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Key Points:
- A coupled hydrological and techno-economic model framework is used to assess hydropower production under global warming levels of 1.5 and 2 °C
- Production provided by 1.5 °C of global warming is greater than that provided by 2 °C of global warming under RCP6.0
- Hydropower generation will be far less than the energy demand when protected areas are excluded as potential sites for hydropower plants

Supporting Information:
- Supporting Information S1

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Hydropower Production Benefits More From 1.5 °C than 2 °C Climate Scenario

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Abstract Hydropower plays an important role as renewable and clean energy in the world's overall energy supply. Electricity generation from hydropower represented approximately 16.6% of the world's total electricity and 70% of all renewable electricity in 2015. Determining the different effects of 1.5 and 2 °C of global warming has become a hot spot in water resources research. However, there are still few studies on the impacts of different global warming levels on gross hydropower potential. This study used a coupled hydrological and techno-economic model framework to assess hydropower production under global warming levels of 1.5 and 2 °C, while also considering gross hydropower potential, power consumption, and economic factors. The results show that both global warming levels will have a positive impact on the hydropower production of a tropical island (Sumatra) relative to the historical period; however, the ratio of hydropower production versus power demand provided by 1.5 °C of global warming is 40% higher than that provided by 2 °C of global warming under RCP6.0. The power generation by hydropower plants shows incongruous changing trends with hydropower potential under the same global warming levels. This inconformity occurs because the optimal sites for hydropower plants were chosen by considering not only hydropower potential but also economic factors. In addition, the reduction in CO_2 emissions under global warming of 1.5 °C (39.06×10^6 t) is greater than that under global warming of 2 °C (10.20×10^6 t), which reveals that global warming decreases the benefits necessary to relieve global warming levels. However, the hydropower generation and the reduction in CO_2 emissions will be far less than the energy demand when protected areas are excluded as potential sites for hydropower plants, with a sharp decrease of 40–80%. Thus, government policy-makers should consider the trade-off between hydropower generation and forest coverage area in nationally determined contributions.

1. Introduction

The Paris Agreement raised an action to limit the global mean temperature increase to less than 2 °C above preindustrial levels and to make efforts to limit to 1.5 °C by 2100 to substantially diminish the risks and effects of climate change (UNFCCC, 2015). Consequently, assessing the influences of global warming up to 1.5 and 2 °C has been a popular focus of research, particularly at the global scale (Russo et al., 2017; Schleussner et al., 2016). The Intergovernmental Panel on Climate Change (IPCC) released a special report based on an assessment of the available scientific literature relevant to global warming of 1.5 °C and the comparison between global warming levels of 1.5 and 2 °C (IPCC, 2018). There are multiple lines of evidence that increases in global temperature by 1.5 and 2 °C relative to the preindustrial period will have impacts on hydrological systems, ecosystems, energy systems, and human systems (Li et al., 2019; Ove Hoegh-Guldberg et al., 2018; Park et al., 2018; Rogelj et al., 2015).

Energy is a major concern under global change (Ferrari et al., 2017). The demand for energy has increased dramatically due to the growth of the global population and socioeconomic development. Hydropower plays an important role as renewable and clean energy in the overall world energy supply, as hydropower makes a significant contribution to meeting escalating global electricity demands and is helpful in the mitigation of greenhouse gas (GHG) emissions as a replacement for fossil fuels (Owusu & Asumadu-Sarkodie, 2016). In 2015, the electricity generated from hydropower represented approximately 16.6% of the world's total

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electricity and 70% of all renewable electricity. Hydropower generation has doubled in the last 30 years and is projected to double from the present level by 2050 (World Energy Council, 2016). In a sustainable and less carbon-intensive future, hydropower will play an increasingly crucial role throughout the 21st century (Yüksel, 2010).

It is well known that changes in water resources will be among the major effects of global warming (Arnell & Gosling, 2013) and these changes will in turn impact the availability and steadiness of hydropower generation (Zeng et al., 2017). Moreover, uncertainties associated with global warming will impact hydropower potential estimation and make hydropower planning and management more challenging (Barnett et al., 2005; Hamududu & Killingtveit, 2012; Reyer et al., 2017). Therefore, the study of the impacts of global warming on hydropower potential will have implications for the planning and operation of hydropower plants, and such research is imperative and critical for the trade-off between energy security and sustainable development. In recent years, considerable progress has been made in understanding the hydrological effects of global warming on hydropower potential (Gernaat et al., 2017; Júnior et al., 2015; Lehner et al., 2005; Minville et al., 2009; van Vliet et al., 2016). Despite this progress, surprisingly little is known about how global warming under 1.5 and 2 °C scenarios will affect hydropower production, especially in terms of whether half a degree of warming will make a difference in this production. To our knowledge, reported comparisons of hydropower production under 1.5 and 2 °C global warming scenarios are rare (Tobin et al., 2018).

Nationally determined contributions (NDCs), which require each country to outline and communicate their post-2020 climate actions requested by the Paris Agreement, are critical to reaching global warming actions. NDCs reflect the efforts of individual countries to decrease national emissions and limit global warming levels. Notably, the NDCs accepted by each country in the United Nations Framework Convention on Climate Change (UNFCCC) have been evaluated under a global warming level of 2.6–3.1 °C (Rogelj et al., 2016). The Government of Indonesia promised a 29% unconditional reduction in emissions but then planned to deliver a reduction of 26% (Tacconi, 2018), which bodes ill for the Paris Agreement. Therefore, targets for reducing emissions in order to achieve a warming level of 1.5 or 2 °C by 2100 should be strengthened over time. In addition, hydropower, which is not only renewable but also clean energy, could contribute to reductions in GHG emissions by replacing fossil fuels and could help to achieve the NDCs. Thus, reducing GHG emissions will be significant for Indonesia.

Here, we investigated the influences of global warming levels of 1.5 and 2 °C on hydropower production in Sumatra using a coupled hydrological and techno-economic model framework. This study investigated the effects of 1.5 and 2 °C increases in global temperature on hydropower potential according to the global gridded projection of discharge provided by a state-of-the-art hydrological model (PCRaster GLObal Water Balance, PCR-GLOBWB). Then, we modeled and visualized optimal locations of hydropower plants in Sumatra based on hydropower potential using a techno-economic model. This approach allowed us to identify locations for hydropower plants by considering economic factors, which have seldom been considered in previous works (Garegnani et al., 2018; Sarzaeim et al., 2018). In addition, we discussed hydropower production based on select hydropower plants and the reduction in carbon emission by using hydropower instead of fossil fuels. This study could significantly contribute to establishing a basis for decision making on energy security under 1.5 and 2 °C global warming scenarios.

2. Materials and Methods

2.1. Study Area

Sumatra, extending from 6°1′S to 5°43′N and 195°8′ to 106°7′E, is the largest island located entirely in Indonesia and is vulnerable to global warming because of sea level rise (Figure 1). Sumatra is mountainous, and the elevation ranges from −54 to 3,668 m. The rainfall in Sumatra is approximately 4,000 mm/year (Supriyadi et al., 2017). The environmental conditions make Sumatra an ideal location for developing and utilizing hydropower resources. Sumatra's power demand is estimated to increase by approximately 9.5% per year from 2012–2030 (Hakam et al., 2012). Therefore, there will be a 2,000 MW gap between the present electricity output capabilities (2012: 1,549 MW) and demand in 2030 (3,493 MW). However, the installed hydropower capacity in Sumatra was only 1,062 MW in 2011 (Hakam et al., 2012). In addition to hydropower, Sumatra plays a vital role in the Indonesian electricity supply system as one of the largest energy

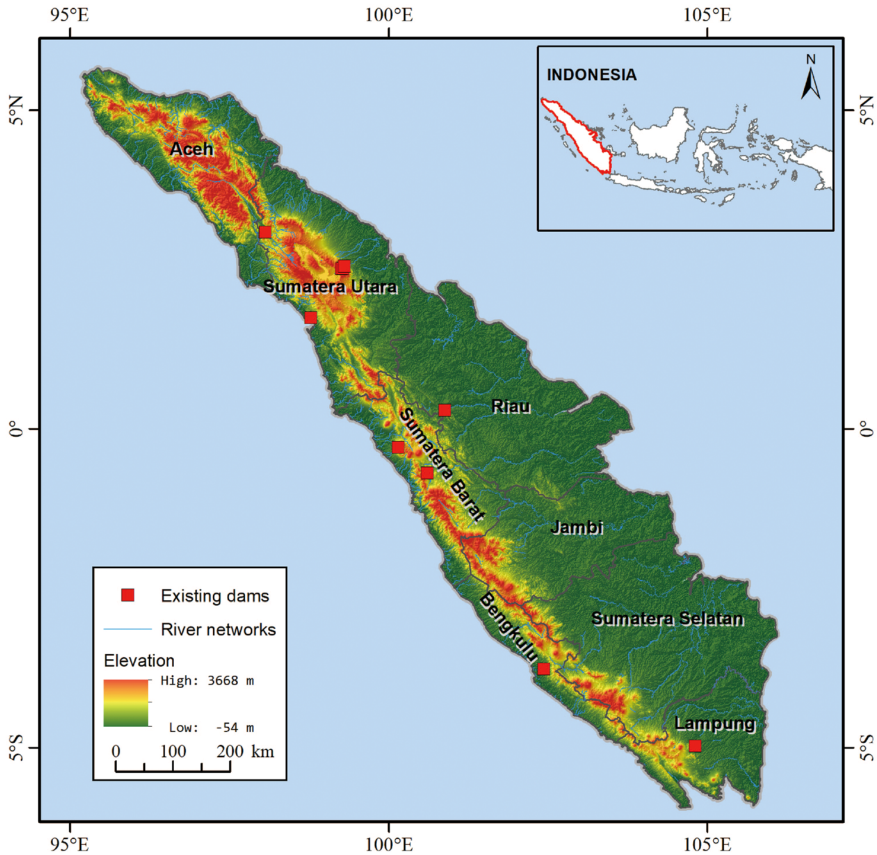

Figure 1. The location, relief, and existing dams of the Sumatra mainland.

sources in Indonesia including both fossil fuel and renewable energy such as geothermal and biomass (Hakam et al., 2012). Nevertheless, currently ~87% power generation in Sumatra is provided by fossil fuels such as coal, gas, and oil, which does not favor reduction in GHG emissions (Wiggins et al., 2018). Therefore, it is essential to consider the effects of different global warming levels on hydropower production to satisfy the increasing energy demand, particularly to assess whether half a degree of warming will make a difference in hydropower production. In addition, assessing the reduction in carbon emissions resulting from the use of hydropower instead of fossil fuel is another key question to be explored.

2.2. Model Description

The model framework is presented in Figure 2. The PCRaster GLOBal Water Balance model (PCR-GLOBWB) is a physically based large-scale hydrological model, suitable to simulated daily discharge at regional and global scales (Van Beek & Bierkens, 2008). The results simulated by PCR-GLOBWB are delivered by the Inter-Sectoral Impact Model Intercomparion Project (ISIMIP), a community-driven modeling attempt that brings together influential modelers across sectors and scales to create coherent and comprehensive projections of effects at different levels of global warming. Then, elevation and flow information, derived from hydrological data and maps based on shuttle elevation derivatives at multiple scales (HydroSHEDS) with a spatial resolution of 15 arc seconds (15″ × 15″, approximately 500 m × 500 m) (Lehner et al., 2008), are considered with discharge data. Finally, the results from the former models will be fed into the BeWhere model, a techno-economic engineering model to identify the optimal locations for hydropower plants under different global warming levels.

First, gross hydropower potential was calculated using discharge data and elevation data. Then, the gross hydropower potential, power demand, electricity grids, existing plants, investment in setting up new hydropower plants, the costs of operation and maintenance, and transmission distances in Sumatra were all considered in the BeWhere model (Figure 2). Among these factors, the power consumption and power

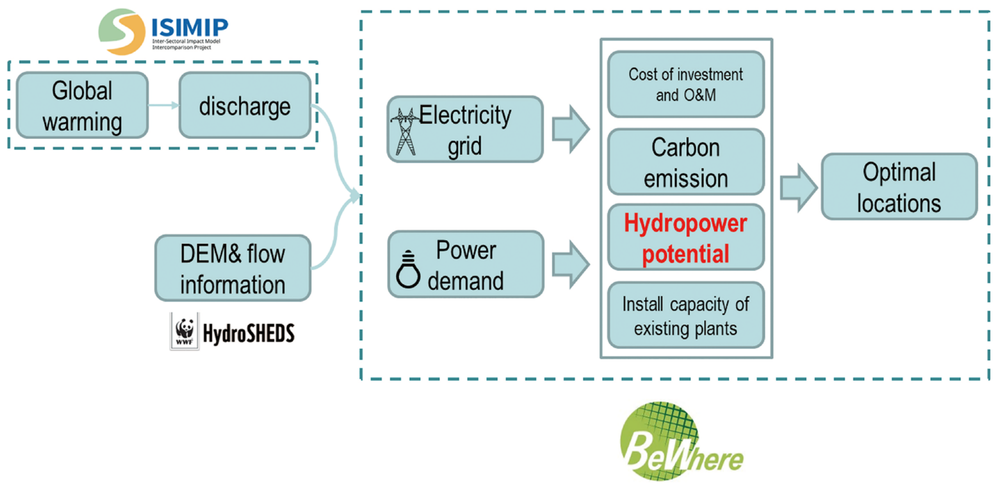

Figure 2. The framework for hydropower assessment.

production sites (electricity grids) were considered to be the two constraints driving the model. Power production sites are driven by the hydropower stations. The power consumption is driven by the consumers and is calculated based on the power consumption at the city level.

2.2.1. Hydropower Potential

The impacts of global warming on hydropower were quantified by changes in the indicator, the gross hydropower potential, which is an important input in the BeWhere model. We used a grid-based method to evaluate the gross hydropower potential (equation 1). The framework relied on discharge information from the global hydrologic model PCR-GLOBWB at a 0.5° × 0.5° (50 km × 50 km) resolution (Van Beek & Bierkens 2008) as well as from elevation and other flow information, such as river basin and flow direction information, derived from hydrological data and maps based on shuttle elevation derivatives at multiple scales (HydroSHEDS) at a 15″ × 15″ (500 m × 500 m) resolution (Lehner et al., 2008). The gross hydropower potential was estimated for each river grid cell using discharge and other flow information. To calculate the gross hydropower potential, discharge data from ISIMIP and elevation data from HydroSHEDS were resampled to the same resolution of 0.25° × 0.25° (25 km × 25 km), according to the requirements of the BeWhere model. Next, we computed the hydrological distance from each grid cell to the basin outlet, measuring along the downstream flow paths. Furthermore, we separately calculated the gross hydropower potential in different provinces of Sumatra under different global warming scenarios (global warming of 1.5 °C under RCP2.6, global warming of 1.5 °C under RCP6.0, and global warming of 2 °C under RCP6.0). The studied provinces distributed from northwest to southeast were Aceh, Sumatera Utara, Sumatera Barat, Riau, Bengkulu, Jambi, Sumatera, and Lampung.

$$P = \rho \cdot g \cdot \Delta H_i \cdot Q, \tag{1}$$

where P is the hydropower capacity (in W), ρ is the density of water (kg/m^3), g is the gravitational acceleration (m/s^2), ΔH_i is the difference in elevation between grid cell i and the lowest grid cell in the basin (m), and Q is the discharge (m^3/s). The maximum annual energy production was accomplished when 100% of the annual streamflow was exhausted for hydropower generation.

PCR-GLOBWB, the global hydrological model used in the study, is a physically based large-scale hydrological model, which is suitable for simulating daily discharge (m^3/s) at regional and global scales (Van Beek & Bierkens 2008). The meteorological forcing for PCR-GLOBWB was provided based on the Coupled Model Intercomparison Project (CIMIP5) outputs. To reduce uncertainties from meteorological forcing data, the bias-corrected climate forcing (Hempel et al., 2013) of four global climate models (GCMs) (HadGEM2-ES, MIROC5, IPSL-CM5A-LR, and GFDL-ESM 2 M) for both RCP2.6 and RCP6.0 was used because a large number of GCM outputs embody the uncertainties in climate models better than a low number of GCM outputs (Tebaldi & Knutti, 2007). We assumed the socioeconomic

Table 1
Costs of Economic Parameters

Parameters	Capital cost	Economic life time	Fixed operation &maintenance cost	Variable operation &maintenance cost
Unit	k$/kW	Years	$/GWh	$/MWh
Value	4.5–6.0[a]	25	0.03–0.185[b]	6[c]

[a]Averaged capital cost ranges for new hydropower plants. Typical capital cost assessments commonly vary between 4.5 and 6.0 k$/kW depending on the size of the hydropower plant. These values were averaged from estimated ranges of 2.5–10 k$/kW when the plant size was less than 1 MW, 2–7.5 k$/kW when the plant size was 1–10 MW, and 1.75–6.25 k$/kW when the plant size was larger than 10 MW. The capacity-levelized capital cost estimation of 3.5 k$/kW (with uncertainties of +35%) is described in Black&Veatch (2012) and lies within the above range. [b]The entire operation and maintenance cost (in $/GWh) for hydropower generation is an averaged range. The operation and maintenance cost may vary between 0.03 and 0.185 $/GWh based on the plant size. These costs were averaged from the estimation of 55–185 $/MWh when the plant size was less than 1 MW, 45–120 $/MWh when the plant size was 1–10 MW, and 40–110 $/MWh when the plant size was larger than 10 MW. The capital of the operation and maintenance cost for each new hydropower setup was evaluated in advance according to the river catchment potential of each demand area. [c]Variable operation and maintenance cost for hydroelectricity ($/MWh) (Black&Veatch, 2012).

conditions that started from 2005 onward were associated with RCP6.0 (no mitigation scenario under SSP2) and RCP2.6 (strong mitigation scenario under SSP2) (Frieler et al., 2017). SSP2 + RCP2.6 is the strong mitigation scenario closest to the global warming limits agreed on in Pairs, and SSP2 + RCP6.0 represents a no-mitigation baseline scenario (Fricko et al., 2017; Frieler et al., 2017). Seasonal variations in the amount of river discharge were not considered because seasonal variations will not influence the hydropower generation over the year (Gernaat et al., 2017).

2.2.2. Determination of 1.5 and 2.0 °C Global Warming Time Periods

According to the ensemble mean of multiple GCMs, global warming of 1.5 °C will occur in 2036 under RCP2.6 and in 2033 under RCP6.0, while global warming of 2 °C will only occur in 2056 under RCP6.0 (Frieler et al., 2017; Hu et al., 2017; Shi et al., 2018). The RCP2.6 emission pathway does not reach a 2 °C increase during the simulation period (van Vuuren et al., 2011). Therefore, we selected the discharges in 2036 and 2033 under RCP2.6 and RCP6.0 to calculate the hydropower potential under global warming of 1.5 °C and the discharges in 2056 under RCP6.0 for global warming of 2 °C. The period of 1971–2010 was extracted to represent the historical period.

2.2.3. BeWhere Model

Long-term planning energy system models are frequently used to assess the feasibility of realizing ambitions of renewable energies and the reduction of GHG emissions (Namany et al., 2019; Ringkjøb et al., 2018; Savvidis et al., 2019). Capacity expansion models have been used to explore the least-cost or integrated resource planning (Dagoumas & Koltsaklis, 2019; Lee et al., 2000; Luss, 1979) such as ReEDS (Cohen et al., 2019) and OsemoSYS (Howells et al., 2011). However, capacity expansion models typically do not explicitly consider power transmission and distribution network (Ahmad et al., 2016) and could not determine the optimal sites and sizes for new power plants, which are increasingly important to current electricity planning decisions (Temraz & Salama, 2002). Therefore, siting models have been developed for determining the optimal locations and sizes of new power plants at the minimum cost, for example, CERF (Vernon et al., 2018) and BeWhere (Leduc, 2009; Leduc et al., 2008; Leduc et al., 2010).

In this study, the BeWhere model was used to identify optimal locations for hydropower plants under different global warming levels (Leduc, 2009; Leduc et al., 2010; Mesfun et al., 2017). This model is based on a mixed integer linear program, written in GAMS and solved using the solver CPLEX. Earlier applications of the BeWhere model mainly concentrated on the planning and localization of biomass energy systems (Khatiwada et al., 2016; Natarajan et al. 2012; Wetterlund et al., 2012) but seldom considered hydropower energy systems (Mesfun et al., 2017, 2018).

The input data in our study were considered at a grid level at a 25 km × 25 km spatial resolution. The model was run daily for the period of 1971–2010, which represents the historical period. The climate warming periods (1.5 and 2 °C) compared with preindustrial periods were selected for each simulation according to the ISIMIP modeling results (Frieler et al., 2017). The overall objective was to minimize the entire cost (C_{tot}) of the overall energy supply chain according to the following expression:

$$C_{tot} = C_{supply\ chain} + E_{supply\ chain} C_{CO_2}, \quad (2)$$

where $C_{supply\ chain}$ is the supply chain cost, $E_{supply\ \mathrm{chain}}$ is the supply emissions, and C_{CO2} is the cost of

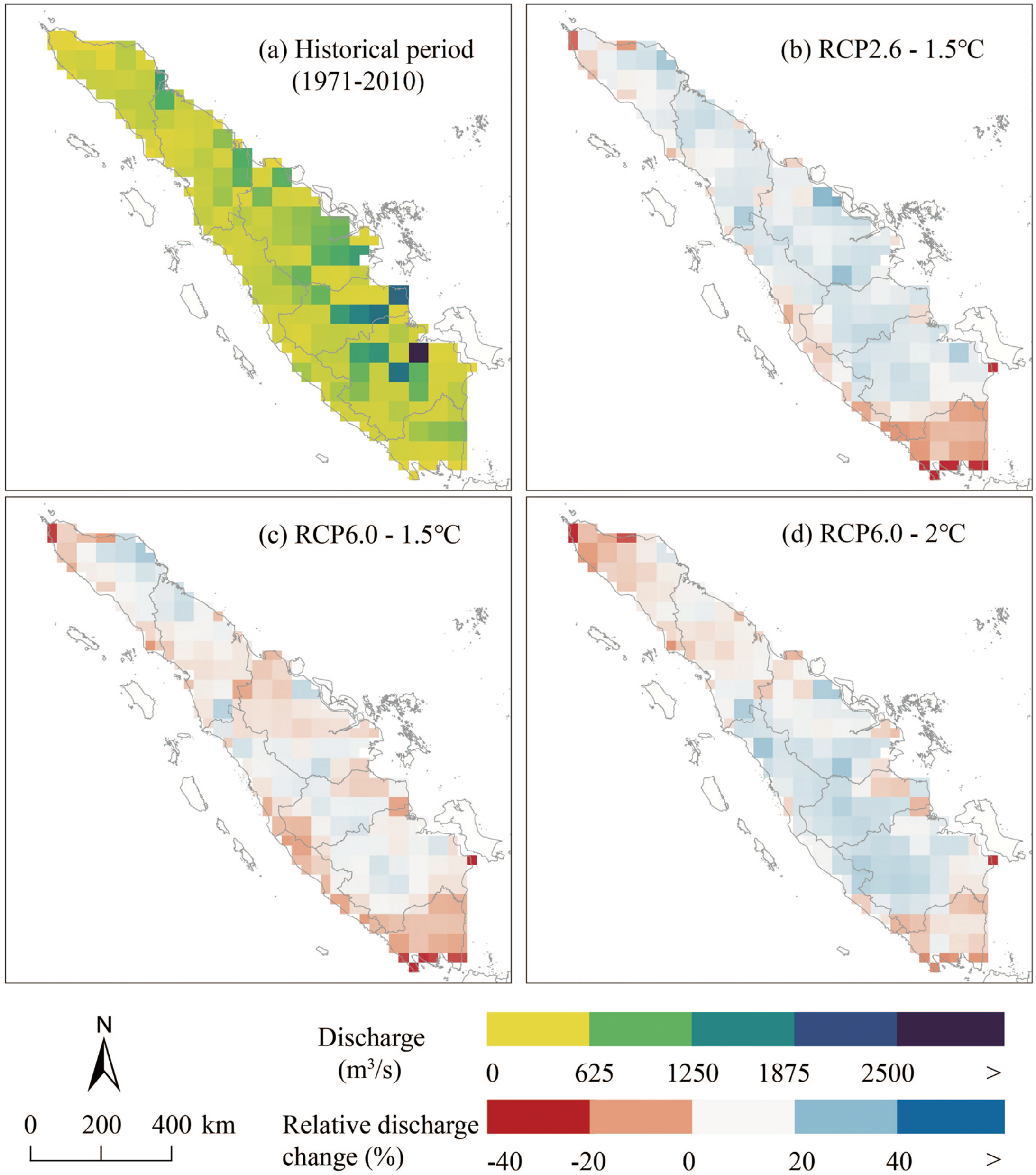

Figure 3. Daily mean discharge (m^3/s) simulated by PCR-GLOBWB for the historical period (1971–2010), and the differences in the daily mean discharge between the historical period and the 1.5 and 2 °C scenarios.

emitting CO_2. The supply chain cost $C_{supply\ \mathrm{chain}}$ accounts for the setup, operation, and maintenance costs of hydropower plants and transmission distances. The supply chain emissions $E_{supply\ \mathrm{chain}}$ include the emissions of fossil CO_2 from fossil-based power.

The first step of the BeWhere model was to find the existing hydropower capacities and the hydropower potential for new installations, which were calculated in section 2.2.1. In the second step, the model needed to satisfy the power demand in the study area as much as possible using the lowest costs or provide as much hydropower generation as possible based on the existing electricity grids using the lowest costs. Thus, power production sites and power consumption were considered as the two constraints driving the BeWhere model. According to these two constraints, we had to find the shortest transmission distance between the available potential hydropower and the existing electricity grids. In the model, hourly generation from hydropower is obtained by averaging the estimates over the total number of hours in a year. Furthermore,

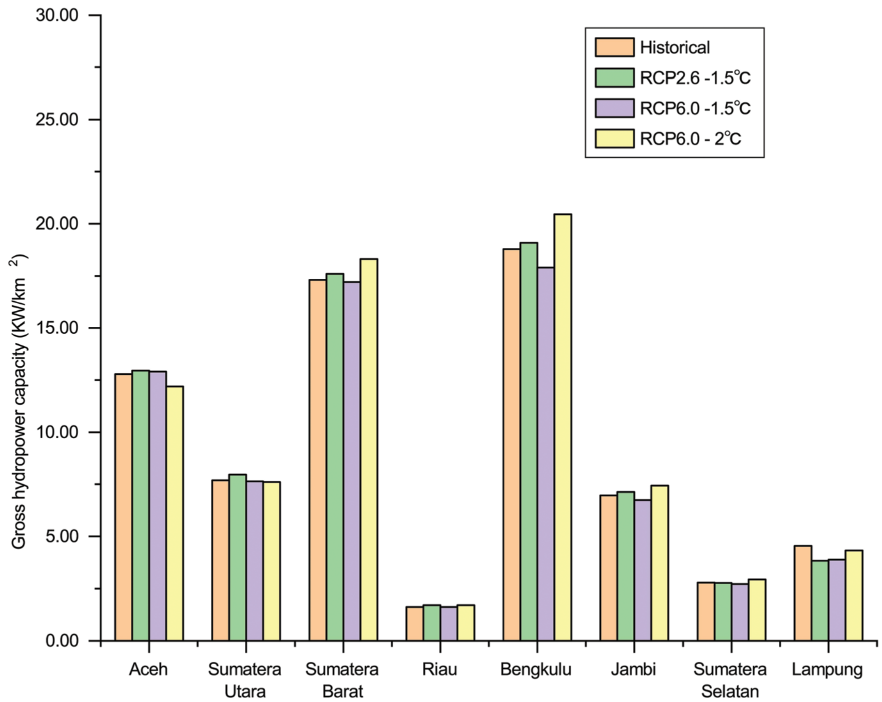

Figure 4. Average of gross hydropower capacity in different provinces of Sumatra under the historical period and under global warming levels of 1.5 and 2 °C.

the model considered investments in the setup of new hydropower plants and the costs of operation and maintenance in Sumatra.

Here, we assumed that hydropower would replace fossil fuels at a 1:1 energy ratio and that hourly hydropower production can be determined by averaging the hourly estimates of all hours in 1 year. Thus, each MWh of hydropower production displaces 685 kg of CO_2 (Herbert et al., 2005). The potential costs for a new hydropower plant are shown in Table 1.

3. Results

3.1. Distribution of Daily Mean Discharge

Figure 3 provides an overview of the simulated historical discharge and the changes in the PCR-GLOBWB simulated discharge resulting under the 1.5 and 2 °C scenarios based on the average discharge results from the four GCMs. Changes in discharge are mainly caused by trends in future climate patterns, such as changes in precipitation and temperature (Biemans et al., 2009; Liao et al., 2012). High discharges are distributed in the southeast of Sumatra during the historical periods. A decreasing discharge trend occurs in large parts of Sumatra under the RCP2.6–1.5 °C scenario (shown in Figure 3a). The area with a decreasing discharge trend in the RCP6.0–1.5 °C scenario is less than that in the RCP2.6–1.5 °C scenario. The decreasing trend occurs in the northwestern and southeastern parts of Sumatra (Figures 3b and 3c). The decreasing trend is concentrated in the southeast of Sumatra under the RCP6.0–2 °C scenario, where the discharge value is highest (Figure 3d). For the comparison of the whole area with the historical period, the mean discharge value increases by 13.56%, 9.60%, and 15.20% under the RCP2.6–1.5 °C, RCP6.0–1.5 °C, and RCP6.0–2 °C scenarios, respectively. The discharge shows an increasing trend in most areas in Sumatra, and the magnitude of discharge increases is far larger than that discharge decreases.

3.2. Gross Hydropower Potential

For the whole island of Sumatra, the total gross hydropower potential is 3,096, 3,127, 3,037, and 3,158 MW under the historical period and the RCP2.6–1.5 °C, RCP6.0–1.5 °C, and RCP6.0–2 °C scenarios, respectively. Figure 4 shows the gross hydropower potential per square kilometer for each province of Sumatra. The gross

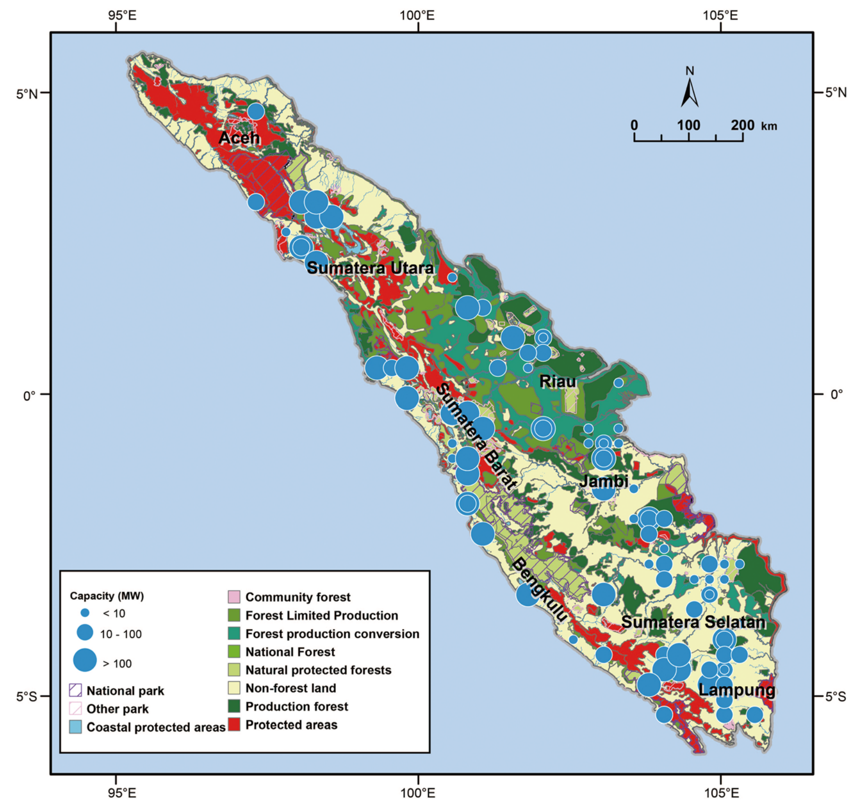

Figure 5. Sites for hydropower plants optimized by the BeWhere model.

hydropower potential shows uneven spatial patterns in different provinces, and it gradually decreases from the northwest to southeast. A comparison of the average gross hydropower capacities of different provinces indicates that provinces located in mountainous areas often have high gross hydropower capacity (such as Aceh, Sumatera Utara, Sumatera Barat, and Bengkulu) due to significant elevation differences. The potential in most provinces, except for Aceh and Sumatera Utara, which are located at the inlet of Sumatra, increases when global warming levels increase. Moreover, the hydropower potential is 0.05–1.19 kW/km^2 greater under the RCP2.6–1.5 °C scenario than under the RCP6.0–1.5 °C scenario in all provinces except Lampung. Furthermore, the hydropower potential is 0.09–2.55 kW/km^2 greater under the RCP6.0–2 °C scenario than under the RCP6.0–1.5 °C scenario, except in Aceh and Sumatera Utara.

3.3. Optimal Locations for Hydropower Plants

All sites suitable for potential hydropower plants simulated by the BeWhere model under different global warming scenarios are presented in Figure 5. Blue circles represent the sites suitable for hydropower plants, and the circle size indicates the capacity of the hydropower plants. Because the location is purely based on the hydropower potential and costs of investment, operation, and maintenance, a few hydropower plants are located on protected areas such as national parks and natural protected forests. We removed these sites manually and obtained the optimal locations for hydropower plants, as indicated by the red circles in Figure 6.

Figure 7 shows that the sites for hydropower plants driven by the power production sites are concentrated in the mountainous areas. In contrast, sites driven by the power demand are distributed in the southeast of Sumatra, where the power demand is larger than that in mountainous areas. The potential capacities driven by the power production sites are larger than those driven by the power demand. As the global warming levels increase under RCP6.0, the magnitude of optimal hydropower plants first increases when the temperature reaches 1.5 °C but decreases as the temperature approaches to 2 °C. In addition, the optimal number of hydropower plants under the RCP2.6–1.5 °C scenario is higher than that under the RCP6.0–1.5 °C

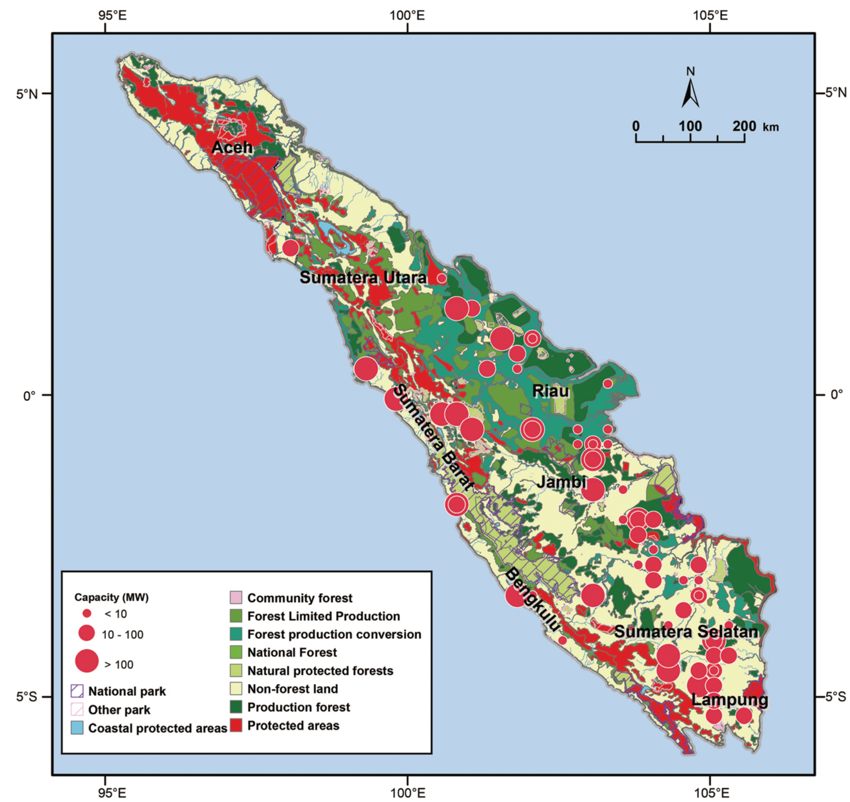

Figure 6. Optimal sites for hydropower plants excluding protected areas.

scenario, but the total potential capacity simulated under the RCP2.6–1.5 °C scenario is higher than that simulated under the RCP6.0–1.5 °C scenario.

3.4. Economic Production of Potential Hydropower Plants

Figure 8 shows the hydropower generation driven by the power demand or power production sites under different global warming scenarios. The total production can meet 94.88%, 94.83%, 94.92%, and 94.83% of the power demand under the historical period and the RCP2.6–1.5 °C, RCP6.0–1.5 °C, and RCP6.0–2 °C scenarios, respectively, when driven by the power production sites. However, excluding protected areas, the total production can only meet 11.92%, 56.88%, 54.26%, and 14.17% of the power demand for the same scenarios, representing decreases of 40–80%. Moreover, the total production driven by the power demand is far less than that driven by the power production sites and can meet 1.08%, 4.03%, 4.99%, and 3.27% of the power demand respecting the scenarios listed above; these percentages are less than half of the corresponding values for production driven by the power production sites. When protected areas are excluded, these values decrease to 0.94%, 2.57%, 3.90%, and 3.07%, respectively. Obviously, the hydropower generation increases with all levels of global warming but increases more under the 1.5 °C warming scenarios than under 2 °C warming scenarios. For example, under RCP2.6–1.5 °C and RCP6.0–1.5 °C scenarios, total production can meet 56.88% and 54.26%, respectively, of the power consumption driven by the power production sites, excluding protected areas. These percentages are 44.96% and 42.34% higher than the values of 11.92% for the historical period. However, under the RCP6.0–2 °C scenario, the total production can meet 14.17% of the power demand, which is 2.22% higher than the percentage for the historical period.

4. Discussion

4.1. Effects of Global Warming on Hydropower Production

Our results show that global warming will have a positive effect on the economic hydropower production in Sumatra compared to the historical period, regardless of the warming level; however, the

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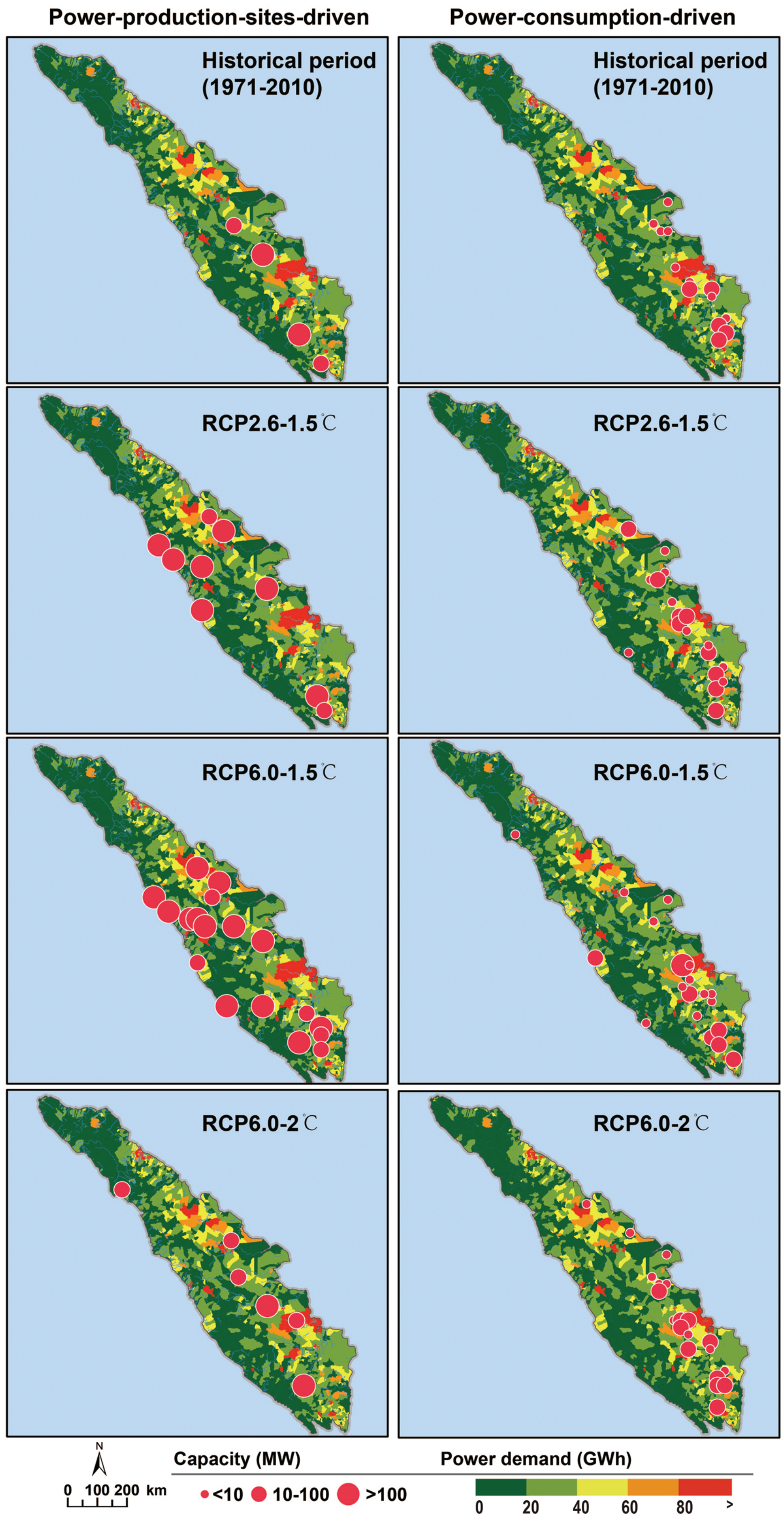

Figure 7. Optimal sites for hydropower plants outside protected areas driven by the power production sites and power demand under different global warming scenarios.

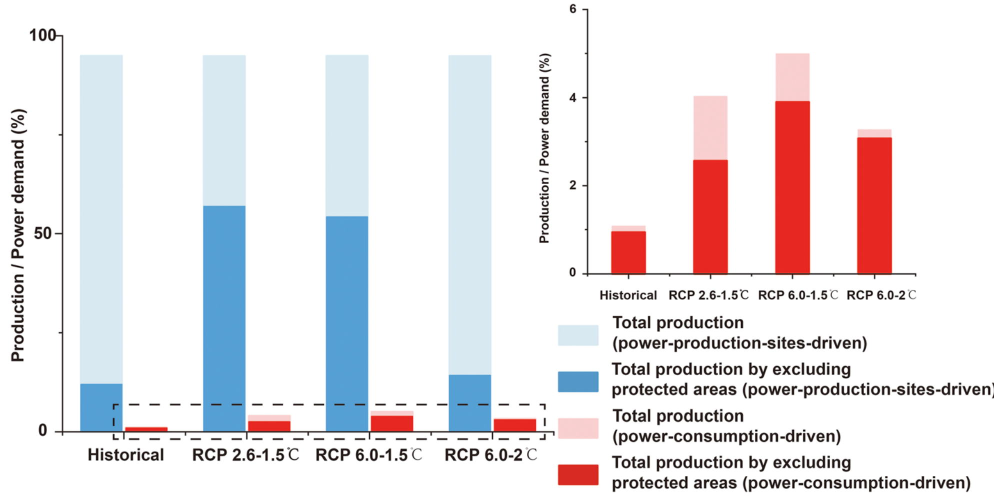

Figure 8. Generation of potential hydropower plants under the historical period and under the RCP2.6–1.5 °C, RCP6.0–1.5 °C, and RCP6.0–2 °C scenarios. Blue indicates the results from the model driven by the power production sites; red indicates the results from the model driven by the power consumption.

hydropower production under a global warming of 1.5 °C is more than that under a global warming of 2 °C (Figure 8). This result is not consistent with the discharge and hydropower potential trends under different global warming scenarios. The discharge quantity and hydropower potential will increase with global warming. This inconformity occurred because the present study selected sites for hydropower plants by considering not only hydropower potential but also economic factors. The study selected the hydropower plants according to the minimum cost of the complete energy supply chain. The objective function that is minimized includes the costs for hydropower production, hydropower transportation, hydropower plant investment and operation, distribution of end generations to energy demand areas, and CO_2 emission cost (Leduc, 2009; Leduc et al., 2010; Mesfun et al., 2017). As a result, the power generation by hydropower plants showed incongruous changing trends with hydropower potential under the same global warming levels. The distributions of discharge and hydropower potential are uneven, causing the above described inconformity. In addition, hydropower generation driven by the power production sites meets the energy demands more easily than that driven by the power demand. There are some electricity grids distributed in mountainous areas, where the hydropower potential is great due to high elevation differences. Thus, the results driven by the power production sites will choose hydropower plants with high capacities in mountainous areas. However, lowlands, where the hydropower potential is low, have a high value of power demand. Therefore, the results with low hydropower capacities driven by the power demand are concentrated on plains (shown in Figure 7). The actual hydropower generation could be influenced by fossil fuel and carbon price. Accordingly, the hydropower generation increases with increasing fossil fuel and

Table 2
Gross Hydropower Potential in Different Provinces of Sumatra Under the Historical Period and Global Warming Levels of 1.5 and 2 °C (units: kW/km^2)

Scenarios	Aceh	Sumatera Utara	Sumatera Barat	Riau	Bengkulu	Jambi	Sumatera Selatan	Lampung
Historical period	12.79	7.69	17.30	1.61	18.78	6.97	2.80	4.55
RCP2.6–1.5 °C	12.97	7.96	17.60	1.69	19.09	7.14	2.76	3.84
RCP6.0–1.5 °C	12.91	7.64	17.20	1.61	17.89	6.76	2.71	3.88
RCP6.0–2 °C	12.20	7.60	18.30	1.70	20.45	7.43	2.93	4.33
[a]RCP2.6-1.5 °C - RCP6.0–1.5 °C	0.05	0.33	0.40	0.08	1.19	0.37	0.05	−0.05
[b]RCP6.0-2 °C - RCP6.0–1.5 °C	−0.71	−0.03	1.10	0.09	2.55	0.66	0.22	0.44

[a]the difference between RCP2.6–1.5 and RCP6.0–1.5 °C scenarios. [b]the difference between RCP6.0–2 and RCP6.0–1.5 °C scenarios.

Table 3
Generation of Potential Hydropower Plants Under the Historical Period and Under the RCP2.6–1.5 °C, RCP6.0–1.5 °C, and RCP6.0–2 °C scenarios (Units: %)

Scenarios	Total production (power-production-sites-driven)	Total production without protected area (power-production-sites-driven)	Total production (power-consumption-driven)	Total production without protected area (power-consumption-driven)
Historical period	99.88	11.92	1.08	0.94
RCP2.6–1.5 °C	94.83	56.88	4.03	2.57
RCP6.0–1.5 °C	94.92	54.26	4.99	3.90
RCP6.0–2 °C	94.83	14.17	3.27	3.07

carbon price (Mesfun et al., 2017). In our study, we mainly assessed the potential hydropower production not the actual hydropower production. The fossil fuel effects on our results are moderate. The sensitivity of fossil fuel cost on our results are presented in Text S4 in the supporting information.

We used the gross hydropower potential to evaluate the hydropower generation in Sumatra, which is different from the technical, economic, and exploitable potentials (Hoes et al., 2017; Zhou et al., 2015). According to Eurelectric (1997) and Zhou et al. (2015), the gross hydropower potential is defined that all natural discharges at all locations are used for hydropower production; the technical hydropower potential represents the hydropower capacity that is readily available under current technology; the economic and exploitable hydropower potentials are calculated based on the technical hydropower potential considering the economic and environmental restrictions, respectively. All technical, economic, and exploitable hydropower potentials incorporate practical design considerations, which strongly vary depending on local conditions (Hoes et al., 2017), and there is no absolute limit on what could be technically deployed (Lehner et al., 2005; Zhou et al., 2015). Therefore, we focus on the gross hydropower potential in our study, which may overestimate the hydropower potential generation in Sumatra. However, we pay more attention to the differences in hydropower generation under global warming of 1.5 and 2 °C. We consider the economic factors and protected areas when selecting the optimal hydropower sites for calculating the hydropower generation, which partially offsets the overestimation caused by using gross hydropower potential.

4.2. Reduction in CO_2 Emissions Using Hydropower Instead of Fossil Fuels

Hydropower, as a clean and renewable energy, could reduce the emission of CO_2 by replacing fossil fuels. The reduction of CO_2 emissions based on the generation of potential hydropower plants in Sumatra is shown in Table 2. The maximum CO_2 emission reduction is approximately 68 Mt and is driven by the power production sites before the removal of the hydropower plants in protected areas. The reduction in CO_2 emissions driven by the power demand is approximately 8.58–40.95 Mt and is less than that driven by the power production sites. The CO_2 emission reduction driven decreased considerably by excluding protected areas, with a drop decline of approximately 0.68–3.59 Mt. Notably, the Government of Indonesia has voluntarily committed an unconditional reduction of 453.2 Mt CO_2 in the energy sector in Indonesia's NDCs. The maximum reduction in our results (68.34 Mt CO_2) will only

Table 4
Reductions in CO_2 Emissions Under Different Global Warming Scenarios

Global warming scenarios	Power production sites		Power consumption	
	Reduction of CO_2 emissions (10^6 t)	Reduction of CO_2 emissions after excluding protected areas (10^6 t)	Reduction of CO_2 emissions (10^6 t)	Reduction of CO_2 emissions by excluding protected areas (10^6 t)
Historical period	68.31	0.77	8.58	0.68
RCP2.6–1.5 °C	68.27	2.90	40.95	1.85
RCP6.0–1.5 °C	68.34	3.59	39.06	2.81
RCP6.0–2 °C	68.27	2.35	10.20	2.21

contribute to only 15% of the carbon emission target. Although Sumatra is only one of the islands of Indonesia, the influence of protected areas in this island is notable in terms of achieving Indonesia's NDCs.

5. Conclusions

We evaluated the impacts of 1.5 and 2 °C of global warming on gross hydropower potential using the PCR-GLOBWB global hydrological model and identified the optimal locations suitable for potential hydropower plants using the BeWhere model to assess hydropower contribution to energy security. We found that both global warming levels will have a positive impact on the hydropower production of a tropical island (Sumatra) relative to the historical period; however, the ratio of hydropower production versus power demand provided by 1.5 °C of global warming is 40% higher than that provided by 2 °C of global warming under RCP6.0. Moreover, the maximum carbon emission reduction in Sumatra will contribute to 15% of the energy sector of Indonesian NDCs. The reduction in CO_2 emissions under global warming of 1.5 °C (39.06×10^6 t) is greater than that under global warming of 2 °C (10.20×10^6 t), which reveals that global warming decreases the benefits necessary to relieve global warming levels. Furthermore, the hydropower generation will be far less than the energy demand after protected areas are excluded, with a sharp decrease of 40–80%. Thus, decision makers from the Government of Indonesia should consider the trade-offs between hydropower generation and environmental conservation in NDCs.

The assessment of the impacts of global warming levels on hydropower potential used only one global hydrological model at a 0.5° × 0.5° (50 km × 50 km) resolution. The analysis would benefit from the inclusion of more global hydrological models and a higher spatial resolution to reduce uncertainties. In addition, our simulated results are mainly driven by power production sites and power consumption in this approach and did not consider the other services, such as flood control and water supply, provided by reservoirs. This will underestimate the benefits brought by setting hydropower dams. And it would be considerate to replenish more functions of hydropower dams in the further work, which could provide more additional benefits with hydropower development for decision makers (Singh, 2015). Furthermore, the consideration of geological conditions was missing due to a lack of information. A more solid analysis could benefit from multiple models and the investigation of local geological condition. This study only focuses on hydropower potential, while including the other renewable energy technologies (e.g., wind and solar) would not virtually affect the estimation of the hydropower capacity, as it does not compete for common resources and can be used for peak time hours (Anderson et al., 2006). It is indeed a more flexible and stable technology than other renewable energy technologies (Carvajal & Li, 2019). A consideration of the other technologies and renewable resource mix would benefit the whole energy system in the further work (Mesfun et al., 2017). Moreover, our assessment focuses on the difference of hydropower potential generated by natural flows. However, regulating flows particularly over multiple reservoirs and in times coincident with the demand will contribute to the generation, so it deserves more studies on optimization and adaptation under climate change in the future (Ho et al., 2017). Including the new dams will help in the water storage for upcoming increases in power demand and at the same time have some major impact on the local environment (Poff & Schmidt, 2016; Siciliano et al., 2018). However, limited by the technical method, we cannot implement the new dams, as other study cases did (Gernaat et al., 2017; Mesfun et al., 2017).

Notwithstanding these limitations, our study synthetically considered the impacts of global warming levels on hydropower potential and carbon emissions using a combined GHM with a techno-economic model. At the same time, we provide the economic-based optimal hydropower sites in Sumatra under different global warming scenarios. The results could facilitate governmental decisions to fight global warming and increase energy demand. Our results illustrate the tension between GHG-related goals and ecosystem conservation-related goals by considering the trade-off between the protected areas and hydropower plant expansion. Furthermore, our results can be an important basis for a large range of follow-up studies, for example, to investigate the trade-off between forest conservancy and hydropower development, to contribute to NDC achievement.

Acronyms

List of symbols

ρ	density of water
C_{CO2}	cost for emitting CO_2
$C_{supply\ chain}$	supply chain cost
$E_{supply\ chain}$	supply emissions
C_{tot}	total cost
g	gravitational acceleration
ΔH_i	elevation difference
P	hydropower capacity
Q	discharge

Acronyms

CIMIP5	Coupled Model Intercomparison Project
GAMS	General Algebraic Modeling System
GCMs	Global Climate Models
GHG	Greenhouse Gas
IIASA	International Institute for Applied Systems Analysis
IPCC	Intergovernmental Panel on Climate Change
ISIMIP	Inter-Sectoral Impact Model Intercomparion Project
MILP	Mixed Integer Linear Programming
NDCs	Nationally Determined Contributions
O&M	Operation and Maintenance
PCR-GLOBWB	PCRaster GLObal Water Balance
RCPs	Representative Concentration Pathways
UNFCCC	United Nations Framework Convention on Climate Change

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