economic Forum is a hub for global, multistakeholder co-operation to accelerate the benefits of science and technology. With Centres in 13 countries around the world, the C4IR Network is working with government, business, academia and civil society to develop, prototype and test pioneering collaborations and governance models to ensure the benefits of technology are maximised, and the risks accounted for. The Centre is co-designing and piloting policy frameworks and governance protocols across six areas of focus.

As the world undergoes a great reset, our ability to harness and disseminate the new technologies of the Fourth Industrial Revolution (4IR) will play a key role in ensuring our recovery from the pandemic and the avoidance of the future crises.

The possibilities of new 4IR technologies, deployed appropriately, should be used as the baseline to reinvent the way we operate in the new context: everything from government services, education and healthcare, to the way business interacts and provides value to its customers.

However, if not directed with purpose, the 4IR has the potential to exacerbate inequality. Human-centricity, Inclusion and Trust must be key principles guiding action - we must take proactive steps to ensure technology adoption does not heighten abuse of power, bias, wealth disparities, exclusion and loss of livelihoods. Whilst technology comes with risks, such as cybersecurity or fraud, it can also provide vast opportunity, such as enhancing education systems, reducing corruption in supply chains or accelerating the adoption of clean energy.

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