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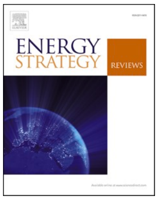

Bioenergy with carbon capture and storage (BECCS) potential and impacts in Indonesia's electricity sector decarbonization

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ABSTRACT

In global scenarios of 2 °C and 1.5 °C warming, integrated assessment model (IAM) studies' results demonstrated that bioenergy coupled with carbon capture and storage (BECCS) can help achieve net zero and net negative emissions within the course of this century by removing CO_2 emissions from the atmosphere at scale while producing energy. However, the feasibility of BECCS depends on the availability of biomass resource, sizeable demand to cover, and access to long-term CO_2 storage that differs from one region to another. Several studies have investigated the BECCS deployment scenarios at national levels. However, most studies have not addressed the implication of BECCS supply chain design in the context of long-term regional electricity system development, considering the regional disparity of energy resource, CO_2 sources, and CO_2 sinks. This study assessed the potential and impacts of BECCS development in Indonesia's electricity sector net zero transition scenarios using capacity expansion model that incorporates grid expansion problem considering the regional disparities of resource and existing infrastructure. In the most stringent emission scenario, 16 GW of BECCS power generation capacities are deployed with a potential emission reduction of 265 Mt CO_2, which requires about 1877 GJ of biomass and expansion of 55,000 Mt-km CO_2 transport pipeline capacity. Model results have demonstrated the role of BECCS as "backstop" technology for decarbonization, considering the high return on emission reduction per dollar spent rather than electricity generation. Scenarios leading to large negative emissions from BECCS will require additional biomass resources larger than the existing domestic supply, which can risk increasing negative impacts toward natural resources and environment.

1. Introduction

1.1. Role of BECCS in achieving Paris goals

The Paris Agreement has set the goal of keeping global-mean surface temperature increase below 2 °C to 1.5 °C (Article 2a) and initiated international efforts to reach a global peaking of greenhouse gas emissions (GHGs) as soon as possible and to achieve a net zero balance between sources and sinks of emissions as early in the second half of this century (Article 4.1) [1]. The initiative to manage development of global emissions commensurate with the limited and dwindling carbon budget required for maintaining "safe" temperature targets by the end of this century. Considering the current global trends of emission and mitigation policies, getting over budget and breaching warming threshold are anticipated. Such scenario can be avoided by combination of increasing emission reduction and negative emission measures to keep cumulative emission in check. Nearly all integrated assessment model (IAM) scenarios considered that limit warming below 2 °C rely on some degree of negative emission technologies (NETs) to accelerate the pace of emission reduction, to offset residual hard-to-abate emissions, and to achieve net negative emission in case when global temperature needs to be curbed down [2]. Moreover, there are no single pathways without large-scale deployment of negative emissions technologies (i.e., Afforestation and BECCS) returning warming to below 1.5 °C by 2100 with either low or

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high overshoots to 2 °C after delaying of actions until 2030 [3,4]. In practice, pathways reaching net-zero GHGs tend to balance out residual non-CO_2 emission with net-negative CO_2 emission [4].

Bioenergy coupled with carbon capture and storage (BECCS) is the most featured NET in IAMs to meet warming targets of 2 °C and below [2,5]. BECCS deliberately removes CO_2 from the atmosphere by capturing CO_2 emission from energy conversion using what is assumed to be carbon-neutral bioenergy (that is, the same amount of CO_2 sequestered by growing biomass feedstock then released during energy conversion) into electricity, heat, or fuels, and transport the captured CO_2 to store in long-term geological repositories. In other words, BECCS is a net transfer of CO_2 from the atmosphere, through the biosphere, into geological layers, and at the same time provides non-fossil fuel source of energy. While BECCS is seen as the least-cost emissions reduction strategy in IAMs, BECCS technologies are not commercially available today, and the viability and economic consequences of large-scale BECCS deployment are not fully understood. Several studies have raised concerns about the institutional and technical limitations of scenarios involving large-scale BECCS deployment, suggesting that before IAM scenarios using BECCS can be confidently relied upon, further evaluation of BECCS assumptions and implementation strategies should be undertaken [2,6–9].

The effectiveness of BECCS for negative emission depends on the system design. From the sourcing of bioenergy that may have negatively impacted land-use change emission, to cofiring with fossil-based energy that increases emissions. The extent of BECCS potential contribution in supplying energy as well as reducing emission are influenced by the biophysical potential of biomass resource and geological potential of carbon sequestration and its permanence, as well as costs of implementation, and socio-economic, natural resource and environmental impacts [10,11]. In a BECCS setup, bioenergy is confronted with substantial concerns regarding competition for land, including impact on food prices, biodiversity, and nutrients, as well as indirect land-use change emission [12–18]. Moreover, carbon capture and storage (CCS) poses its own risks of leakage, which not only reverses the positive mitigation effect but also causes health and environmental damages [19,20].

1.2. BECCS relevance in Indonesia electricity system development context

Indonesia is an archipelagic country with more than 17,000 islands, home for about 270 million people, and a growing economy with an average about 5% per year increase of gross domestic production (GDP) for the past 20-years—except during COVID-19, when GDP contracted by 2.1% in 2020 and followed with slower growth of 3.7% during recovery period in 2021 [21]. The development of a more affluent and productive modern society necessitates increasing supply of electricity to power homes, industries, and transportation. From 2000 to 2020, Indonesia's electricity consumption has rapidly increased from 82.6 TW h to 268.1 TWh or more than 3-fold [22]. In per-capita terms, Indonesia electricity consumption has grown from about 386 kW h to 986 kW h. Indonesia's electricity demand is unevenly spread across the archipelago; the islands of Java, Madura and Bali account for approximately 75% of Indonesia's total electricity demand, and the other islands (i.e., Sumatera, Kalimantan, Nusa Tenggara, Sulawesi, Maluku, and Papua) combined for only 25%. In addition to the Java–Madura–Bali (Jamali) transmission system, other transmission systems are found with lesser coverage and interconnection, i.e., Sumatra, Kalimantan, and Sulawesi. The remaining electricity supply is spread across more than 600 isolated systems.

Historically, Indonesia's GHG emissions were dominated by land-use change and forestry emissions [23]. However, there is a trend of growing emissions in the energy sector due to expansion of coal power in recent years. It is expected that the energy sector's emissions will overtake the land sector's emissions in the following years unless additional mitigation efforts are considered [24]. In 2020, 275 TW h of Indonesia's electricity generation was generated out of 63.3 GW of installed capacities [22,25]. About 82 % of electricity generated came from fossil fuel sources (62% coal, 18% natural gas, and 2% oil), while the rest came from renewable energy sources (6% hydropower, 5.7% geothermal, 4% bioenergy, 3% solar, <0.1% wind). The average grid emission factor was 0.87 kg CO_2/kWh [26], which will continue to increase through 2030 (0.97 kg CO_2/kWh) owing to the planned addition of primarily coal-based electricity generation capacity and the delay of renewables electricity generation projects (RUPTL 2019-2030). Indonesia is endowed with vast and highly diverse energy resources, but its geographical complexity and lack of investment on infrastructure present challenges in the development of national electricity sector.

Indonesia has shown growing aspiration to increase its ambition to further reduce GHG emissions and transition towards a more sustainable means of energy provision [27,28]. Such ambition also has attracted international support in accelerating decarbonization efforts in Indonesia's energy sector such as Just Energy Transition Partnership (JETP), which focuses on the development low-carbon electricity sector in achieving net zero emission targets [29]. Furthermore, such mitigation efforts also reciprocate with industrial requirements for boosting trade and international cooperation. Industries are challenged by “carbon footprint”, a non-tariff trade barrier such as European Carbon Border Adjustment Mechanism (CBAM) [30,31], which can negatively impact Indonesian production and exports unless the means of production were decarbonized—in this case, electricity.

Bestowed with huge natural resources, vast forested areas and degraded lands, and suitable conditions for the development of oil palm, bioenergy is considered as a key measure to achieve energy development, diversification, and decarbonization targets in Indonesia. The potential for bioenergy development is assumed to be significant, as millions of hectares of degraded land could theoretically be used for the production of various kinds of biomass, either in the form of residues from agriculture, forestry or municipal waste, alternative energy carrier (e.g., biodiesel, bioethanol), or dedicated tree plantation that are established and managed specifically to supply biomass feedstock for energy conversion [32]. Moreover, Government of Indonesia have plans to stimulate the restoration of degraded lands and to improve access to electricity in remote rural areas, which are expected to have synergies with bioenergy development. However, not all biomass resources are considered as an effective energy decarbonization option since most potential, compared to others, are more costly to access and may risk greater negative impact on natural resource and environment than its climate change mitigation benefits [33]. Indonesia's high biomass productivity holds great potential for nature-based carbon sequestration but also for BECCS negative emission. Moreover, deployment of BECCS in Indonesia can provide the opportunity to address both electricity demand growth and decarbonization requirements for the region. Previous studies shows that Indonesia have about 2.5M ton CO2 reduction potential from in-situ BECCS power generation capacity of 1185 MW [34].

1.3. Knowledge gaps & motivation

Several studies have presented different scenarios of cost-effective BECCS deployment on the national scope. Studies using GIS tools has investigated the near-term potential for BECCS in the USA from collocated CO_2 sources and sinks without considering long-distance CO_2 transport [35] and potential negative emission from bio-refineries with considering large-capacity CO_2 transport across regions in the USA [36]. Studies using spatially explicit energy system optimization modelling frameworks has assessed the optimal supply chain configuration of bioenergy production plants, their sizing and locations of ‘in situ’ BECCS in Japan, South Korea, and Rusia [37–39] and analyze the cost-effective configurations of bioenergy supply chain and CCS options for reducing existing US coal power plant emissions [40]. Study using SWITCH model of North America has assessed BECCS potential and impacts in scenarios of electricity sector development with high-level spatial aggregation using supply cost curve to consider distance effect on costs [41].

From the literature, there is currently no detailed analysis that investigates the uncertainties surrounding the energy and CO_2 supply-chains of BECCS system. Previous studies have not considered the cost uncertainties coming from the different locations to source fuels, deploy power generation facility, transmit energy, transport CO_2, and store CO_2—all together in the selection of cost-effective BECCS along with other power generation options. Some studies only analyze the near-term BECCS deployment potential based on existing biomass resource and CO_2 transport and storage without considering other power generation technologies [37–39] [35] [36]. Investigation of BECCS potential and impacts in long-term power system development has been carried out with detailed power system analysis but disregarded the detailed analysis of electricity transmission network infrastructure expansion [41]. Meanwhile, some other studies only considers different bioenergy feedstock options but disregards electricity transmission and CO_2 transport options [37–39] [35] or only consider options of bioenergy feedstock and CO_2 transport network for a predetermined BECCS power plant location [40].

Models' limitation on representing different regions and transmission networks can distort the costs of access of different resources that are critical in determining the cost optimal long-term technology deployment strategies. To address the regionality aspects of energy and CCS development in an archipelagic and a developing economy, it is critical for the use of spatial-explicit model that can address spatial distribution of resources. Model representation of potential transmission network expansion with high granularity that are sufficient in representing the cost significance of accessing different resources are critical when comparing the option to deploy BECCS with other energy technologies (e.g., biomass, renewables, fossil energy, electricity generation, and CO_2 sink) [42].

Previous studies also consider short-sighted targets in designing long-term scenarios of system development. This approach limits the selection of mitigation options to only address targets in the short run, rather than optimizing for the long run. In assessing optimal long-term development pathways, it is crucial for the model to consider the different plausible technology deployment strategies and emissions trajectories that can achieve a given cumulative target [43].

1.4. *Scope & objectives*

Given the importance of BECCS for realizing Paris goal and the potential opportunity in Indonesia, this study aims to answer several key questions pertaining to BECCS development at national levels: 1) What are the potential contribution of BECCS in varying decarbonization scenarios of Indonesia's electricity sector? Looking at potential emission reduction, required capacity deployment, as well as costs and investment in comparison with other electricity supply technology options. 2) What are the implications of these potential contributions towards bioenergy development? Looking at bioenergy supply requirements. 3) What are the required BECCS infrastructure deployment in different regions of Indonesia? Looking at different locations, types, and sizes of BECCS infrastructure requirements (i.e., bioenergy feedstock and transport, electricity generation and transmission, and CO_2 capture, transport and storage). This study assesses the potential and impacts of BECCS technologies in Indonesia's electricity sector decarbonization scenarios. Various long-term BECCS scenarios are generated using a spatially explicit energy system optimization model for capacity expansion of electricity generation, transmission, and CCS. The long-term optimization model is based on perfect foresight to derive optimal development pathways of technology and emission in achieving given cumulative targets of emissions, i.e. long-term carbon budget. The model leverages region specific estimates of biomass resource and geological CO_2 storage potentials as well as inter-region infrastructure requirements in the selection of cost-effective BECCS configuration.

2. Methodology

The assessment of BECCS potential and impacts in scenarios of electricity system decarbonization was carried out using energy system modelling and optimization framework. The energy system model provided a consistent accounting framework for evaluating representative energy systems, which was useful for this study in quantifying the cost and performance of BECCS and other electricity supply technologies. The optimization algorithm was used to generate the least-cost power sector development trajectory and helped us identify the optimal contribution of BECCS vis-à-vis other decarbonization technologies in achieving below the cumulative emission target. Assessment of BECCS deployment potential and impacts are carried out in various scenarios of electricity system decarbonization in Indonesia. In addition, mitigation scenario results are compared to the baseline, or reference scenario without additional climate change mitigation, to assess the required measures or system transformation potential and impacts.

2.1. *SELARU modelling and optimization framework*

Using SELARU, a spatially explicit energy system optimization model, this study presented various regional electricity system development trajectories for various long-term emission goals. The model represents regional disparities of resource, demand, and infrastructure at high spatial resolution (more granular than provincial level aggregation). The model was used in previous studies investigating the impacts of model representation of grid-expansion problem [42] and decision-making foresights towards optimization results of long-term power system development and emission scenarios [43]. The model formulation of infrastructure capacity and network expansion considers the effect of economies-of-scale from both large-scale capacity deployment (bulk-investment) and larger network expansion (interconnection). This approach provided detailed analysis of regional specific infrastructure requirements that are critical in assessing energy infrastructure requirements of BECCS in a national electricity system context. In generating optimal trajectories of resources, technologies and emission development to achieve a cumulative goal, the optimization model considers perfect foresight planning as all information about future developments has already been anticipated for all decisions along the planning time-horizon. This approach ensures the selection of technology deployment strategies to deliver long-term optimal pathway of technology deployment strategies in addressing long-term cumulative target of emissions.

The regional electricity system is represented by nodes and lines for connection between nodes. At each node, electricity demand can be fulfilled by various options of power generation and transmission-in from other nodes, minus transmission-out to other nodes. Nodal balance and transfers also apply for fuel feedstock and CO_2. Deployment of infrastructures' capacity increases the flow of energy conversion, voltage transformation, transmission flow, as well as CO_2 capture, transport, and storage. Model spatial representation of resource and technology provided detailed analysis of BECCS supply chain in the broader context of electricity system. Fig. 1 illustrates the SELARU Modelling framework. Further details of the model formulation and input data are available in supplementary information.

2.2. *Scenario analysis*

We considered various scenarios of cumulative emission target from 2020 to 2100 for Indonesia's electricity sector climate change mitigation in line with global 2 °C and 1.5 °C goals (see Fig. 2). The cumulative emission targets are based on 32 global emission trajectories representing various SSPs under RCP 2.6 and 1.9—allocated to national level using 13 burden-sharing frameworks—resulting in 416 different national emission trajectories [44]. The 13 allocation frameworks represent 5 "fairness" principles in climate mitigation, namely: "equality",

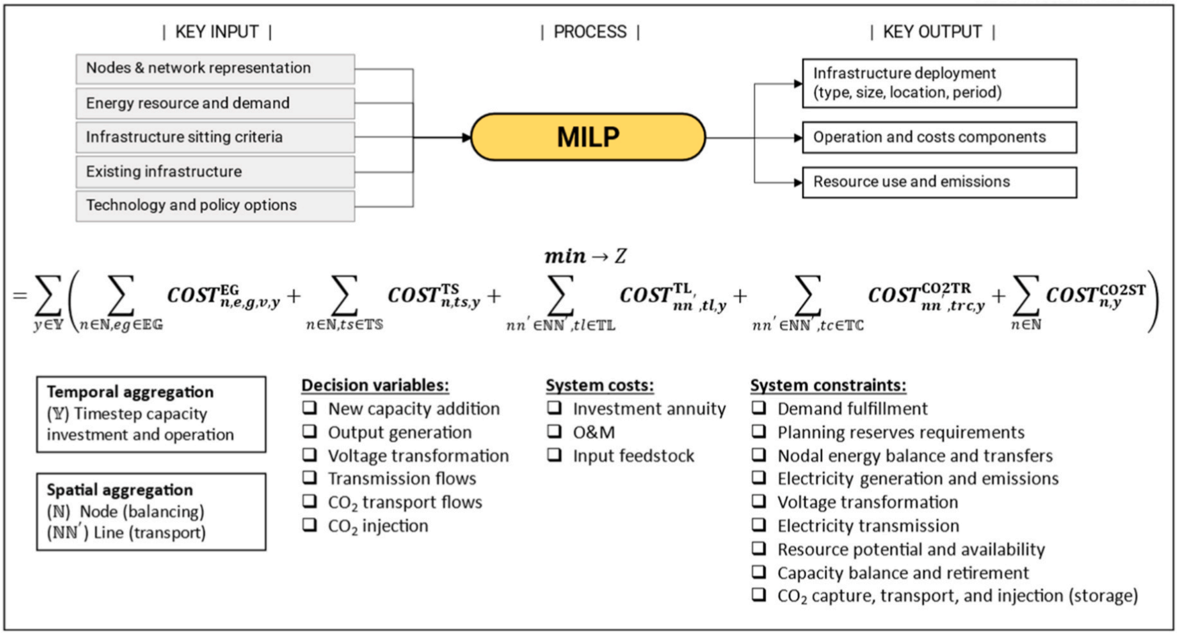

Fig. 1. SELARU modelling framework.

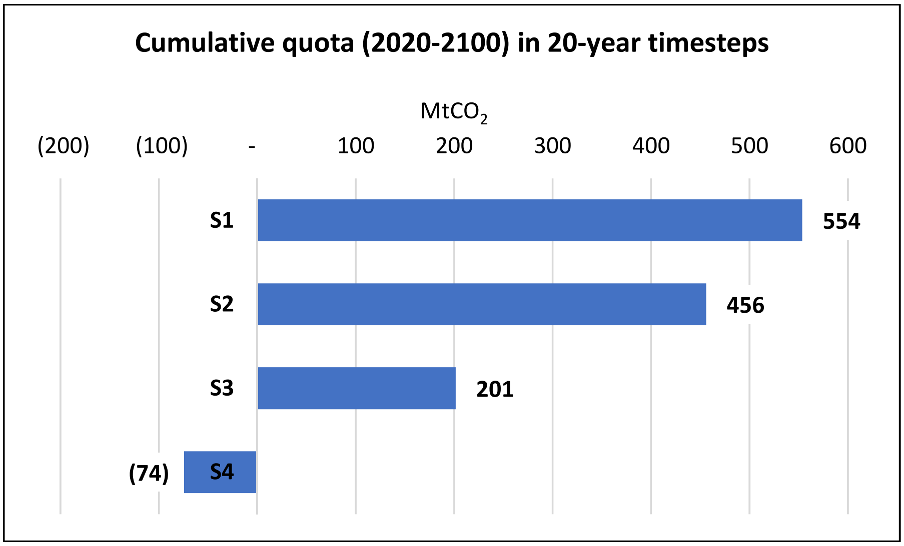

Fig. 2. Scenarios of long-term emission targets.

"responsibility", "capacity", "rights-to-development", and "grandfathering". 416 pathways are then sorted based on the earliest year of achieving net zero and grouped into 4 scenarios as follows: last 25% (S1) with no net zero until 2100 (least stringent); third 25% (S2) with net zero around 2080; second 25% (S3) with net zero around 2070; and first 25% (S4) with net zero around 2050 (most stringent). The allocated national emission projections are then decomposed based on extrapolated composition of sectoral emissions and final energy mix to obtain electricity sector emission targets. For each mitigation scenario, the cumulative emission targets are 554 (S1), 456 (S2), 201 (S3), and −74 (S4) Mt CO_2 for 2020-2100 in 20-year intervals (i.e., for the years 2020, 2040, 2060, 2080, and 2100).

The analysis of different scenarios of national electricity system decarbonization was carried out to compare the different potential and impacts of cost-effective development of BECCS as well as other electricity supply technologies. This setup enables the comparison of BECCS with other electricity supply technologies whilst considering its potential emission reduction measure against other mitigation options in the electricity sector. In addition, emission reduction scenarios were compared to the baseline scenario (BL) for evaluating the additional mitigation requirements (i.e., costs, investment, capacity deployment, resource use, etc.). BL considers no additional climate mitigation measures to be considered for the development.

2.3. Electricity and CCS systems parameterization

The model represents Indonesia electricity and CCS systems in 500 nodes and 1624 lines connecting different nodes. The model also represents regional fuel availability in 34 provincial regions. Temporal information is aggregated at annual resolution in 20-year intervals focusing on investment decision analysis throughout 2020-2100. Regional power generation load characteristics and capacity factors are simplified in annual resolution using assumption on power generation firm capacities by type and increased productivity for energy storage coupled systems. National electricity demand is projected to grow by an average of 2% per annum based on linear regression with considering the development of drivers of energy demand, i.e., population growth and gross domestic product (GDP) growth. The population growth assumption follows SSP2 dataset [45] while the GDP growth assumption is based on historical trend [46]. Demand projection at national level is then disaggregated to province level, then to city or regencies, and ultimately down to village level using information of demand, population and GDP at different spatial resolutions [22,46,47]. The high spatial resolution demand projection at village level is then aggregated to nodes level.

Input data related to renewable energy resources (i.e., Hydropower, Geothermal, Bioenergy, Solar, Wind) potential and geographical distribution are processed from publicly available dataset [48–51]. This study considers domestically available bioenergy from existing annual waste generation of plantations and pulp-paper and wood processing industries up to 402 PJ per year, 1640 MW potential power generation capacity based on biogas, and existing production of biodiesel and bioethanol of 269 PJ per year. Information on location specific biomass resource potentials are obtained from Directorate General of New and Renewable Energy and Conservation of Energy of the Ministry of Energy and Mineral Resources (MEMR) assessments [50]. CO_2 storage potential capacity and locations are adapted from National Research and Development Center for Oil and Gas (LEMIGAS), MEMR and Indonesia's Center of Excellence for Carbon Capture, Utilization, and Storage (CoE-CCUS) internal analysis [52]. This study considers total CO_2 storage potential of 1157 $GtCO_2$ distributed in various sites, both on-shore and off-shore, with maximum CO_2 injection rate ranging from 0.4 to 445 $MtCO_2$ per year with the cost of CO_2 injection about 10 \$/tCO_2. Topography [53], land cover [54], and protection areas [55] influence the technology-location suitability and maximum capacity to build at different nodes. Existing and planned infrastructure [50,56] are also considered in the capacity optimization model.

For this study, we considered different options for BECCS: pre-combustion or post-combustion CO_2 capture; and dedicated bioenergy or cofiring with fossil fuels. In addition to BECCS, we consider options for fossil power generation with and without CCS, as well as other renewable energy sources, and nuclear. The analysis also includes electricity transmission and CO_2 transport infrastructure requirements as well as regional biomass sourcing strategies. Each infrastructure capacity can be deployed in different types and sizes while also considering technologies' capital cost evolution from 2020 to 2060 [57–60]. All technologies considered in the model are assumed to have technical lifetimes between 20 and 100 years. Fossil-fuels (coal, oil, and natural gas) and biofuels (biomass wastes, biodiesel, and biogas) potential and availability across different regions were adapted from Ref. [50]. This study considers domestically available bioenergy from existing annual waste generation from plantations and pulp-paper and wood processing industries, biogas production potential, and existing production of biodiesel and bioethanol industries. We assume no nuclear resources are available domestically. Fuel prices, energy specification, and emission factors information was obtained from national and international references [22]. Prices of energy feedstock and infrastructure operation and maintenance costs are assumed to have no change throughout the years. Additional energy feedstock on top of domestic supply is assumed at a higher price (about 75% higher).

3. Results

3.1. Emission reduction measures

The resulting trajectories of emission reduction for each decarbonization scenario (S1-S4) are shown in Fig. 3. The top line represents the emissions projection under baseline scenario (BL) and the bottom line represents the net emissions after mitigation. Emissions reduction contributions by type of technology are represented in wedges. By 2100, the least stringent emission scenario (S1) resulted in 572 Mt CO_2 reduction while more stringent targets in S2, S3, and S4 lead to 613, 719, and 830 Mt CO_2 reduction from the baseline scenario (BL) of 683 Mt CO_2. Across S1-S4, most of emission reduction are generated from increasing renewable energy (RE). About 536-548 Mt of CO_2 emissions can be reduced in 2100 b y expanding renewable power capacity. Meanwhile, emission reduction from BECCS varies across different decarbonization scenarios. BECCS contribution is not significantly required to achieve less stringent emission targets (S1 and S2). There is no BECCS required under S1 and insignificant amount of BECCS is required under S2 (5 Mt CO_2, 0.8% of total emission reduction in 2100). However, BECCS contribution increased significantly as more stringent targets are

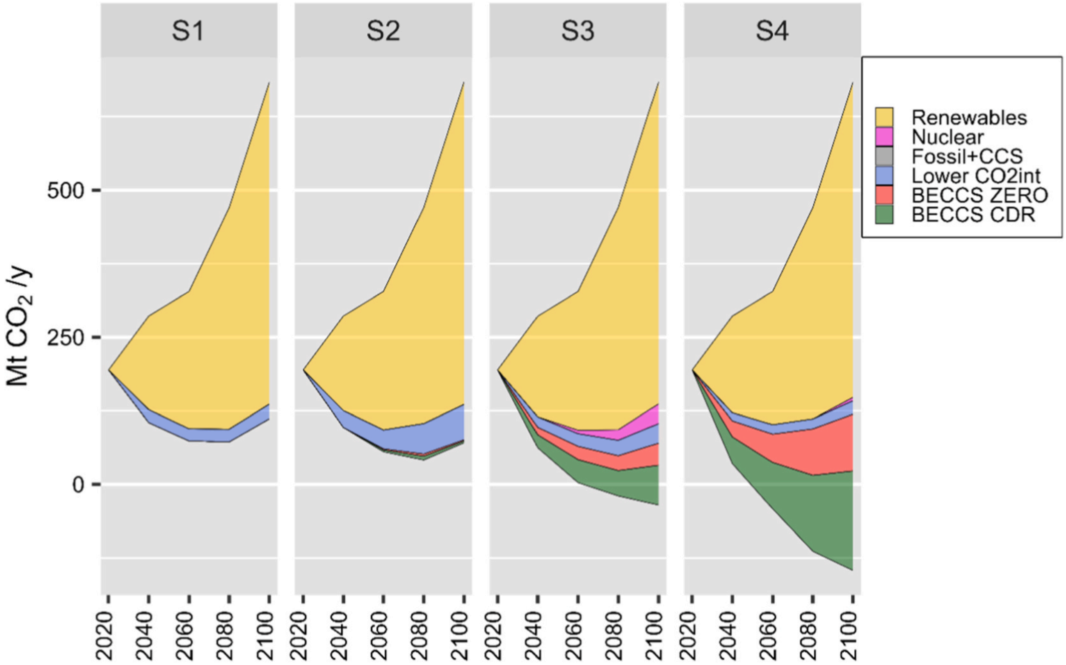

Fig. 3. Development of emission reduction contribution (in Mt CO_2 y^{-1}) by technologies from 2020 to 2100 in different decarbonization scenarios (S1-S4).

considered (S3 and S4). Under S3 and S4, BECCS contribution increased to 105 and 265 Mt CO_2 (15% and 32% total emission reduction in 2100). Emission reduction from BECCS comprised of both avoided fossil emission (BECCS-ZERO), calculated from the amount of coal emissions in baseline scenario that are avoided by shifting to bioenergy; and carbon dioxide removal (BECCS-CDR), calculated from the amount of CO_2 captured and stored.

Besides transitioning to non-fossil, reduction of fossil power emission also came from shifting to lower emitting fuels, i.e., shifting from coal to natural gas input for power generation, thus lowering CO2 emission intensity of power generation (Lower CO2int). Moving from S1 to S2 the additional emission reduction, on top of deploying renewables, comes from replacing coal power with lower emitting gas. However, moving from S2 to S3, the option for gas is replaced with nuclear power. Emission reduction via nuclear power is only selected under S3 and S4—with S3 resulting in larger nuclear capacity than S4. It is important to note that the increasing negative emission requirement in S4 leads to larger BECCS deployment, which also replaces the nuclear option.

3.2. Electricity generation capacity deployment

The resulting trajectories of electricity generation capacity for each decarbonization scenario (S1-S4) are shown in Fig. 4. More stringent emission scenarios (S3 and S4) results in 6 and 16 GW BECCS electricity generation capacity in 2100, about 1% and 2.3% of total installed capacity. Meanwhile, less stringent emission scenarios (S1 and S2) require zero to 0.3 GW of BECCS capacity (0.04% total). In contrast, RE capacity deployment is significantly larger than BECCS. With or without BECCS, large-scale deployment of RE capacity (635-650 GW by 2100) is required in all decarbonization scenarios (S1-S4). In contrast, only about 16 GW of BECCS are deployed in the most stringent scenario (S4). RE capacity is dominated by solar (93% of total RE), followed by hydropower (5%), geothermal (2%), and insignificant wind contribution (<0.01%). Note that the expansive deployment of RE capacity is mainly due to the low-capacity factor solar power generation. There is no nuclear power being deployed under S1 and S2. However, nuclear capacities have increased to 6 GW under S3, which is higher than S4 of 1 GW.

Fossil power generation capacities are brought down from 75 GW in 2020 to 25 GW in 2100 under S1, to 35 GW under S2, and to around 60 GW under S3 and S4. Meanwhile under BL, fossil power generation capacities are increased to over 180 GW. This is mostly contributed by new additional coal power generation capacity. S1 and S2 result in small coal power generation capacity remaining up to 2100. Meanwhile, S3 and S4 scenarios result in complete shift away from coal power generation by around 2060. Gas and oil power generation capacities remain up to 2100 but also demonstrate a significant decrease in deployment as compared to BL. Fossil power generation with CCS are not selected in any scenario.

3.3. System costs and investment requirement

The resulting trajectories of annual system costs for each decarbonization scenarios (S1-S4) are shown in Fig. 5. All decarbonization scenarios (S1-S4) resulted in \$46.6 B-\$53 B of average annual system costs throughout 2020-2100, or 4.7%-19.1% higher compared to baseline scenario (BL) of \$44.5 B. Under BL, most of the costs are attributed to fossil power generation. Meanwhile under S1-S4, most of the costs come from renewables power generation with about the same scale and pace of development. The costs of renewables have increased on a similar scale and pace of development across all scenarios (S1-S4), from about \$3 B in 2020 to over \$62 B in 2100, or 182% higher compared to baseline scenario (\$22 B in 2100). By 2100, the costs of nuclear power under S3 (\$3.7 B) are over 7 times larger than S4 (\$0.5 B). Moreover, fossil power costs have reduced from \$20 B in 2020 to around \$12 B in 2100 under S1 and S2, \$6 B under S3, and \$5 B under S4. Meanwhile, fossil power costs increased to about \$47 B under BL. All decarbonization scenarios (S1-S4) resulted in higher transmission costs than the baseline scenario (BL). BL leads to increased transmission cost from \$0.5 B in 2020 to \$1.5 B in 2100 while S1 and S3 lead to about \$2.2 B, and S2 and S4 lead to \$3.5 B and \$4.8 B.

The costs of BECCS vary significantly across different decarbonization scenarios. In more stringent emission scenarios (S3 and S4), costs of BECCS increased from \$2.2 B and \$4.7 B in 2040 to \$6.9 B and \$18.4 B in 2100. Meanwhile less stringent emission scenario (S2) resulted in \$0.5 B of BECCS costs in 2060 and increased to \$0.7 B in 2100. Increasing BECCS costs are mainly due to the increasing bioenergy feedstock requirements, power generation infrastructure investment annuities, and CO_2 capture, transport, and storage. Under S4, the costs of

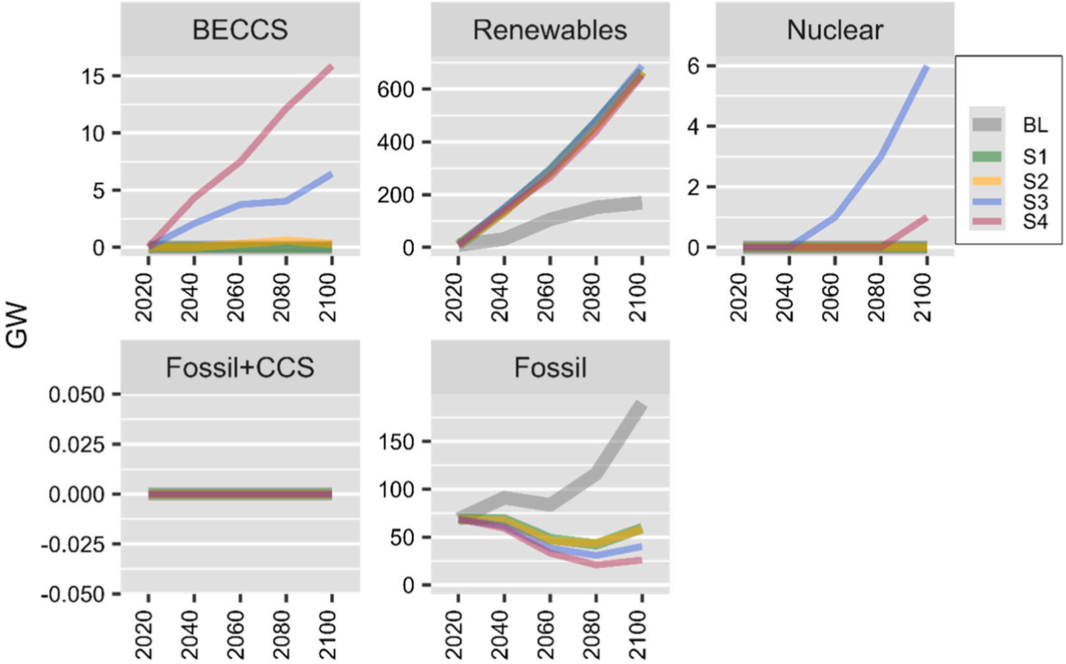

Fig. 4. Development of installed electricity generation capacity (in GW) by technologies from 2020 to 2100 in different decarbonization scenarios (S1-S4).

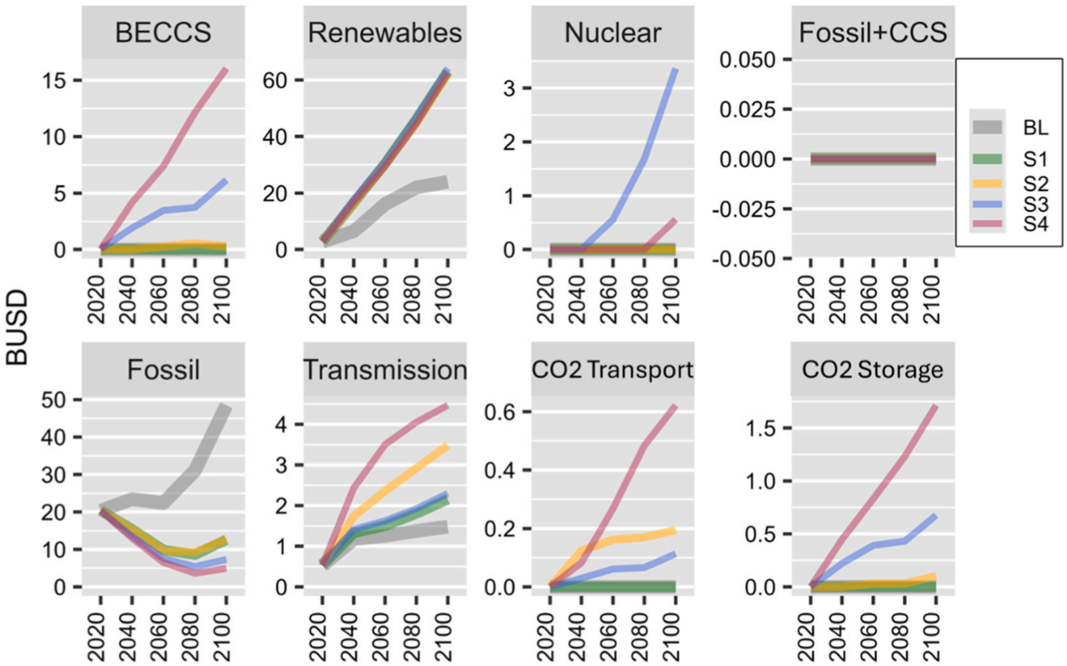

Fig. 5. Development of annual system costs (in billion \$ y^{-1}) by technologies from 2020 to 2100 in different decarbonization scenarios (S1-S4).

BECCS comprise of fuel (41%), power generation capital and operational expenditures (25%), CO_2 capture (21%), CO_2 transport (2%), and CO_2 storage (9%).

The resulting trajectories of capital investment requirement for each decarbonization scenario (S1-S4) are shown in Fig. 6. All decarbonization scenarios (S1-S4) resulted in \$828 B-\$882 B of cumulative capital investment throughout 2020-2100, or 38%-47% higher compared to baseline scenario (BL) of \$601 B. Most of the required investment is attributed to the deployment of renewable power capacities (86%-90% total). S1-S4 resulted in \$677 B-\$713 B of cumulative renewables investment, 141%-154% higher compared to baseline scenario (BL) of \$281 B. At the same time, cumulative fossil power investment has been reduced from \$297 B under BL to around \$58 B-\$103 B under S1-S4. In addition, S3 and S4 resulted in \$27 B and \$4.5 B of new nuclear power capacities. In addition, S1-S4 resulted in higher transmission investment requirements than the baseline scenario (BL). About \$21 B is required throughout 2020-2100 to invest in transmission capacities under BL. Meanwhile, the required transmission investment is 10% higher under S1 and S3 (\$23.2 B) and 16% and 23% higher under S2 and S4 (\$24 B and \$26 B).

Throughout 2020-2100, S4 requires \$65 B of capital investment for developing BECCS infrastructures (i.e., power generation and

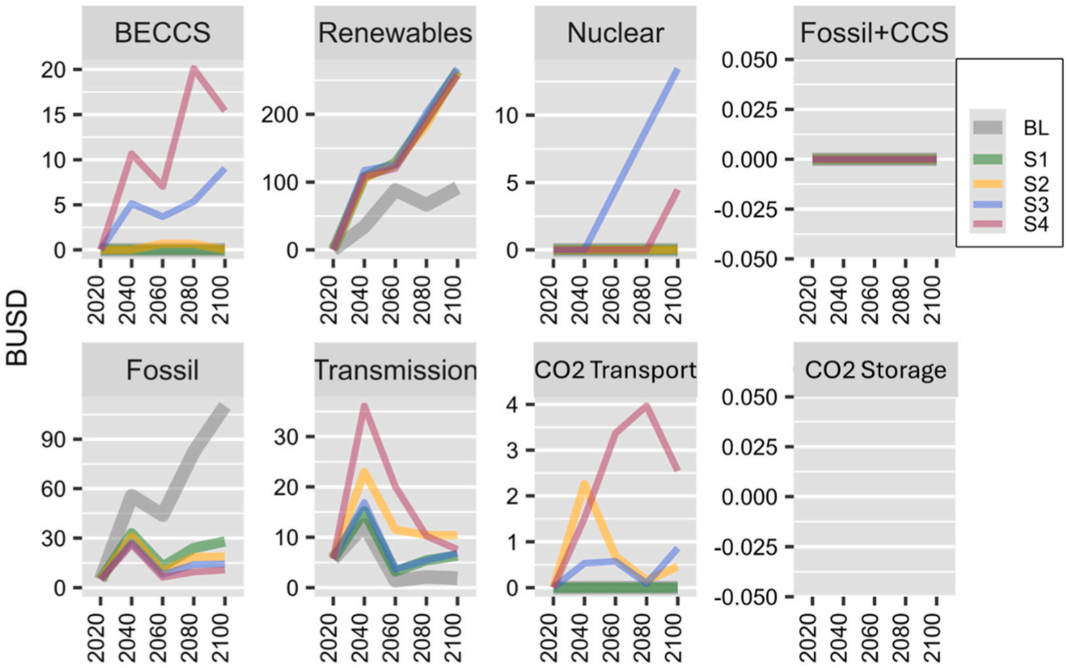

Fig. 6. Development of capital investment requirement (in billion \$) by technologies from 2020 to 2100 in 20 years intervals across different decarbonization scenarios (S1-S4).

transmission, as well as CO_2 capture and transport) or about 12% of total electricity sector investment ($883 B). BECSS capital investment comprises of $27 B for 9 GW new power generation, $26 B for 95 Mtpa CO_2 capture, and $11 B for 2160 Mtpa-km CO_2 transport capacities.

3.4. *Energy input requirement*

The resulting trajectories of fuel input for power generation in each decarbonization scenarios (S1-S4) are shown in Fig. 7. S1-S4 resulted in reduction of fossil fuel input from 2208 PJ/y in 2020 to 396-1397 PJ/y in 2100. Fossil reduction is mainly contributed from lowering coal consumption. In addition, oil input is reduced significantly. However, natural gas input increased significantly from 2020 to 2100 under S1 and S2, larger than S3 and S4. Achieving the least stringent target (S1) requires up to 207 PJ of biomass feedstock for bioenergy electricity without CCS by 2100 or about 51% of existing domestic supply (403 PJ/y in 2020). Meanwhile, aiming for the most stringent target (S4) requires up to 1877 PJ per year of biomass input for BECCS electricity by 2100.

3.5. *BECCS infrastructure design*

The resulting infrastructure design of BECCS systems for S3 and S4 in 2100 are shown in Fig. 8. In S3 and S4, BECCS power generation capacities are deployed in both Northwest and Northeast of the Java Island. Deployment of CO_2 transport capacities that connect the different locations of CO_2 capture with BECCS power generation to nearby CO_2 storage locations, both on-shore and off-shore. Scenarios with increasing BECCS negative emission require more extensive CO_2 infrastructure to connect more CO_2 sources to larger set of CO_2 sinks across wider regions. This can be observed in S4, where deployment of CO_2 transport infrastructure connects wider regions, from Northwest and Northeast of the Java Island. Meanwhile, deployment of CO_2 infrastructure is not as extensive under S3—where most captured CO_2 are injected in nearby CO_2 storage locations. In both S3 and S4, locations that are selected for deployment of BECCS power plant remain the same. All additional BECCS power generation capacities are based on dedicated biomass power plants with post-combustion CO_2 capture technologies. BECCS cofiring with coal, gas, oil as well as BECCS in biogas- and biodiesel power plants are not selected.

4. Discussions

4.1. *The role of BECCS in electricity decarbonization scenarios*

This study provides quantitative insights on the potential and impact of BECCS in Indonesia's electricity system decarbonization scenarios. The scenarios are based on long-term optimization of the energy system aimed at fulfilling the projected demand development at minimum cost by selecting technology deployment strategies that also comply with the emission targets. Therefore, the selection of optimal technology configuration is not only based on their cost-competitiveness in supplying electricity but also in reducing emission.

The resulting scenarios have demonstrated that the cost trade-offs between supplying electricity and reducing emissions are significantly different for BECCS, RE, and Nuclear. Across different decarbonization scenarios (S1-S4), BECCS is considered as a “backstop” technology despite having slightly lower cost for emission reduction than RE and Nuclear, since BECCS is far more expensive in generating electricity. Note that Nuclear is more expensive than RE in both supplying electricity and reducing emissions. The comparison of BECCS, RE, and nuclear cost performances in supplying electricity and reducing emission are shown in Table 1.

The results of this modelling exercise correspond to a reference range of values obtained from various literatures. Fuss et al. reviewed the cost of CO_2 emission reduction via BECCS within the range of $15-$400/t [10]. Meanwhile, Gillingham et al. estimated that RE reduce CO_2 emission at $25-133/t and Nuclear at about $59/t [61]. Saharudin et al. summarized the cost of electricity generation via BECCS from 10 studies across different regions (i.e., UK, Australia, China, US, Europe, Sweden), which ranges about $89-366/MWh [62]. OECD countries' estimated costs of electricity generation based on RE is about $29-$274/MWh and Nuclear is about $28-101/MWh [63].

BECCS is valued for its negative emission potential in achieving more stringent emission reduction targets rather than electricity generation. Therefore, BECCS are only significantly required when there is a clear requirement for achieving net negative emissions, signaled by more stringent long-term emission target or cumulative carbon budget (i.e. towards S4). Insignificant contribution of BECCS in less stringent emission reduction scenarios (i.e. towards S1) implies significant

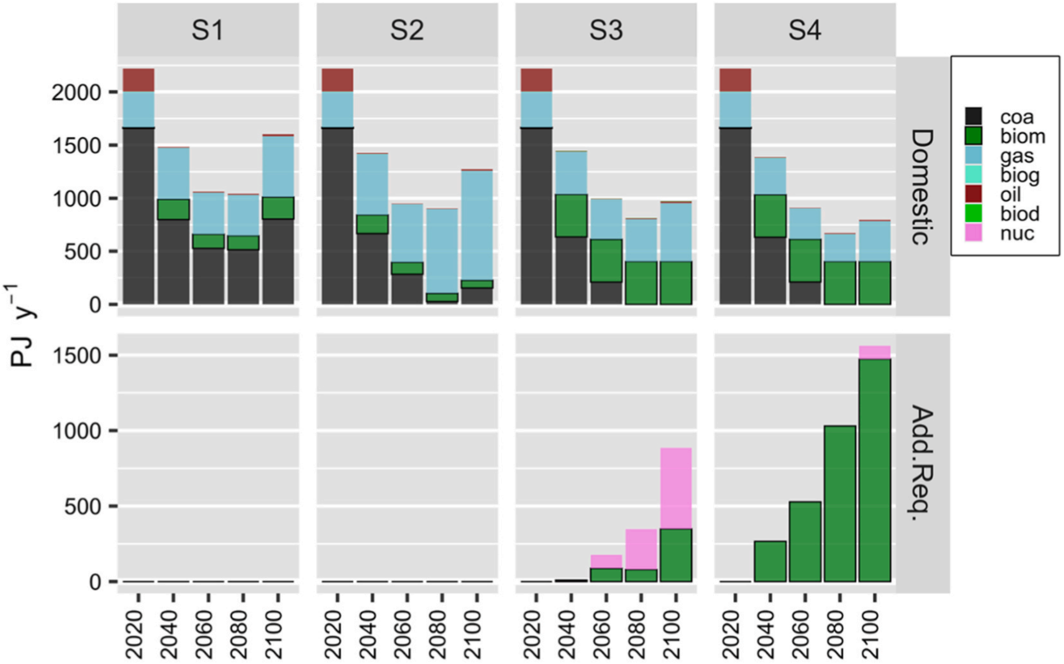

Fig. 7. Development of fuel energy input for power generation (in PJ y^{-1}) by type of fuel from 2020 to 2100 in different decarbonization scenarios (S1-S4).

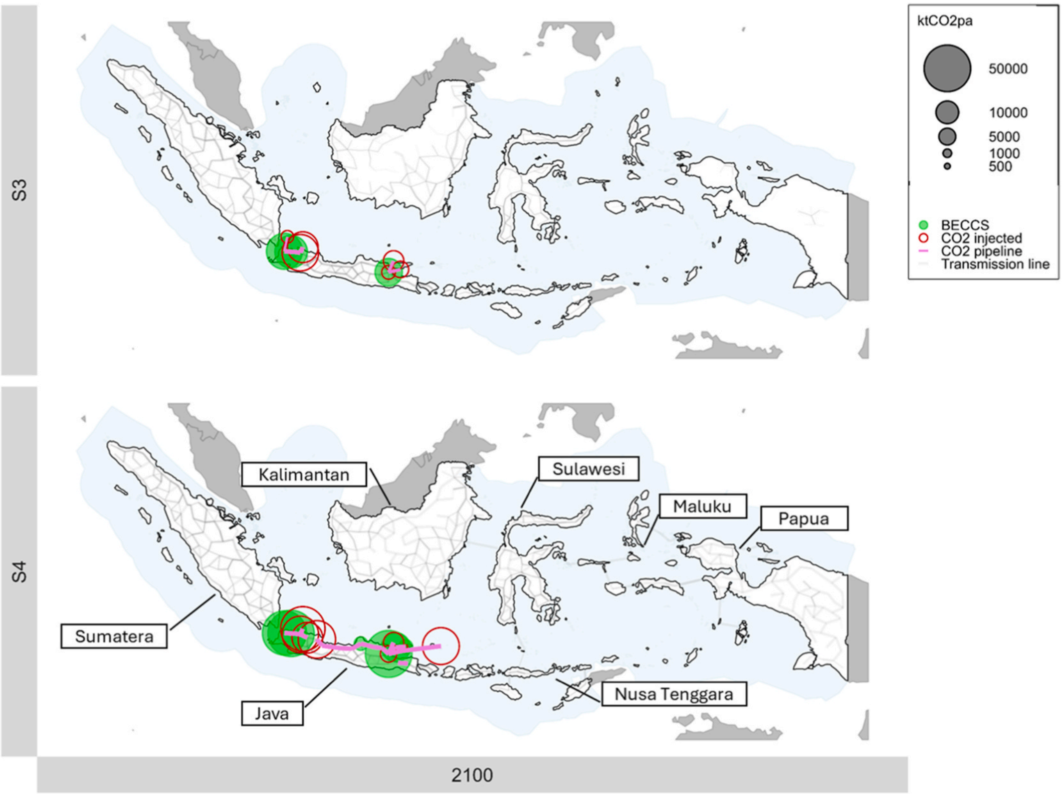

Fig. 8. Projected BECCS infrastructure design, overlaying electricity transmission network design (in grey transparent lines), in 2100 under S3 and S4. Green filled circles represent CO_2 captured from BECCS power plants and red lined circles represent CO_2 injected at CO_2 storage sites. Purple lines represent CO_2 pipeline deployment locations.

Table 1
Comparison of BECCS, RE, and nuclear cost performances in supplying electricity and reducing emissions from the studied scenarios.

		BECCS	RE	Nuclear
Cost of CO_2 reduction	\$/t CO_2	59-63	65-68	98
Cost of electricity	\$/MWh	114-128	51-134	75
of CAPEX	\$/MWh	26-27	43-87	51
of fixed OPEX	\$/MWh	12	8-47	16
of variable OPEX	\$/MWh	6.2	0.3-0.6	2.4
of fuel costs	\$/MWh	70-84	0	5.8
Annual CO_2 reduction per unit electricity generation capacity	t CO_2/kW	12	1.3	6.3
CO_2 emission reduction per capital invested	t CO_2/\$	8401	1902	1699

challenge in delivering low cost BECCS electricity due to the high cost of fuel requirement, which cannot compete with the near zero marginal cost of RE electricity generation. Moreover, incentivizing on lowering the capital cost of BECCS will not be sufficient to compete with the low operating cost of RE, especially with the fast-decreasing capital requirements of Solar PV. It is also worth noting that emission reduction via BECCS can increase in scenarios with delaying of emission reduction, which was demonstrated in scenarios depicting short-sighted decision-making in modelling cost-effective decarbonization pathway demonstrated in other study using the same modelling framework [43]. In managing long-term emissions, scenarios with delayed emission reduction will require increasing emission reduction in later periods. This may also increase emission removal requirements as more negative emissions are required in more stringent emission reduction scenarios.

4.2. The impacts of BECCS expansion on bioenergy supply requirements

Scenarios leading to larger BECCS deployment will require new sources of biomass supply. In the most stringent emission reduction scenario (S4), over 89M t/y of (oven-dry) biomass feedstock is required for BECCS electricity generation by 2100 (assuming 16.8 GJ/t net calorific value of biomass feedstock). The demand for biomass can reach about 3.7-times the existing potential of biomass from wastes in Indonesia (24M t/y). The additionally required biomass supplies are equivalent to 114M m^3 of timber, which is about 2.8-times the annual average production of industrial forest timber in 2020 (39.45M m^3). Note that currently the industrial forest area covers about 11.27M ha. This implies a significant need for expanding biomass supply, which can lead to conversion of large areas of land for biomass production. Another option is by increasing biomass supplies through imports, which replace land-use emissions to outside the national boundary but will significantly increase the emissions of transporting biomass from further distances. Moreover, importing large amounts of biomass can also risk external energy dependency, trade deficits and worsening of the economy [64]. Scaling up of biomass production can negatively impact the environment by affecting water quantity and quality, increasing greenhouse gas emissions, reducing biodiversity, depleting soil organic carbon, and causing soil erosion [12–18]. For instance, land conversion for expanding agricultural production, both for food or feed and chemicals or energy, has negatively impacted biodiversity in Indonesia as well as other agricultural-rich producing countries [65–67]. Moreover, growing bioenergy crops also often requires large amounts of water, and the use of chemicals in the plantations could pollute water bodies—thus risk of higher water stress levels [68,69]. These adverse effects vary significantly depending on the type of biomass, location of the land, and management practices [15]. By identifying suitable cultivation sites, selecting appropriate bioenergy crops, and implementing optimal management practices, along with effective regulation and law enforcement, it is possible to minimize environmental risks and ensure the sustainable development of the bioenergy industry—which are important to ensure the effective implementation of BECCS.

4.3. Cost-effective BECCS infrastructure deployment strategy

Optimization model results of the location selection of BECCS power generation capacity have considered the least-cost approach to accumulate negative emission whilst delivering economically sufficient electricity supply. Although biomass energy conversion has lower efficiency and will incur higher cost of biomass feedstock as compared to utilizing coal, zero use of fossil fuel in dedicated BECCS is more cost efficient in terms of generating negative emission. BECCS cofiring with fossil is also more expensive than other zero emission technologies, i.e., renewables and nuclear. This was demonstrated in scenarios that can be achieved with zero to minimum negative emission, where power generation capacities coupled with CCS other than dedicated BECCS are not selected. The selection of BECCS with dedicated biomass power plant corresponds to the cost comparative advantage of negative emission accumulation rather than electricity generation. Although BECCS cofiring with fossil fuels can reduce the cost for generating electricity, it remains at disadvantage as compared to RE and Nuclear. This implies a greater focus needs to be given to developing RE and Nuclear electricity earlier to avoid costly BECCS negative emission. And in scenarios where negative emissions are required, the role of zero emission technologies remains important as it is considered the economical option to supply electricity, complemented using dedicated BECCS for achieving negative emission targets.

The selection of bioenergy sources, BECCS power plant and CO_2 storage locations as well as the design of electricity transmission and CO_2 transport network are dependent on the distance related costs. Scenarios with stringent emission reduction targets have resulted in deployment of BECCS electricity generation capacities located near to high demand concentrations with ample grid connectivity and within considerable distance to CO_2 storage locations. West Java and East Java represent two of the largest electricity demand concentrations in Indonesia. In both regions, large potential CO_2 storage is also present within considerable distance, both on-shore and off-shore (Northwest and Northeast Java). When all cost-effective nearby CO_2 storage potential has been utilized, deployment of a more geographically extensive CO_2 transport infrastructure is necessary to connect more CO_2 sources to a larger set of CO_2 sinks across wider regions. This is demonstrated in the most stringent emission reduction scenario (S4), where large-capacity and long-distance CO_2 pipeline is deployed to connect larger sets of CO_2 sources and sink across longer distances, from Western to Eastern Java and vice versa. Meanwhile, both CO_2 source-sink-rich regions remain disconnected in the second most stringent emission reduction scenario (S3).

4.4. Study limitations and outlook

Model results of optimal technology deployment and location selection are based on minimum total system cost under a given set of parameters. Other factors not considered in this study can affect the results. The exploration of long-term system development scenarios is based on perfect information about future demand development. With this study setup, uncertainties related to demand development due to changes of the supply system and price volatility are not considered. Moreover, uncertainties of infrastructure placement costs and location suitability due to considerations of existing right-of-way, logistic infrastructures, and other spatial regulations can influence the resulting infrastructure deployment strategies e.g., selection of optimal route for electricity transmission, CO_2 transport, or regional biomass feedstock sourcing alternatives. The results of [42] have demonstrated that the spatial energy system long-term optimization model results are sensitive to input parameterization of costs that are related directly to distance-based infrastructure, i.e., transmission lines. Similarly in a long-term planning context, the model can also be sensitive in how future information is included. For instance, changes in commodity prices and technology costs can also influence the deployment of infrastructures, both in different times and locations.

This study only considers CCS options within the national electricity system. By not including other CCS options in other sectors, e.g., CCS in manufacturing industries, other CO_2 capture and utilization (CCU) options, nor Direct Air Carbon Capture and Storage (DACCS), the analysis has disregarded the potential development of a larger-scale CO_2 transport infrastructure. Integration of other CCUS options outside the electricity sector can help lower the marginal cost of CO_2 transport by deploying larger CO_2 transport capacity and network to cover a larger set of CO_2 sources. Further studies should include the consideration of a broader CCU and CCS system development potential and impact that also covers other sectors. This study is limited to the existing information on CO_2 storage potential capacities, locations, and costs. Further exploration of CO2 storage sites can affect the potential contribution of BECCS as more CO_2 storage capacities, especially with proximity to potential BECCS sites, can alter the costs as well as infrastructure design of BECCS deployment. Similarly, the exclusion of other energy sectors in the analysis has disregarded the potential and impacts of energy substitutes in different stages of the energy supply chains across various energy suppliers and users, be it liquid, gaseous, solid fuels, and heat or electricity. For instance, incorporating the option of BECCS in the electrification of building and transport in the analysis. BECCS can also be included in other energy value chains such as hydrogen production. Moreover, DACCS is energy intensive and are not well suited for Indonesia socio-economic context, whereas Indonesia still requires significant need for energy development and electrification for the masses. Furthermore, including DACCS in the analysis should also consider broader system effect, such as temporal variability. The opportunity to utilize low price electricity in periods with a large supply of renewables from solar and wind energy can help increase the cost-competitiveness of DACCS compared to BECCS, especially when biomass also becomes more expensive [70].

By focusing the scope of analysis only on the national electricity system, potential integration and synergies with other energy systems, i.e., power-to-fuels, and other CDR measures in land systems, i.e., Nature-based Solutions (NBS) such as afforestation or reforestation, are not considered. Increasing the scope of analysis will require larger computational resources to solve larger sets of equations and constraints in describing more intricate relationships between different energy systems as well as land systems unless simplifications are made. In this study we have made simplification to the short-term operational constraint of electricity system as more focus is given to solving capacity expansion problems with long-time horizon and taking into consideration varying technologies at high spatial resolution. This is done by assuming system constraints at annual resolution that represent the different typical operation of power generation systems, i.e., base load, peak load, intermittent without energy storage, or with energy storage. The minimum electricity generation in a year is set for power plants with planned reserve capacities. The maximum annual production limits are introduced to differentiate peak load power plants. Further detailed analysis of system operational reliability in sub-annual resolution as well as energy storage requirements will require increasing model temporal resolution in addressing short-term dynamics of electricity systems. The 20-years decision time-step used in this study may mask ramp-up and retirement dynamics. However, simplifications are needed to maintain tractability in solving large spatial energy systems within a long planning horizon. In addition, the 20-years decision time-step are deemed to be sufficient in representing the investment decisions of technologies with lifetimes ranging from 20 to 100 years.

5. Conclusion

Using SELARU, a spatially explicit energy system optimization model, we have demonstrated and assessed the role of BECCS in scenarios of electricity decarbonization in Indonesia. By comparing the resulting technology selection in different decarbonization scenarios, we have derived insightful information regarding the role of BECCS as a "backstop" technology in achieving long-term emission goals. Although BECCS is less costly in reducing emissions, BECCS is more expensive in supplying electricity compared to RE and nuclear. This implies that BECCS is selected only when there is a need for drastic emission reduction that requires accumulation of negative emissions. By focusing more on negative emission accumulation, BECCS with dedicated biomass is selected over BECCS cofire with fossil fuels. This is due to higher negative emission yield per dollar spent on dedicated BECCS, although incurring higher cost for generating electricity that is mainly contributed by the higher cost of fuel configuration.

Achieving larger emission reduction using BECCS negative emission will require a larger supply of biomass, which may not be sufficient with the existing supply of domestically available biomass. The increase of biomass demand can also increase the risk of negatively impacting land sector production and the environment as larger land conversion are needed to produce more biomass for energy feedstock. However, there can also be opportunities for positive impacts, e.g. land restoration, improved water quality, reduced soil erosion, and improved forest management. It is important to note that BECCS effective mitigation potential can be reduced due to emission leakage and become less attractive with the increasing risk of environmental damage and biodiversity loss. Consideration of negative impacts of biomass production, i.e., indirect land-use change emission, is critical in the selection of BECCS as an effective negative emission technology. With more informed strategies that can help ensure sustainable bioenergy supply and environmental integrity, BECCS implementation can be effective in carrying out emission reduction.

In addition, large expansion of BECCS electricity will also require the expansion of transmission capacities with extensive network connecting BECCS power plants with different demand centers, as well as an extensive network of CO_2 transport infrastructure in delivering captured CO_2 from BECCS power plants to selection of CO_2 storage sites. This study has demonstrated that the loss of electricity transmission is far more costly than expanding on CO_2 transport infrastructure when considering BECCS power plant location. Careful selection of BECCS power location can be detrimental in shifting the costs between biomass feedstock logistics, electricity transmission, and CO_2 transportation.

Future research can focus on integrating land resource management options in the analysis of energy system scenarios with large scale bioenergy deployment. By integrating land resource and energy system strategies, trade-offs and potential synergies can be assessed by incorporating both effective land resource management and selection of energy system technologies.

Author contributions

BY and PY conceived the idea and developed the concept for the study. BY performed input data collection and processing. BY performed model formalization and execution. BY and PY led the writing and analysis. All authors discussed the idea and contributed to the manuscript. PY supervised the study.

CRediT authorship contribution statement

Bintang Yuwono: Conceptualization, Data curation, Formal analysis, Investigation, Methodology, Project administration, Software, Visualization, Writing – original draft. **Lukas Kranzl:** Supervision, Writing – review & editing. **Reinhard Haas:** Supervision, Writing – review & editing. **Retno Gumilang Dewi:** Writing – review & editing. **Ucok Welo Risma Siagian:** Writing – review & editing. **Mohammad Rachmat Sule:** Resources, Writing – review & editing. **Florian Kraxner:** Supervision, Writing – review & editing. **Ping Yowargana:** Conceptualization, Funding acquisition, Supervision, Validation, Writing – review & editing.

Declaration of competing interest

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

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Appendix A. Supplementary data

Supplementary data to this article can be found athttps://doi.org/10.1016/j.esr.2026.102270.

Data availability

All datasets that are used for the calculation are available from the cited references. Compilation of these datasets can be accessed through https://doi.org/10.5281/zenodo.15739704. Summary of input data and calculation results can be found in the Supplementary Information. Complete results of model runs can be reproduced using datasets and GAMS codes in https://doi.org/10.5281/zenodo.15739704..

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