Chapter 5

A resilient energy system to climate change

COORDINATOR

Manh-Hung Nguyen [TSE, INRAE]

CONTRIBUTORS

Manh-Hung Nguyen [TSE, INRAE]
Chon Van Le [IREEDS]
Minh-Bao Nguyen [IE]
Thu Ha Nguyen [Thuyloi University]
Tien Viet Nguyen [IREEDS]
Hong Xuan Do [Nong Lam University]
Etienne Espagne [AFD]

Abstract

Chapter 5 analyses the sensitivity of Viet Nam's energy system — including both demand and supply sides — to weather conditions, projects the potential impact of climate change and proposes adaptation strategies. Key results confirm the significant effect of fluctuations in weather factors such as precipitation and temperature on residential, commercial and industrial energy demand, and hydropower generation. One additional degree Celsius is estimated to increase household electricity consumption by 4.86 per cent and firms' energy demand by 4.31 per cent. In addition, climate change would introduce a great deal of uncertainty into hydropower generation, which currently accounts for a significant part of Viet Nam's energy production. Our projections under RCP4.5 and RCP8.5 for the 2017–2050 period using the Low Emissions Analysis Platform (LEAP) suggest climate change would cumulatively raise electricity demand by US$ 4,227.5–7,675.3 million, and emissions by 161.9–288.3 MtCO2e. Close monitoring, early planning, and prompt response measures based on strengthened scientific and technological capability are recommended, to cope with the various impacts of climate change on the energy system.

Tóm tắt

Chương 5 phân tích mức độ nhạy cảm của hệ thống năng lượng Việt Nam, bao gồm cả phía cung và cầu, đối với các điều kiện thời tiết, dự báo khả năng tác động của biến đổi khí hậu và đề xuất các chiến lược ứng phó. Các kết quả chính cho thấy sự biến động của các yếu tố thời tiết như lượng mưa và nhiệt độ đối đã ảnh hưởng đáng kể đến nhu cầu năng lượng khu vực hộ gia đình, thương mại và công nghiệp và sản xuất thủy điện. Ứng với mỗi độ C tăng thêm ước tính sẽ làm tăng mức tiêu thụ điện trong các hộ gia đình lên 4,86% và nhu cầu năng lượng của các doanh nghiệp lên 4,31%. Ngoài ra, biến đổi khí hậu sẽ gây ra nhiều bất ổn cho việc sản xuất thủy điện, hiện đang chiếm một phần đáng kể trong sản xuất năng lượng của Việt Nam. Các kết quả dự báo theo mô hình phân tích phát thải thấp (LEAP) trên cơ sở các kịch bản RCP4.5 và RCP8.5 cho thấy biến đổi khí hậu sẽ làm tăng thêm tổng nhu cầu điện, tương ứng với 4.227,5–7.675,3 triệu đô la Mỹ và 161,9–288,3 triệu tấn CO2e phát thải tích lũy cho cả giai đoạn 2017–2050 . Từ đó đề xuất các khuyến nghị như: giám sát chặt chẽ, lập kế hoạch sớm và các biện pháp ứng phó kịp thời dựa trên việc tăng cường năng lực khoa học và công nghệ để đối phó với các tác động khác nhau của biến đổi khí hậu đối với hệ thống năng lượng.

Résumé

Le chapitre 5 analyse la sensibilité du système énergétique vietnamien — tant du côté de la demande que de l'offre — aux conditions météorologiques. Il projette l'impact potentiel du changement climatique et propose des stratégies d'adaptation. Les principaux résultats confirment l'effet significatif des fluctuations des facteurs météorologiques tels que les précipitations et la température sur la demande d'énergie résidentielle, commerciale et industrielle, ainsi que sur la production d'hydroélectricité. On estime qu'un degré Celsius supplémentaire augmente la consommation d'électricité des ménages de 4,9% et la demande d'énergie des entreprises de 4,3%. En outre, le changement climatique introduirait une grande incertitude dans la production d'hydroélectricité, qui représente actuellement une part importante de la production énergétique du Viet Nam. Selon nos projections dans le cadre des scénarios RCP4.5 et RCP8.5 pour la période 2017–2050, réalisées à l'aide du modèle LEAP, le changement climatique entraînerait une augmentation cumulée de la demande d'électricité de 4 227,5 à 7 675,3 millions de dollars américains, et des émissions de 161,9 à 288,3 MtCO2e. Il est recommandé d'assurer une surveillance étroite, une planification précoce et des mesures de réaction rapide fondées sur le renforcement des capacités scientifiques et technologiques, afin de faire face aux différents impacts du changement climatique sur le système énergétique.

1. Introduction

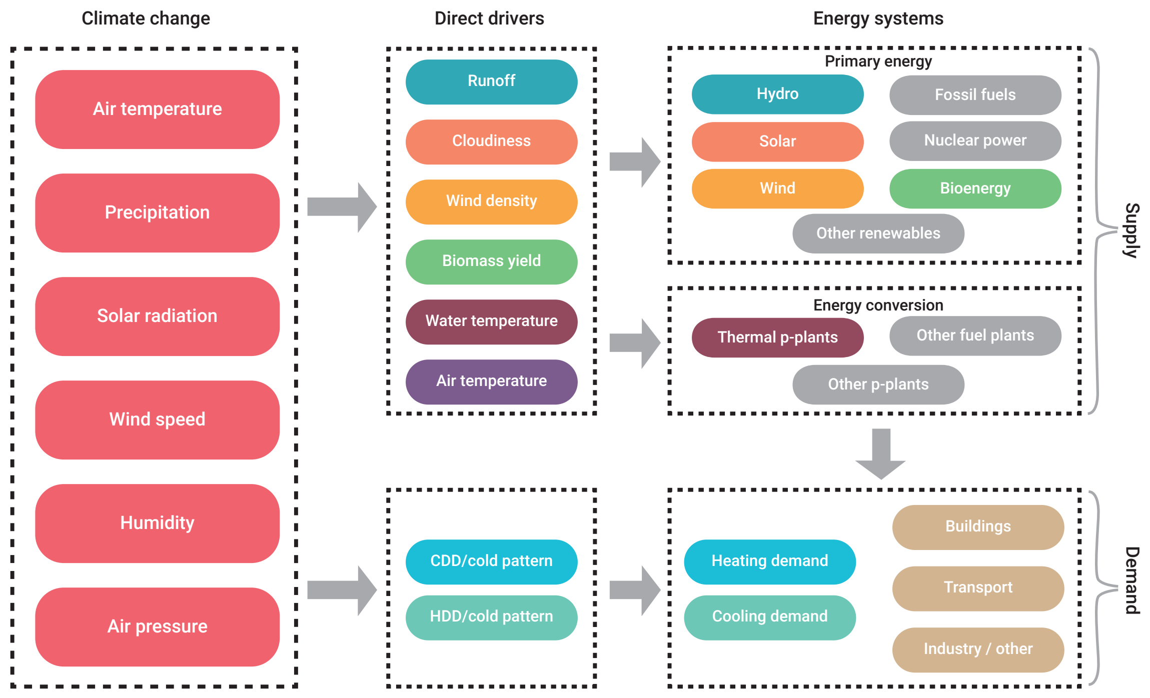
In general, there is a strong connection between energy consumption and economic development. Viet Nam could serve as a prominent example. It has been "one of the best-performing economies in the world over the past decade" [WB, 2011], and maintained a GDP per capita growth rate second only to China [WB and MPI, 2016]. Rising power demand has accompanied economic growth. Viet Nam's impressive average annual growth rate of 7.5% between 1995 and 2005 coexisted with a growth rate of 15% in demand for energy [Huu, 2015]. In terms of equity, Viet Nam succeeded in reducing its poverty rate from 58% in 1993 to under 6% (US$3.2/day PPP) [World Bank, 2021]. In parallel, the proportion of households with access to electricity has risen substantially from under 2.5% in 1975 to 99% by 2016, comparable to higher average to upper middle-income countries like China or Thailand [World Bank, 2021]. In 2014, off-grid households accounted for less than 2%, and just under 3% reported unmet electricity needs [Ha-Minh and Nguyen, 2017].

Projections suggest that Viet Nam's thirst for energy will continue to fuel its ambition of economic development and improve the living standards of its people. The baseline scenario of Power Development Plan VIII forecasts national power demand to reach 491.3 TWh by 2030, and 877.1 TWh by 2045 [IE, 2021]. These figures compare to 210.5 TWh in 2019. Meanwhile, per capita energy consumption is projected to increase to 4,588 kWh by 2030 [IE, 2021], from 985 kWh in 2010 [ADB, 2013]. The strong link between energy consumption and economic development in the past implies that a failure to satisfy energy demand may hinder or even reverse the development achieved. It has been shown that during its development progress, robust performance in Viet Nam has become more sensitive to power unreliability [Elliott *et al.*, 2021]. A reliable energy development strategy associated with thorough consideration of energy sources is pivotal to the country's development.

Le (2019) found that the elasticity of electricity to GDP (growth rate of electricity consumption/ GDP growth rate) in Viet Nam is between 1.5 and 2: remarkably high compared to other countries at a similar level of development. This is reasonable, since in the initial stage of economic development, energy-intensive industries are likely to grow faster. However, they will give way to low-energy, high-efficiency industries in the future, when the economic structure changes.

In assessing climate change's impacts on energy systems, Yalew *et al.* (2020) proposed a conceptual framework based on previous studies. Figure 5.1 shows different elements of climate change that can directly influence various sources of energy supply, such as hydro, solar, wind, fossil fuels, nuclear power and bioenergy, and energy demand for heating and cooling purposes. In Viet Nam, coal, hydropower, and natural gas are the most important primary energy sources, accounting for 98.1% of total electricity production [Figure 5.2]. Of these three sources, hydropower generation is supposed to be most directly affected by climate change. Changes in precipitation and seasonal patterns due to climate change, especially extreme weather events, can result in reduced precipitation (or water flow) in dry seasons and reduced water level in reservoirs in almost all regions. This could in turn reduce capacity utilization of hydropower generation facilities. Consequently, as regards energy supply, this chapter confines itself to hydropower generation

[Figure 5.1]
Conceptual framework to assess climate change impacts on energy system



Source: Yalew *et al.*, 2020.

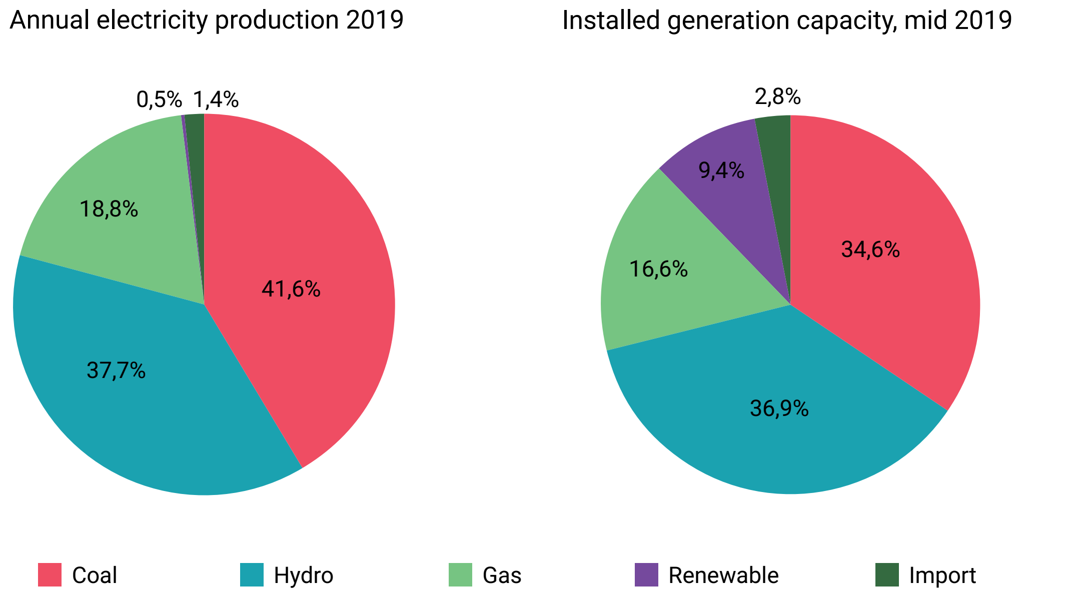
Up to now, 100% of all communes and 99.6% of all households in Viet Nam have access to the national electricity grid. In addition, increasing income and the rapid popularization of electrical home appliances has increased electricity demand among households and firms considerably. Climate change in the form of rising temperature and weather extremes will strongly impact residential electricity demand: mainly electricity consumption for air conditioners, refrigerators and electric fans.

Therefore, the objectives of this study are to evaluate the impact of climate change on electricity demand, hydropower production, and the whole energy system up to 2050 in its economic and environmental aspects and to propose measures to cope with this impact.

A range of different approaches or methods can be used to assess climate change impacts. These include quantitative and predictive models, empirical studies, expert judgment, and experimentation. Each of these approaches has its own advantages and weaknesses, and a good strategy may be to use a combination of approaches in different parts of the assessment or at different stages of the analysis .

Our study will first employ quantitative methods to evaluate impacts of climate change on electricity demand for both household cooling and manufacturing firms' consumption

[Figure 5.2]
Electricity production and installed capacity by source, 2019



Source: GIZ energy support programme, 2019.

of electricity, and on hydropower production. To assess the impacts on the whole energy system, we shall develop several scenarios for comparison. We start with the Business As Usual (BAU) Scenario that outlines future energy consumption, assuming no impacts from climate changes. Then, under the Viet Nam Climate Change and Sea-level Rise Scenarios (hereafter referred to as climate change scenario), typical studies on the impacts of climate change on electricity demand and hydropower plants are used to develop scenarios for climate change impacts (CCI). In this study, the Low Emissions Analysis Platform (LEAP) is used as a tool to analyse and quantify the impacts of climate change on Viet Nam's energy system. LEAP is flexible and can be used to create models of different energy systems based on available data, ranging from bottom-up, end-use techniques, to top-down approaches. Moreover, LEAP is also used to evaluate costs and benefits for different policy strategies on both demand and supply sides, to deal with the impacts of climate change on the energy system in Viet Nam.

This chapter is structured as follows. Sections 2 and 3 provide a separate assessment of climate change's impacts on electricity demand and hydropower production, respectively. Section 4 presents a comprehensive (integrated) evaluation of the energy system under different scenarios. In Section 5, several measures are proposed with associated social costs and benefits. Conclusions and recommendations are in Section 6.

2. Assessment of climate change's impacts on electricity demand

The impressive performance of the Vietnamese economy over the last few decades has been closely associated with the rapid expansion of the national grid to different parts of the country. Easy access to electricity for firms and households has improved not only productivity, but also living conditions for millions of people. Since it takes time to change electricity generation capacity, long-term planning requires a reasonably accurate forecast of future electricity demand. However, this task has been complicated by temperature rise due to global warming [Slingo and Palmer, 2011] (see Chapter 1 for the past trends in temperature).

There is a rich literature on the effect of climate change, especially temperature, on electricity demand [Sailor and Pavlova, 2003]. This effect is mainly attributed to the rapid proliferation of electric cooling and heating appliances in firms and households, in residential and commercial/industrial sectors. While there have been many studies on household electricity demand [Conevska and Urpelainen, 2020], the extent of research on firms' electricity demand is more modest.

The objective of this section is to estimate the impact of temperature changes on electricity demand among firms and households, while observing other underlying determinants of electricity demand. Since firms are able to resort to different energy sources, such as electricity, gasoline, charcoal, diesel, gas, etc., we also consider substitution among these inputs as a result of prevailing relative input prices. Then, we forecast firms' and households' electricity demands under different scenarios of temperature rise due to climate change and economic growth.

2.1 Methodology

Using different methods, most previous studies demonstrated that household energy consumption in developed and developing countries is related to various factors that can be classified into four categories, including household head characteristics, household characteristics, dwelling attributes, and climatic factors [Galvin and Sunikka-Blank, 2018].

Deschenes and Greenstone (2011) applied the panel approach with flexible functional forms to explore the relationship between climate changes and household electricity demand in the United States between 1968 and 2002. They found that daily temperatures have a significant impact. This relationship is non-linear, *i.e.* residential electricity consumption tends to increase considerably at the extremes of the temperature distribution. Since the temperature in Viet Nam typically ranges from 21°C to 35°C — higher than the estimated threshold temperature in Moral-Carcedo and Perez-Garcia (2015) — the heating needs for firms are correspondingly limited. In this chapter, we do not estimate a non-linear relationship between temperature and electricity demand.

In addition, electricity is only one of energy sources available to firms. The objective of profit maximization (or cost minimization), along with large-scale production, causes firms to consider alternative sources such as gasoline, charcoal, diesel, gas, etc. This is especially significant in developing countries, where electricity supplies tend to be unreliable and susceptible to exogenous shocks. Electricity shortages, which may be frequent under extreme circumstances, can adversely affect firms' production and revenue [Abeberese, 2017]. As temperature increases under global warming, firms may plan lower production or switch to more modern, 'greener' or more labour-intensive technologies. The latter strategy requires consideration of possible substitution among factors of production, and among different fuels. Therefore, we apply econometric methods with the model in Bardazzi *et al.* (2015).

We are going to estimate two systems: (i) one with three production factors, *i.e.* labour, capital, and energy, and (ii) one with five fuel sources, *i.e.*, electricity, gasoline, charcoal, diesel, and gas (see Box 5.1 below). To estimate the impact of temperature on household electricity consumption, we regress households' annual electricity spending on observed and unobserved attributes at the household level, and average temperature in the district in which households are located.

Another way to represent the non-linear relationship is to sort each day's average temperature into one of 14 temperature bins. They are the first, fifth, tenth, twentieth, thirtieth, fortieth, fiftieth, sixtieth, seventieth, eightieth, ninetieth, nine-fifth, and ninety-ninth percentiles of the temperature distribution . It is expected that on extremely cold and hot days, households are likely to consume more electricity for heating and cooling.

[Box 5.1]

The general share equation for both systems is adapted from Bardazzi *et al.* (2015):

$$S_{ift} = d_i + \tau_i temp_{ft} + \sum_{j=1}^{n-1} \alpha_{ij} \, ln\left(\frac{p_{jft}}{p_{kft}}\right) + \beta_i ln\left(\frac{Y_{ft}}{P_t}\right) + \delta_i ln(employment_{ft})$$

$$+ \sum_t \gamma_{it} \, year_t + \sum_l \theta_{il} \, industry_{fl} + \sum_m \omega_{fm} \, ownership_{fm} + u_{ift}, \qquad (5.1)$$

where S_{ift} is the cost share of input *i* of the f^{th} firm in year *t*, $temp_{ft}$ is the tth year's average temperature in the province where the f^{th} firm was officially registered, P_{jft} is the jth input price, $\frac{Y_{ft}}{P_t}$ is the level of real output of the f^{th} firm, $year_t$, $industry_{fl}$ and $ownership_{fm}$ are the year, industry, and types of ownership dummies. Since the production function may not have constant returns to scale, we need to include the logarithm of the number of workers, $ln(employment_{ft})$, as a proxy for firm size and three groups of dummy variables.

To estimate the impact of temperature on household electricity consumption, we regress a function of the form

$$ln(q_{it}) = \alpha_i + \beta temperature_{it} + \delta temperature_{it}^2 + \gamma Z_{it} + u_{it}, \qquad (5.2)$$

where $ln(q_{it})$ is the natural logarithm of household *i*'s annual electricity spending (adjusted for electricity price) in year *t*, Z_{it} is a vector of observed attributes at the household level, α_i is time-invariant and unobserved household fixed effect, $temperature_{it}$ is average temperature of year t in the district in which household *i* is located. We add a quadratic term $temperature_{it}^2$ to account for the possible non-linear impact of temperature on electricity consumption.

A popular estimation equation that reflects the non-linear relationship with 14 temperature bins is [Maximilian, 2018; Deschenes and Greenstone, 2011]

$$ln(q_{it}) = \alpha_i + \sum_{b=1}^{14} \beta_b \, D_{bit} + \gamma Z_{it} + u_{it}, \qquad (5.3)$$

where D_{bit} is the number of days of which average temperature falls into bin *b* (experienced by household *i* in year *t*. Annual data postulate that $\sum_{b=1}^{14} D_{bit} = 365$ or 366, we need to drop one bin which is considered the base group to avoid perfect collinearity.

2.2 Estimated effects of temperature on residential, manufacturing, and aggregate electricity consumption

This chapter utilizes Viet Nam Enterprise Surveys conducted by the General Statistics Office (GSO) of Viet Nam. The surveys were initiated by the World Bank in 1998. They were designed to survey thousands of small, medium, and large companies across all geographic regions, so that they could be representative samples of firms in the economy. However, these surveys are subject to extensive missing data and measurement errors. We have used the last three surveys from 2016 to 2018, each of which covers around 500,000 businesses. As our panel dataset spans just three years, we do not expect there to be much variation in temperature experienced by firms. Therefore, the factor and fuel demand systems do not include a quadratic term in temperature like the residential electricity consumption function.

The estimation results of the factor demand system are displayed in Table 5.1. With capital being chosen as the numeraire input, the system comprises two cost share equations for labour and energy. As temperature rises, firms are likely to spend relatively more on labour and energy, and less on capital. Labour and energy cost shares tend to increase 0.09 and 0.06% for each additional degree Celsius, all other things being equal. The median firm has to consume 4.31% more on energy. The same holds true if the firm size (measured in terms of the number of workers) grows. However, a 1% increase in a firm's real output is associated with a higher energy cost share (up by 0.06%), but a lower labour cost share (down by 0.06%).

Based on the Standard Industrial Classification (SIC), we divide firms into four industries: (i) agriculture, forestry, fisheries, and other sectors, (ii) mining, industry, and manufacturing, (iii) electricity, steaming, conditioner production, and (iv) water supply, construction, vehicle, automobile repairs and all services. The firms in industries (iii) and (iv) consume relatively more energy than firms operating in agricultural sectors. Labour cost shares are highest among firms in industry (iii), followed by the base group, then industries (iv) and (ii).

It should be noted that foreign — and domestic privately-owned firms employ Viet Nam's abundant factor of production — labour more intensively, as their labour cost shares are higher than those of state-owned enterprises. However, their energy consumption is comparatively lower than SOEs. All other things being equal, over time firms spend more on labour and less on energy. This is particularly desireable, as global warming requires a cutback on energy — especially fossil — consumption.

Although energy cost shares increase with temperature, the fuel demand system in Table 5.2 shows that electricity and charcoal cost shares, among firms which are currently using five fuels, decrease while their diesel, gas, and gasoline cost shares rise. On hot days, the aggregated electricity consumption in both the residential and commercial/industrial sectors is expected to skyrocket, imposing intense pressure on the country's electric power generation and transmission system. Firms are inclined to resort to other energy sources, for example their own electric generators using diesel or gasoline, in order to cope with the higher electricity prices that are applied to their bigger usage load.

[Table 5.1]

Estimation results of factor demand system

Dependent variable	Labor cost share	Energy cost share
Average temperature	0.00088 (0.00010)***	0.00055 (0.00008)***
$Ln\left(\frac{P_{labor}}{P_{capital}}\right)$	0.12768 (0.00016)***	-0.01567 (0.00013)***
$Ln\left(\frac{P_{energy}}{P_{capital}}\right)$	-0.01312 (0.00012)***	0.03911 (0.00009)***
$Ln\left(\frac{Y}{P}\right)$	-0.00059 (0.00013)***	0.00062 (0.00010)***
Ln(employment)	0.00423 (0.00024)***	0.00111 (0.00020)***
Industry 2	-0.01350 (0.00134)***	0.00068 (0.00108)
Industry 3	0.01092 (0.00332)***	0.06406 (0.00268)***
Industry 4	-0.00909 (0.00130)***	0.02783 (0.00105)***
Domestic privately-owned	0.01577 (0.00108)***	-0.01945 (0.00087)***
Foreign-owned	0.02051 (0.00131)***	-0.01755 (0.00105)***
Year 2017	0.00368 (0.00079)***	-0.00640 (0.00064)***
Year 2018	0.00855 (0.00052)***	-0.01297 (0.00042)***
R^2	0.84	0.53
Observations	179,208	179,208

Notes: The numeraire factor is capital. Constants are not reported.
*** significant at 1% level.
Source: Authors' calculation.

[Table 5.2]

Estimation results of fuel demand system

Dependent variable	Electricity cost share	Charcoal cost share	Diesel cost share	Gas cost share
Average temperature	-0.02460 (0.00360)***	-0.01804 (0.00217)***	0.03184 (0.00336)***	0.00393 (0.00135)***
$Ln\left(\frac{P_{electricity}}{P_{gasoline}}\right)$	-0.07890 (0.01539)***	0.00307 (0.00927)	0.04886 (0.01436)***	-0.00007 (0.00575)
$Ln\left(\frac{P_{charcoal}}{P_{gasoline}}\right)$	0.06540 (0.00858)***	0.03771 (0.00517)***	-0.04373 (0.00801)***	-0.03773 (0.00321)***
$Ln\left(\frac{P_{diesel}}{P_{gasoline}}\right)$	-0.04442 (0.00644)***	0.01504 (0.00388)***	0.03442 (0.00601)***	-0.00999 (0.00241)***
$Ln\left(\frac{P_{gas}}{P_{gasoline}}\right)$	0.00322 (0.00516)	-0.03022 (0.00311)***	0.02535 (0.00482)***	0.00079 (0.00193)
$Ln\left(\frac{Y}{P}\right)$	0.00783 (0.00255)***	-0.00332 (0.00153)**	-0.00320 (0.00238)	-0.00019 (0.00095)
Ln(employment)	0.02391 (0.00592)***	-0.00803 (0.00357)**	-0.02620 (0.00553)***	0.01701 (0.00221)***
Industry 3	-0.20772 (0.05108)***	-0.13896 (0.03077)***	0.33036 (0.04768)***	-0.01385 (0.01909)
Industry 4	0.05326 (0.01283)***	-0.10330 (0.00773)***	0.08064 (0.01198)***	0.04117 (0.00480)***
Domestic privately-owned	0.03658 (0.02844)	-0.04248 (0.01713)**	0.01082 (0.02655)	-0.00991 (0.01063)
Foreign-owned	0.06433 (0.03845)*	0.00436 (0.02316)	-0.06914 (0.03589)*	0.00573 (0.01437)
Year 2017	0.00605 (0.04324)	0.01682 (0.02605)	-0.01636 (0.04037)	0.02921 (0.01616)*
Year 2018	0.11101 (0.03414)***	-0.04880 (0.02057)**	0.00463 (0.03187)	-0.03506 (0.01276)***
R^2	0.11	0.36	0.34	0.18
Observations	1,863	1,863	1,863	1,863

Notes: The numeraire fuel is gasoline. Constants are not reported.
***, **, * significant at 1%, 5%, 10% levels, respectively.
Source: Authors' calculation.

We do not forecast consumption for the five fuels due to the limited number of firms in the inter-fuel demand system. In Table 5.1, an increase in the real output $\frac{Y}{P}$ raises energy cost share, which shifts down over time thanks to technological progress. It seems that year dummies reduce energy cost share considerably. But we should be prudent because the time horizon in our sample is short. Forecasts about Viet Nam's real output growth between now and 2050 are taken from the BAU scenario (see Section 4 below for further detail). We assume that technical progress over time will mitigate the impact of real output growth on energy cost share by 2% per annum. For example, if real output increases by 5%, then as a result of technological progress, energy cost share in that year is subject to a 3% increase in real output.

Temperature projection is based on Global Circulation Models (GCMs) under different Representative Concentration Pathways (RCPs). Simulations of 31 models in the fifth phase of the Coupled Model Intercomparison Project (CMIP5) generate 31 values of average temperature for each year. All of them are used to forecast firms' energy consumption. If there is no noticeable change in the current trend, by the middle of this century energy consumption in production will be more than two and a half times larger. This dramatic acceleration calls for promoting renewable sources, and switching to less energy-intensive industries or more energy-efficient technologies.

For residential electricity consumption, the dataset is compiled from the Viet Nam Household Living Standard Surveys (VHLSS) that were undertaken by the GSO every two years (in the years ending with even numbers) from 2002 to 2018. Since there are unobserved but important household-level attributes (effects) that cause heterogeneity in households' electricity consumption, we have constructed a panel dataset in which each household must show up at least twice over time. The GSO implemented a 50% rotation of households being interviewed from one survey to the next. Therefore, the panel dataset currently available is unbalanced.

[Table 5.3]
Estimation results of residential electricity consumption

	Equation (5.2)	Equation (5.3)
Average temperature	-0.27157 (0.08030)***	
Average temperature^2	0.00646 (0.00166)***	
D1		0.00678 (0.00083)***
D2		0.00135 (0.00040)***
D6		0.00188 (0.00032)***
D7		0.00148 (0.00032)***
D8		0.00162 (0.00034)***
D9		0.00282 (0.00035)***
D10		0.00298 (0.00034)***
D11		0.00354 (0.00037)***
D12		0.00430 (0.00047)***
D13		0.00342 (0.00037)***
D14		0.00272 (0.00047)***
Ln(real income)	0.35377 (0.00456)***	0.34376 (0.00451)***
Household size	0.03445 (0.00206)***	0.03730 (0.00202)***
Self production	0.04579 (0.00711)***	0.04957 (0.00696)***
Housing area (m^2)	0.00140 (0.00006)***	0.00138 (0.00006)***
No. refrigerators	0.51007 (0.00677)***	0.50394 (0.00663)***
No. air conditioners	0.13708 (0.00736)***	0.13199 (0.00721)***
No. washing machines	0.14525 (0.00834)***	0.14482 (0.00815)***
No. electric water heaters	0.10544 (0.00833)***	0.10336 (0.00817)***
R^2	0.68	0.66
Observations	55,319	57,331

Notes: Household constants are not reported.
*** significant at 1%level.
Source: Authors' calculation.

Estimation results of equations (5.2) and (5.3) (see Box 5.1 are reported in Table 5.3. Coefficient estimates of household characteristics are very consistent in the two model specifications. The second column in Table 5.3 shows that temperature has a nonlinear impact on residential electricity use. At the median temperature of 24.8 degrees Celsius, a one degree increase raises electricity consumption by 4.86%. However, as temperature goes up, electricity demand increases at an increasing rate. In the last column, we choose the third, fourth, and fifth bins which encounter the least electricity consumption as the base group. Each additional extreme cold day in bin 1 raises annual electricity demand by 0.68%. As it gets warmer, demand first decreases then increases at temperatures higher than 22.87 degrees Celsius. The fact that the coefficients of extreme hot bins 13 and 14 are smaller than that of bin 12 does not tally with the convex effect of temperature as indicated in Equation (5.2). A closer look at the dataset shows that most households which are exposed to excessively hot weather all year round are located along the coastal provinces. Frequent extreme weather conditions (including tropical storms and depressions) make local people more adaptive, *i.e.* less dependent on electricity.

The annual electricity consumption data blur seasonal temperature effects. Therefore, we have used the results of Equation (5.2) to forecast residential electricity demand in the future. If the current consumption pattern remains unchanged, then residential electricity consumption will increase by more than 80% by 2050.

3. Assessment of climate change's impacts on hydropower production

3.1 Introduction

Viet Nam has considerable potential to develop its hydropower, thanks to an intensive system of more than 2,360 rivers and streams longer than 10 km. The ten major rivers that can be adapted to hydropower construction have an approximate total potential capacity of 21–24 GW [UNIDO and ICSHP, 2013]. Such potential has been transformed into power supply to meet increasing power demand. With more than 70 years of hydropower development since independence (in 1945) and an increase in construction of hydro-plants over the past two decades, Viet Nam has already exploited nearly 70% of its theoretical hydropower potential, compared with the global average rate of 35% [Huu, 2015]. In 2020, hydropower made up 30% of Viet Nam's installed power capacity, amounting to 20.7 GW [IE, 2021].

Hydropower is generally perceived as an affordable, adjustable and sustainable power source. However, it is sensitive to the variations in the hydrological conditions, which in turn respond to the variability of weather factors such as rainfall and temperature [IFC, 2015]. This concern is particularly relevant to Viet Nam, a country forecast to be severely affected by climate change. Some previous assessments provide relevant implications for the hydropower sector, including (1) increases in energy demand as a result of rising temperatures [MONRE, 2010]; (2) the potential impact of changing stream flows on hydropower production [WB, 2011], and conflicts over water resources among the agriculture, industry and energy sectors [ADB, 2013]. However, these studies provide mainly qualitative assessments for general sectors, and call for more quantitative analysis.

The objective of this section is to quantify the potential impact of climate change on the generation of hydropower plants in large basins representing different climate zones across Viet Nam. More specifically, the analysis aims at (1) calibrating rainfall-runoff models to simulate inflows into selected hydropower plants at a daily time step; (2) setting up hydropower dam models for selected hydropower reservoir systems; and (3) quantifying the impact of climate change on hydropower production using the hydropower dam model and multiple GCMs and emission scenarios.

3.2 Methodology and Data

Figure 5.3 shows the general methodology applied to model the impacts of climate change on hydropower production. This framework has been applied to a large number of hydropower plants in main river basins across Viet Nam. According to Figure 5.3, quantifying climate change impacts on hydropower production is achieved in two main steps, as follows:

Step 1: Generate the multi-GCM and multi-scenario projections of daily inflows into the selected hydropower dams. Historical and projected climate variables from multiple GCMs are first processed to create the data input formats required for simulating inflows to hydropower dams. Rainfall — runoff models are then set up for the selected river basins, using observed rainfall, temperature, runoff, topography, soil and land use datasets. We finally generate baseline and future inflows for all hydropower dams by forcing the calibrated rainfall — runoff models with the observed climate variables and multi-GCM climate variables under different emission scenarios.

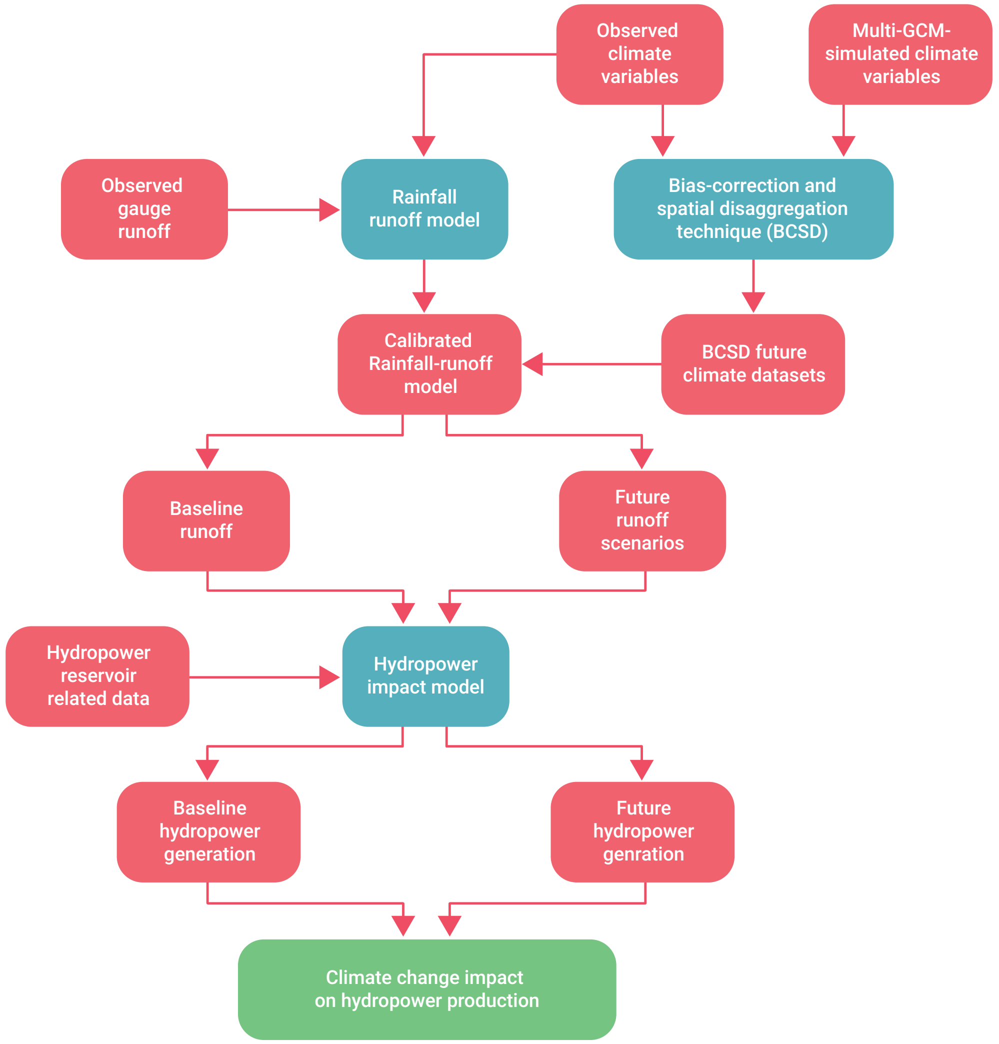
Step 2: Produce the multi-GCM and multi-scenario projections of hydropower production for all of the selected dams. In this step, we first need to build hydropower impact models for all of the selected hydropower dams, using their distinct physical-hydraulic characteristics and historical inflows simulated in Step 1. Then the hydropower impact models are forced using multi-RCM and multi-scenario inflow projections generated from Step 1 to produce the multi-RCM and multi-scenario projections of hydropower production for all of the selected dams. Finally, the potential impacts of climate change on hydropower production across Viet Nam are explored by statistical and visual exploratory analysis of the results.

The following subsections describe the methodology for hydrological simulation, hydropower generation modelling and the data sets used for the analysis in more detail.

Hydrological simulation

For discharge simulation purposes, we employ SWAT (Soil and Water Assessment Tool). This physically-based, continuous, semi-distributed model is widely used around the world to address numerous hydrologic and environmental problems [Gassman *et al.*, 2014]. The model is also applied in various contexts related to Viet Nam at different scales, and contributes to knowledge about drivers that might alter hydrological processes such as

[Figure 5.3]
Methodological framework flowchart



This figure shows a general methodology applied to model the impacts of climate change on hydropower production. According to this figure, the quantification of climate change impacts on hydropower production is achieved by two main steps: (1) Generate the multi-GCM and multi-scenario projections of daily inflows into the selected hydropower dams; (2) Produce the multi-GCM and multi-scenario projections of hydropower production for all of the selected dams.

climate change, deforestation, soil protection, crop conversion and hydropower activities.

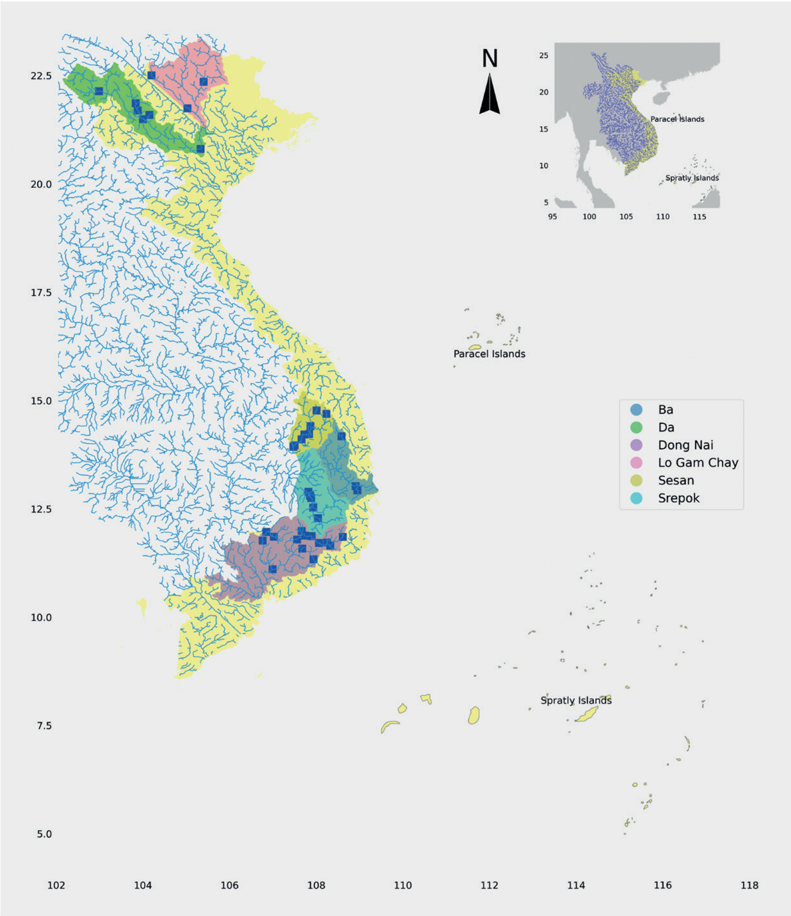
For each given watershed, SWAT uses inputted topographic and hydrological data to partition the watershed into multiple sub-basins given a desired level of granularity. Subsequently, sub-basins are broken down further into hydrologic response units (HRUs), which are the smallest component of the analysis, with a specific profile of land cover, soil and management characteristics. The simulation of hydrological cycles at the watershed level is comprised of two processes. The land phase calculates runoffs at the HRU level, then aggregates them at the sub-basin level based on the water balance equation. Accordingly, changes in soil water content at a daily time step are explained by the difference between the amount of precipitation and the total amounts of processes including surface runoff, evapotranspiration, percolation and bypass flow exiting the soil profile bottom, and return flow. In the land phase, the total amount of runoff at the sub-basin level is calculated, and then routed to the main channel through the stream network such that water discharges downstream except for losses due to evaporation and transmission through the bed of the channel, and removal for agricultural and human use. The SWAT model is calibrated and validated using the sequential uncertainty fitting version 2 (SUFI-2) algorithm in SWAT-CUP.

Hydro power generation modelling

Given the scope of this study, we employ both process-based and regression-based models to simulate hydropower generation. The former is used for basins where information is more complete, the coordination between existing dams is well known, and the assumption on maximising power generation under constraints is plausible. The latter is used where the process-based model is less feasible or sensible. For example, there is a lack of information on meteorological variables beyond Viet Nam's border and their future trends that is consistent with the high-resolution meteorological datasets used in this study. The operational procedure of upstream dams located outside Viet Nam is also not accessible. This means modelling hydropower generation in affected basins requires a pragmatic approach that can tolerate missing information, and allows the model's explainability to be assessed given the lack of information. In addition, rule-based simulation is less likely to be applicable to basins where there is substantial competing water demand other than power generation, especially where anecdotal evidence on water conflicts are recorded.

For the process-based model, which is applied for the Dong Nai, Sesan and Srepok basins, we have reproduced the flow and diversion of water, and the physical operations of reservoirs and hydropower plants in a system of reservoirs and river reaches, by employing a river-reservoir system simulation model, namely HEC-ResSim model. HEC-ResSim was developed by the U.S. Army Corps of Engineers [HEC, 2007]. The HEC-ResSim model was widely and successfully employed in many previous studies around the world to model water resource allocation and reservoir operations at one or more reservoirs for a variety of operational goals and constraints, and also to generate production outputs from daily flow data [Piman *et al.*, 2016; Tilmant *et al.*, 2011; Uysal *et al.*, 2016]. The model uses an original rule-based approach plus user-specified operating rules for the operational goals and constraints that reservoir operators must

[Figure 5.4]
Analysed hydropower dams and basins (domestic area)



This figure uses underlying data from HydroSHEDS/HydroBASINS [Lehner *et al.*, 2008, Lehner and Grill, 2013], Rivers in South and East Asia [FAO, 2014], and Global Administrative unit layers [FAO, 2015].

use to meet multipurpose goals, including flood reduction, water supply, hydropower generation, and stream flow requirements. In our study, simulated daily flows for each sub-basin from SWAT are lumped at the dam sites and used as input to the model. In addition, physical, hydraulic, and energy characteristics, as well as operation rules for reservoirs, are also required inputs to the model.

Regarding the regression-based method, which is applied for the Da, Lo-Gam-Chay and Ba basins, we have fitted the observed series for monthly generation at each dam with a set of information about hydrological conditions and operation. We start with a simple empirical specification as proposed by Cole *et al.* (2014), which uses the quadratic function of contemporaneous simulated river flow to pre-

[Table 5.4]
Data sources

Data types	Sources	Notes
Basin boundary and river networks	FAO Rivers in South and East Asia and HydroBASINS	~ 30 arc-seconds
Digital Elevation Model (DEM)	HydroSHEDSvoid-filled DEM	~ 3 arc-seconds
Soil	Digital Soil Map of the World version 3.6	~ 5 arc minutes
Land cover	UMD Land Cover classification collection	~ 1 km pixels
Historical weather data	VnGP and VnGC dataset	0.1 deg ~ 10km, from 147 temperature and 481 rainfall stations
Climate change scenarios	Bias Correction and Spatial Downscaling (BCSD) GCM dataset (see Chapter 1 for more details)	0.1 deg ~ 10km, various models for 2 RCPs
Physical and hydraulic characteristics, operation rules of reservoirs, and hydropower production	Regulations issued by the Vietnamese Government on promulgating the reservoir operating procedures; Institute of Energy	Large hydropower plants with a capacity of more than 30 megawatts (MW)
Historical river flow	Viet Nam's Hydro-Meteorological Data Center	Most relevant stations

dict hydropower generation. We improve this specification in a number of ways. First, we model the dynamic effect and include a quadratic function of lagged simulated river flow to take into account the water storage role of large reservoirs attached to dams. Second, we model the impact of upstream dams where a cascade is formed. Technically, we include interaction terms between a binary variable for the operation of a particular upstream dam and the quadratic function of river flow to downstream dams. In another extension, we also take account of the cascade effect dependent on the simulated flow to upstream dams.

Data

In this study, we examine 6 major basins that are representative of different climate regions across the country. In addition, the hydropower plants in the selected river basins represent a significant contribution to national hydropower energy, accounting for more than 80% of the national installed hydropower capacity. The selected basins as illustrated in Figure 5.4 include Da, Lo-Gam-Chay, Ba, Sesan, Srepok and Dong Nai.

Our analysis is based on a range of data as summarized in Table 5.4. We note that for the projections of hydropower generation changes, we rely on projected daily time series for rainfall, maximum and minimum temperature from 31 GCM simulations processed by the Laboratory for REmote sensing and MOdelling of Surface and ATmosphere (REMOSAT) (See Chapter 1 for more details). Two emission scenarios are chosen, including an intermediate emissions scenario, referred to as RCP 4.5 and a high emissions scenario, referred to as RCP 8.5. Finally, for the purpose of evaluating the changes in hydropower production resulting from projected changes in climate, we set the baseline period to 1999–2018 and the future period to 2041–2060.

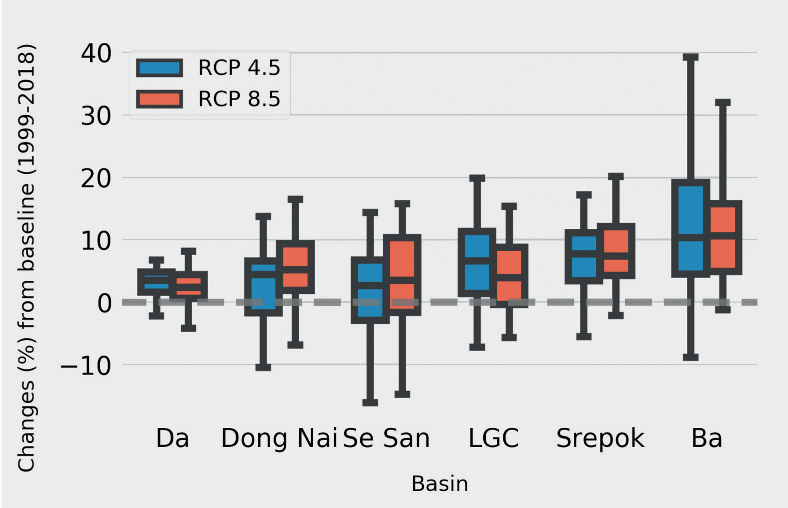
3.3 Results and Discussion

As can be seen from Figure 5.5, climate change's impact on annual hydropower generation varies across the country, reflecting the climatic, topographic and hydrological diversity of Viet Nam. The impact is highly uncertain, with the sign being either positive or negative, dependent on climate models and emission scenarios. The ensemble medians of 31 climate models report an increasing trend in all basins under both studied RCPs, which is mainly driven by the increase in precipitation projected across the country by the mid-century (see Chapter 1). In many basins, climate change is however likely to reduce discharge in the dry season, putting pressure on hydropower generation and the energy system. We will, in turn, discuss the impact at basin level below.

Originating from China and flowing through the Northwest of Viet Nam, the Da river basin has played a critical role in the national hydropower system. It has hosted the country's largest hydropower plants, including Hoa Binh (1920 MW) since 1994 and then Son La (2400 MW) since 2012, and accounts for 43.9% of Viet Nam's installed hydropower capacity (as of 2017). Besides their importance in energy production, large reservoirs attached to hydropower cascades in Da River also contribute substantially to other purposes, such as irrigation and flood control for the downstream regions, including the capital Hanoi. Our projected changes in Da River's hydropower generation for the 2050s using RCP4.5 and 29 climate models (excluding 2 outliers GFDL-CM3 and MIROC5) vary between a decrease of 2.2% and an increase of 6.8% compared with the baseline period (1999–2018). Projections for RCP8.5 present a larger range of uncertainty, with changes from the baseline varying between -4.1% and +8.2% across 31 climate models. The median models for RCP 4.5 and 8.5 suggest an increase in generation by 3.5% and 2.4%, respectively. A more detailed analysis suggests that climate change is more likely to reduce hydropower generation in Da basin between January-February and May-June. The ensemble median change in June is -3.7% for RCP 4.5 and -4.7% for RCP 8.5. A reduction in the hydropower production of large dams in early summer would be a cause for concern. It would coincide with the time when energy demand typically soars, chiefly for cooling purposes, and potentially compromises the power system's reliability.

The Dong Nai river basin is the second-largest national river basin, covering a drainage area of 40,863 km^2. The basin originates in the Central Highlands of Viet Nam, flows down through many provinces in the southern part of the country including Ho Chi Minh City, and finally pours into the East Sea. In terms of hydropower potential, the Dong Nai river has the second highest rank in Viet Nam, after the Da river basin. The total installed hydropower capacity of Dong Nai river basin reached about 2,650 MW, accounting for 17% of the total national hydropower capacity (as of year 2017).

[Figure 5.5]
Projected Annual Hydropower Generation by basin (2041–2060)



As can be seen in Figure 5.5, the ensemble median change in annual hydropower production is +5% under RCP4.5 and +6% under RCP8.5. The change ranges from -1% to +7% over the future period with RCP4.5 and from +2% to +10% with RCP8.5 [Figure 5.5]. Our projected changes in the Dong Nai river's monthly hydropower production also show large uncertainty among the 31 GCM simulations, and higher median increases are simulated under RCP8.5 for most months. Under RCP8.5, the majority of GCM simulations forecast increased changes in hydropower production for most months — with the exception of May, June and August — with the increased changes varying from 0 to 18%. The projected changes for May, June and August vary between -4% to 7% with RCP8.5. Under RCP 4.5, results for hydropower production show a tendency for very marginal increases in many months, namely in January, February, May, June, and August, averaging 1% in a range of -7% to 5% across all the GCM models.

The Se San river is one of the major tributaries of the lower Mekong basin flows, located in the Central Highlands of Viet Nam and flowing down to north-east Cambodia. It has a total area of 17,300 km^2, of which 9,340 km^2 is in Viet Nam. The Se San river has the third-largest hydroelectric power potential after the Da and Dong Nai rivers, accounting for nearly 12% of the total national hydropower production (as of year 2017). As depicted in Figure 5.5, the majority of GCMs forecast increased changes in the annual hydropower production of the Se San river basin, and the RCP8.5 emissions scenario imply changes higher increased change than the RCP4.5 emissions scenario. We project an average change in the Se San river's annual hydropower of 3% in a range of -2% to 7 under RCP4.5, and of 7% in a range of -1% to 10% under RCP8.5 by the 2050s. Average monthly energy production results also show a more uncertain forecast for the months of December, January, February, June, July, and August compared to the other months under both scenarios. The simulations for March, April, May, June and August show a projected change of hydropower production in both increasing and decreasing directions within a range of -7% to 5% across the GCMs and RCPs. For the other months, most of the GCM and emission scenarios agree on an increase in hydropower production within a range of 1% to 20%.

Lo-Gam-Chay is a trans-boundary basin, which originates in China and flows through many north-western provinces of Viet Nam. It is the second most important hydropower basin in the North, and accounts for 5.6% of the total national hydropower capacity. Though there is no consensus across all 31 models on the impact of climate change on annual hydropower generation in the Lo-Gam-Chay basin, most models report a growing tendency by the mid-century. The ensemble median changes under RCPs 4.5 and 8.5 are +6.6% and +4.0% respectively. More specifically, an increase in power generation is expected to be seen throughout the year, except for December–February (both RCPs) and May (RCP 8.5). Generation in April is projected to increase substantially with middle projections of +25.4% (RCP 4.5) and +19.2% (RCP 8.5). Meanwhile, ensemble median changes in January and February report a decrease by 7.0%–11.0% under RCP 4.5, and 9.0%–11.3% under RCP 8.5.

The Srepok river basin is also one of the major tributaries of the Mekong River Basin, originating in the Central Highlands of Viet Nam, and flowing down to Cambodia before joining the Mekong mainstream. The basin has a total area of 30,900 km^2, of which 59% is in Viet Nam and 41% in Cambodia. The Srepok river basin also has potential to develop hydropower stations due to its topographic conditions, with the total installed hydropower capacity of 730 MW accounting for about 5% of total national hydropower capacity (as of year 2017). The ensemble of the 31 GCM simulations under RCPs 4.5 and 8.5 also produce increases in the Se San river's annual hydropower production, which ranges from 3% to 11% under RCP 4.5 and from 4% to 12% under RCP 8.5 [Figure 5.5]. The median of the 31 CMIP5 mean monthly hydropower generation data over the Se San river shows increases in the wet season (from June to December) and decreases in the dry season (from January to May). Results of the projections during the wet season (especially in August to November) have the least variance among all the GCM simulations, and show a significant increase averaging at 12%. There are relatively high uncertainties in the projected mean monthly energy production results in the dry season (especially in March, April and May) among the climate models, and the change is within the range of -25% to 25% for all the GCMs and scenarios.

Ba river is the largest river in the Central Coast, flowing through Kon Tum, Gia Lai, Đak Lak and Phu Yen. Rainfall and water resources are distributed unevenly in space and time, with competing interests and even conflicts in water usage recorded in many occasions. Our middle climate models report an increase between 10.4% and 10.6% in annual hydropower under RCPs 4.5 and 8.5 respectively. However, the uncertainty range is very wide, with a decrease of 8.8% (RCP 4.5) and 18.8% (RCP 8.5) reported in the worst case. Ensemble median changes under both RCPs in monthly generation report a moderate decrease between February and May, a substantial increase between october and December, and a marginal change in other months.

Several insights from the above analysis merit further discussion. Though the median results suggest a potential increase in hydropower generation across the country due to more frequent and intense rainfall, the range of uncertainty must be taken into account in adaptive management. For example, power source planning should not be over-reliant on any single point estimate, such as the mean or median scenarios, but also consider the best and worst cases, such as wet and dry scenarios covered in our results for all 31 climate models. Second, as climate change could induce more extreme weather events such as droughts and floods and increase the seasonal variability of river flows, hydropower generation could become more volatile. As presented in our monthly analysis for some large basins, the reduction in hydropower generation during the dry season due to a shortage of water is reasonably likely to occur. This calls for contingency plans to avoid power disruption adversely affecting firms' performance and household welfare. Meanwhile, climate-proofing engineering interventions could be considered to enhance the resilience of hydropower facilities in the face of higher risk of severe floods in wet seasons. Finally, as the impact of climate change tends to vary across basins, local monitoring is critical to provide early warnings, while regional and national coordination and management could help spatially to smooth out the adverse consequences of climate risks.

4. Assessment of climate change's impacts on energy system

4.1 Introduction

Energy systems can be vulnerable to climate change. Both energy demand and supply can be altered by climate change. Warmer winters can reduce space heating demand, and hotter summers can raise cooling demand. The supply side of the energy sector may also experience positive and negative impacts. For instance, hydroelectricity output may be enhanced in some regions thanks to increased rainfall patterns, but thermoelectric power may become more vulnerable due to lower summer flows and higher water temperatures [Ciscar and Dowling, 2014].

The objective of this section is to assess the impact of climate change on the energy system in Viet Nam, focusing on electricity demand and hydropower generation up to 2050, and to propose adaptation measures in response to these impacts.

Two groups of models can be distinguished for modelling climate impacts on the energy system: economic and engineering models. According to the way the energy system is represented, they can also be named top-down (economic) and bottom-up (engineering or techno-economic) models [Ciscar and Dowling, 2014].

A common feature of the economic models is that they use a standard economic demand equation, where energy demand is a function of energy prices, income and climate variables. Because the economic models typically use income and prices as variables, these models are well-suited for analysing tax and subsidy policies [UNEP, 1998].

Engineering models for analysis of the impacts of climate change typically involve the analysis of demand by end use (*e.g.*, space heating, space cooling), using engineering principles. To assess climate change impacts, only a few end-uses need to be addressed, which simplifies the analysis. Engineering methods also can encompass hydrological models of the effects on hydroelectric generation for river flows [UNEP, 1998].

For this section, the assessment is based on the LEAP model, an engineering model developed for Viet Nam's energy system. In the LEAP model, demand for residential cooling from Section 2 would be broken down by urban and rural areas, and hydro power plants are classified according to river basins in different regions. To understand the integrated effects on the whole energy system, we simultaneously model temperature-induced changes in cooling demand, leading to changes in the capacity utilization of power generation and transmission lines, which themselves are affected by climate change. The model will use country-wide temperature and precipitation projections for the years 2020–2050 under various climate change scenarios. The differences between the BAU and climate change impact scenarios demonstrate the impacts of climate change on the energy system, in terms of primary energy consumption and production costs as well as GHG emissions.

4.2 Methodology and data assumptions

Methodology

The evaluations conducted for this section make use of two independent approaches. Regression approaches are used to analyse the overall impact of changes in temperature and rainfall on electricity demand and hydropower production (as shown in Sections 2 & 3 above). Most of this section looks at modelling that is performed using a bottom-up energy accounting approach, using LEAP software.

Firstly, a BAU is developed to outline future energy demand during 2017–2050, based on GDP, population projections, electricity demand, fuel mix and costs for power generation, which are derived from the Power Plan Development (PDP) VIII draft version 05/2021,the National Master Plan for Energy Development, and other published documents.

Taking the BAU electricity projection (that is developed for PDPVIII) as a base, this model seeks to investigate the impacts of climate change on the aspects of the economy and environment over the next three decades. Two climate change impact scenarios (for electricity demand and hydropower production) have been developed for comparison to the BAU model. To enable the impacts of climate changes to be modelled, this model is supplemented with assumptions on: i) the relationship between temperature changes and electricity demand; ii) the relationship between rainfall and temperature changes, and annual hydropower production; and iii) what temperature and rainfall changes will take place under RCP4.5 and RCP 8.5.

Data and assumption

These climate change impact scenarios are developed based on Viet Nam's climate change scenarios combined with forecasts for electricity demand and hydropower plants in a warming climate, with the input data and assumptions as follows:

[Table 5.5]

Annual average temperature changes (°C) in comparison with the 2017 baseline

	2025	2030	2035	2040	2045	2050	2055
RCP 4.5	0.18	0.29	0.41	0.52	0.63	0.75	0.84
RCP 8.5	0.31	0.51	0.72	0.93	1.15	1.39	1.62

Source: Authors' estimations based on RCPs 4.5 & 8.5 scenarios.

Basic energy and environmental data

In the generation module, data on power capacity, process efficiencies, capital cost, and operations and maintenance (O&M) costs were taken from Viet Nam's Nationally Determined Contributions for Energy and Transport Sectors and PDP VIII of Viet Nam.

In other modules (such as natural gas production, oil refining, crude oil production, and coal production), the capacity data and other data on process efficiencies, capital costs, O&M costs, and others were referred to the PDP VIII and other studies or overseas data.

The environmental externality costs are also included in this study. As yet, Viet Nam has not officially carried out any study on the external costs associated with electricity generation. Due to a lack of sufficient data and specific evaluations to calculate externality costs in the power sector, external cost factors are extrapolated from other relevant studies in China, including nitrogen oxides (NO_x), sulphur dioxide (SO_2), and particulate matter (PM_{10}). The average cost of CO_2 control is referred from studies in China and Europe [H.A Nguyen-Trinh and M. Ha-Duong, 2015].

Warming climate data

To generate climate change scenarios for Viet Nam, we rely on a national climate dataset (downscaled from outputs of global climate models) that was developed by the Laboratory for REmote sensing and MOdelling of Surface and ATmosphere (REMOSAT) in chapter 1. Specifically, the bias-correction and spatial disaggregation technique [BCSD; Wood *et al.*, 2002] is used to disaggregate global simulations of 31 models contributing to the CMIP5 experiment under emission scenarios RCP4.5 and RCP8.5 to a 0.1 arc-degree resolution. We then estimate daily temperature for Viet Nam (from 1980 to 2005 for the historical simulation and from 2006 to 2100 for future simulations) by averaging daily mean temperature across all grid cells within Viet Nam. The daily time series is then aggregated by calendar year to get an annual time series of temperature over Viet Nam (from 1980 to 2100). This procedure is applied for each of the models available through this project.

Relationship between electricity demand and temperature changes

Changes in temperature will result in changes of electricity demand. The relationship between changes in temperature and changes in electricity demand is defined as the proportionate increase in the quantity of demand per 1°C increase in temperature.

Table 5.5 provides an overview of changes in annual average temperature using the 2017

[Table 5.6]
The increase rate of electricity demand due to climate change up to 2050

		In comparison with 2017					
		2025	2030	2035	2040	2045	2050
RCP 4.5	Residential	0.87%	1.41%	1.99%	2.53%	3.06%	3.65%
	Industrial	0.78%	1.25%	1.77%	2.24%	2.72%	3.23%
RCP 8.5	Residential	1.51%	2.48%	3.50%	4.52%	5.59%	6.76%
	Industrial	1.34%	2.20%	3.10%	4.01%	4.96%	5.99%

Source: Authors' estimations.

baseline. We note that each year (as shown in these exhibitions) was used as the notation to represent a specific 20-year period. For instance, "2017 temperature" was averaged using annual temperature for Viet Nam from 2008 to 2027. Similarly, future temperatures were also calculated for each of the 20-year periods (*e.g.* the 2025 temperature was calculated from annual temperature from 2016 to 2035).

The increase of average temperatures in climate change scenarios compared to those in 2017 is the basis for assessing the impacts of temperature changes on electricity demand in the period 2017–2050. The evaluative results on the impacts of climate change on residential and industrial electricity consumption (as indicate in Section 2.2) indicate that average ambient temperature has significant impacts on electricity consumption. An increase of 1°C in the temperature will result in an increase of 4.86% and 4.31% in residential and industrial electricity consumption, respectively. With these evaluative results, by 2050, the additional increase rate of residential and industrial electricity demand due to climate change will be 3.65% and 3.23% according to RCP 4.5 and 6.76% and 5.99% according to RCP 8.5 (see Table 5.6).

Relationship between hydropower production and rainfall changes

The amount of electricity that can be generated from hydropower plants depends not only on the installed generation capacity, but also on the variation in water inflows to the plants reservoirs. Higher precipitation could increase seasonal river flows and water storage in the reservoir. Thus, rainfall changes can directly affect hydropower output.

According to the RCP4.5 scenario, at the beginning of the century, annual rainfall will tend to increase by 5–10% in most of the country. By the mid-century, the rainfall will likely increase by 5–15% in general. Some coastal provinces in the Red River Delta, the North Central Coast and Central Coast may have rainfall rise by above 20%. As in the RCP8.5 scenario, annual rainfall will likely increase in most of the country at the beginning of the century, by 3–10% in general. By the mid-century, the increase trend of annual rainfall will likely be similar to the increase trend of the RCP4.5 scenario.

The evaluative results on the impacts of climate change on hydropower production indicate that hydropower production for all the river basins is projected to increase under both RCP 4.5 and RCP 8.5. As shown in Section 3.3, the annual production change could be estimated ranging from -3.5% to +25.7% with RCP4.5 and from -3.3% to +23.1% with RCP 8.5 over the future periods in the six main basins.

4.3 Climate change's impacts on the energy system

The results of modelling the impacts of climate change suggest that, given the assumptions we have made above, climate change's impacts on electricity demand in both the residential and industrial sectors could result in a significant increase in electricity demand. However, climate change impact on hydropower production suggests that climate change has little or even a positive impact on hydropower generation. Under the climate change scenarios (RCP 4.5 and RCP 8.5), the additional increase in electricity demand (from BAU scenario) is much higher than the additional increase in hydropower generation, resulting in increased fuels and costs for power generation, as well as primary energy supply and GHG emissions.

Increase in primary energy supply

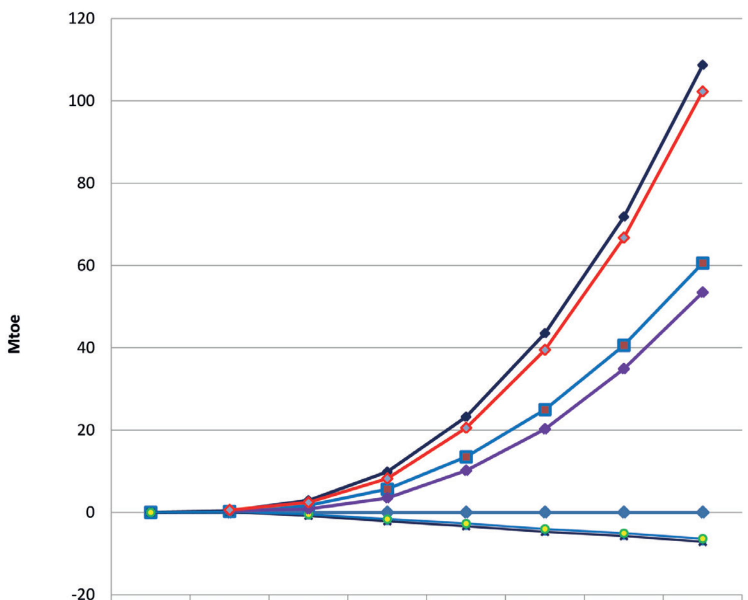
Electricity demand significantly increases from the BAU scenario, due to the increase of temperature, ranging from 2.8% to 5.2% by 2050 under RCP4.5 and RCP8.5 scenarios, respectively. These increases result in corresponding increases of primary energy supply (due to the increase of input fuels for power generation) of 1.3% and 2.4% under RCP4.5 and RCP8.5, respectively. If the whole period from 2017 to 2050 is examined, the total cumulative additional increase of primary energy demand will show a large and rapid increase, from 1.7 Mtoe and 2.9 Mtoe by 2025 to 60.6 Mtoe and 108.7 Mtoe by 2050 under RCP4.5 and RCP8.5, respectively. These additional increases are mostly fuels used for power generation, to meet the additional increase of electricity demand due to climate change.

Contrary to the electricity demand due side, the increase in precipitation due to climate change will drive an increase in electricity generation output from hydropower. However, this increase is negligible and similar in both scenarios RCP4.5 and RCP8.5, ranging from 0.04% to 0.13% of BAU's electricity generation output during the period 2017–2050. This increase in electricity generation output results in the decrease of other substitute fuels used for power generation, and thus decreases the appropriate primary energy supply demand. The total cumulative decrease of other substitute fuels will be modest, with 7.1 Mtoe and 6.4 Mtoe by 2050 under RCP4.5 and RCP8.5, respectively. This decrease of primary energy supply is smaller than the additional increase in primary energy supply due to the impacts of climate change on electricity demand. On the energy system aspect, the impacts of climate change on the energy system will cause a significant and rapid increase of primary energy demand, with a cumulative additional increase from 0.9 Mtoe and 2.4 Mtoe by 2020 to 53.5 Mtoe and 102.3 Mtoe by 2050 under RCP4.5 and RCP8.5, respectively [Figure 5.6].

Increase in emissions from the power generation sector

As a result of the impact of climate change on electricity demand, the additional increase in fuels for power generation results in additional emissions increases from the power sector from 1.9% to 3.6% by 2050 under RCP4.5

[Figure 5.6]
Cumulative total primary energy supply demand up to 2050, CCI scenarios v.s BAU



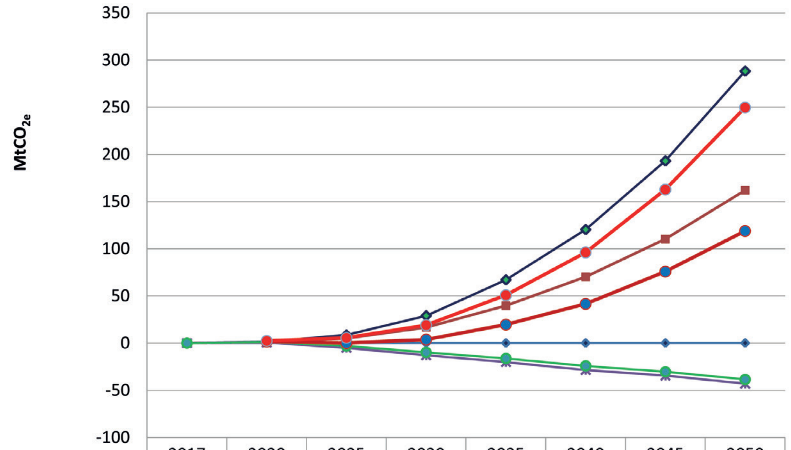
	2017	2020	2025	2030	2035	2040	2045	2050
BAU	-	-	-	-	-	-	-	-
CCI on ED RCP4.5	-	0.2	1.7	5.6	13.5	25.0	40.6	60.6
CCI on ED RCP8.5	-	0.4	2.9	9.9	23.2	43.5	71.8	108.7
CCI on HPP RCP4.5	-	0.1	-0.8	-2.1	-3.3	-4.7	-5.7	-7.1
CCI on HPP RCP8.5	-	0.2	-0.5	-1.6	-2.7	-4.0	-5.1	-6.4
CCI on ES RCP4.5		0.4	0.9	3.5	10.2	20.2	34.9	53.5
CCI on ES RCP8.5		0.6	2.4	8.2	20.5	39.5	66.8	102.3

BAU: Business-As-Usual / CCI on ED = climate change impacts on electricity demand.
CCI on HPP = climate change impacts on hydropower production.
CCI on ES = climate change impacts on the energy system.
Source: Authors' calculations.

and RCP8.5, respectively. For the whole period 2017–2050, the total cumulative additional increase of emissions in the power sector will be significant, with 161.9 MtCO2e and 288.3 MtCO2e by 2050 under RCP4.5 and RCP8.5, respectively.

Contrary to electricity demand, the decrease of other substitute fuels used for power generation due to the increase in electricity generation output from hydropower under climate change scenarios results in the decrease of CO_2 emissions from the power sector. The total cumulative decrease of CO_2 emissions from hydropower production will be modest with 43.0 MtCO2e and 38.6 MtCO2e by 2050 under RCP4.5 and RCP8.5, respectively. This decrease in emissions from hydropower is smaller than the additional increase in CO_2 emissions due to the impacts of climate change on electricity demand, and with respect to the energy system aspect, the impacts of climate change on the energy system will cause a significant increase in CO_2 emissions, with a cumulative additional increase of 118.8 MtCO2e and 249.7 MtCO2e by 2050 under RCP4.5 and RCP8.5, respectively [Figure 5.7].

[Figure 5.7]
Cumulative increase emissions in power sector, CCI scenarios v.s BAU



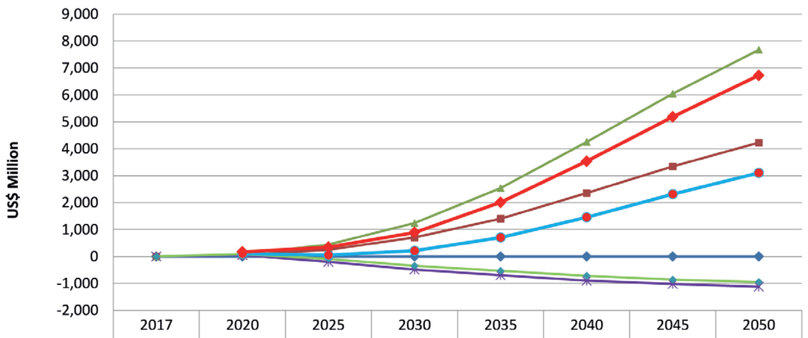
	2017	2020	2025	2030	2035	2040	2045	2050
BAU	-	-	-	-	-	-	-	-
CCI on ED RCP4.5	-	0.7	4.9	16.6	39.6	70.1	110.3	161.9
CCI on ED RCP8.5	-	1.2	8.5	29.0	67.0	120.3	193.1	288.3
CCI on HPP RCP4.5	-	0.8	-4.9	-12.8	-20.1	-28.5	-34.4	-43.0
CCI on HPP RCP8.5	-	1.2	-3.0	-9.9	-16.3	-24.2	-30.5	-38.6
CCI on ES RCP4.5		1.5	0.0	3.8	19.5	41.6	75.9	118.8
CCI on ES RCP8.5		2.4	5.6	19.1	50.7	96.1	162.7	249.7

BAU: Business-As-Usual / CCI on ED = climate change impacts on electricity demand.
CCI on HPP = climate change impacts on hydropower production.
CCI on ES = climate change impacts on the energy system.
Source: Authors' calculations.

Social cost impact of CCI scenarios

The increase in electricity demand as a result of climate change scenarios results in an increase in the costs for power production, including fuel costs and O&M costs, as well as additional external costs of GHG emissions. The calculation results [Figure 5.8] show that the total cumulative costs of CCIs on electricity demand under RCP4.5 and RCP8.5 in the 2017–2050 period (discounted at 10.0%) are approximately US$ 4,227.1 million and US$ 7,675.3 million, respectively: imported fuel costs account for most of that (at least 80%) in both CCIs, while the remainder represents external costs of GHG (around 10%), and operation and management costs for power generation (see Table 5.7 for more details). On the other hand, the increase in electricity production for hydropower due to CCI scenarios results in a decrease in other input fuels and thus in the costs of power generation, including costs for fuels and O&M costs, as well as additional external costs of GHG emissions.

[Figure 5.8]
The results of social-economic impact of climate change on energy system



	2017	2020	2025	2030	2035	2040	2045	2050
BAU	-	-	-	-	-	-	-	-
CCI on ED RCP4.5	-	50.7	251.2	705.8	1,404.4	2,353.3	3,342.6	4,227.1
CCI on ED RCP8.5	-	87.4	441.4	1,239.2	2,541.9	4,253.3	6,045.1	7,675.3
CCI on HPP RCP4.5	-	55.3	-199.7	-489.9	-698.9	-895.7	-1,024.3	-1,121.8
CCI on HPP RCP8.5	-	84.0	-94.3	-344.9	-531.2	-716.0	-857.8	-948.7
CCI on ES RCP4.5		106.1	51.5	215.9	705.5	1,457.6	2,318.3	3,105.3
CCI on ES RCP8.5		171.4	347.1	894.3	2,010.7	3,537.2	5,187.4	6,726.5

BAU: Business-As-Usual / CCI on ED = climate change impacts on electricity demand
CCI on HPP = climate change impacts on hydropower production
CCI on ES = climate change impacts on the energy system.
Source: Authors' calculations.

The calculation results [Figure 5.8] show that total cumulative decreased costs of CCIs on hydropower production under RCP4.5 and RCP8.5 in the 2017–2050 period (discounted at 10.0%) are approximately US$ 1,121.8 million and US$ 948.7 million, respectively: imported fuel costs account for most of that (at least 80%) in both CCIs, while the remainder represents external costs of GHG (around 10%), and operation and management costs for power generation.

The decrease in hydropower's social costs is smaller than the additional increase in social costs due to the impacts of climate change on electricity demand, and with respect to the energy system, the impacts of climate change on the energy system will cause a significant increase in social costs, with a cumulative additional increase of US$ 3,105.3 million and US$ 6,726.5 million by 2050 under RCP4.5 and RCP8.5, respectively. In both RCP4.5 and RCP8.5, the additional fuels are mostly imported fuels for power generation, which increases dependency on fuel imports and is thus a threat to national energy security.

5. Proposed adaptation measures responding to climate change

As analysed above, the impacts of climate change on the energy system can raise electricity demand, mostly for cooling uses, which is likely to lead to an increase in fuel consumption, costs and GHG emissions in power generation. The decreased use of electricity for cooling uses through the promotion of more efficient air conditioners and other electricity-efficient devices may mitigate these impacts of climate change on electricity demand. Similarly, the development of other alternative renewable electricity sources to reduce GHG emissions could be potential measures to respond to climate change.

The proposed adaptation measures responding to climate change are based on a cost-benefit analysis of the technological responses to climate change that are selected, including: Residential energy efficiency air conditioning (EE-AC), residential high efficiency refrigerators (EE-R), residential energy efficiency lighting (EE-L), solar photovoltaic power plants and wind power plants.

This section focuses on the cost-benefit analysis of EE and renewable energy (RE) technologies, based on basic assumptions and input data.

5.1 Basic assumptions

On the demand side, it is assumed that EE technologies such as residential air conditioning, residential refrigerators and residential lighting will penetrate at high rate — at least 75% in rural areas and 90% in urban areas – and that EE technologies in the industrial sector will help save around 5.0% and 6.5% of energy demand by 2030 and 2050, respectively.

On power generation, solar PV and wind technologies are expected to achieve 50,000 MW and 40,000 MW respectively in 2050, replacing imported coal power plants (as referred from PDPVIII-Base case scenario).

Data on the economic and technical specifications of each EE and RE technology option are taken from WB's study and Viet Nam's Nationally Determined Contributions for Energy and Transport Sectors.

5.2. Social costs and benefits of proposed adaptation measures

Table 5.7 presents a summary of the results of the social-economic impact of climate change and adaptation measures in response to climate change, including costs and benefits of the impacts implemented in the 2017–2050 period (discounted at 10%), GHG emission reduction potentials and cost of avoiding GHGs.

From the calculation results [Table 5.7], some comments can be drawn, as follows:

- The calculations show that the total additional investment costs for wind power plants is US$14,368.6 million, while it can save US$ 13,150.4 million by economising fuel for power generation and reduce 1,521.5 MtCO2e at an abatement cost of US$ 0.8/tCO2e. As for the economic aspect, the total investment cost is slightly higher than benefits, but this option is a good mitigation option with great GHG savings and low GHG abatement costs: wind power could thus be one of options for adaptation measures. Other remaining measures are feasible because of high economic return and low GHG abatement costs, and could be good solutions in response to the impacts of climate change.

▸Under climate change scenarios, the increase in electricity demand results in an increase in costs for power production and GHG emissions. The total cumulative costs of CCIs in the 2017–2050 period range from US$ 4,227.5 million to US$ 7,675.3 million (including the external costs of GHG emissions), with cumulative additional emissions of 161.9 MtCO2e and 288.3 MtCO2e under RCP4.5 and RCP8.5 respectively.

▸The total costs (including investment costs and O&M costs) of adaptation measures for energy demand in residential and industrial sectors and renewable electricity development are approximately US$ 21,239.7 million, resulting in social benefits of almost US$ 31,770.7 million, with the majority accounted for inreduced fuel imports (US$ 22,948.8 million), while it can also in reduced 2,837.7 MtCO2e at an abatement cost of US$ -3.7/tCO2e. Thus, the implementation of these technology measures can save US$ 10,531.1 million, which is higher than the costs of CCIs on electricity demand in the 2017–2050 period under RCP8.5, by US$ 7,675.3 million at the discount rate of 10%. However, there is uncertainty over the discount rate, which could have a significant impact on the viability on benefits of the proposed measures. With a higher discount rate of 12%, these technology measures can save US$ 5,559.1 million, which is still higher than the costs of CCIs on electricity demand under RCP8.5, by US$ 5,205.0 million. Therefore, implementing these technology measures not only completely eliminates the impacts of climate change, but also significantly contributes to GHG reduction and sustainable economic development. In the case of a higher discount rate of 13%, these technology measures can save only US$ 3,854.7 million, which is lower than the costs of CCIs on electricity demand under RCP8.5, by US$ 4,327.6 million, and become unfeasible.

[Table 5.7]

The results of social-economic impact of climate change and technology measures in response to climate change

	CCI on the energy system				Technology measures in response to CCI						
	CCI on ED RCP4.5	CCI on ED RCP8.5	CCI on HPP RCP4.5	CCI on HPP RCP8.5	Residential EEAC	Residential EER	Residential EE Lamps	Industrial EE Tech.	Solar PV	Wind Power	Total
Costs	4,227.5	7,675.3	1.9	6.2	1,410.3	396.3	583.0	2,760.1	1,721.4	14,368.6	21,239.7
At the demand side	-	-	-	-	1,410.2	396.1	582.0	2,759.0	0	0	5,147.3
At the supply side	4,227.5	7,675.3	1.9	6.2	0.1	0.2	1.0	1.1	1,721.4	14,368.6	16,092.4
Electricity generation	207.8	362.4							1,721.4	14,368.6	16,090.0
Energy production	38.9	70.0	1.9	6.2							
Imports	3,563.6	6,512.1									
Exports		2.3			0.1	0.2	1.0	1.1			2.4
Environmental Externalities	417.2	728.5									
Benefits	-0.4	-	-1,123.7	-954.9	-2,002.2	-698.9	-3,308.9	-8,342.2	-4,268.2	-13,150.4	-31,770.7
Electricity generation			-25.0	-18.2	-112.0	-41.8	-226.6	-469.3			-849.7
Energy production					-23.8	-7.4	-37.4	-76.9	-	-	-145.4
Imports			-925.3	-802.1	-1,640.2	-566.2	-2,592.9	-6,455.4	-2,869.5	-8,824.6	-22,948.8
Exports	-0.4		-0.5	-0.7					-	-	
Environmental Externalities			-173.0	-133.9	-226.2	-83.5	-452.0	-1,340.6	-1,398.7	-4,325.7	-7,826.8
Total Net Present Value	4,227.1	7,675.3	-1,121.8	-948.7	-592.0	-302.6	-2,726.0	-5,582.0	-2,546.8	1,218.3	-10,531.1
GHG Savings (MtCO2e)	-161.9	-288.3	43.0	38.6	110.0	29.1	138.7	489.0	549.4	1,521.5	2,837.7
Cost of Avoided GHGs (USD/tCO2e)	n/a	n/a	-26.1	-24.6	-5.4	-10.4	-19.7	-11.4	-4.6	0.8	-3.7

CCI on ED = climate change impacts on electricity demand, CCI on HPP = climate change impacts on hydropower production, EE-AC = energy efficiency air conditioning, EE-R = energy efficiency refrigerator, EE-L = energy efficiency lighting
Unit: 2017 US$ million (discounted at 10.0% to year 2017). Source: Calculation results from LEAP model.

6. Conclusions and Recommendations

6.1 Conclusions

Climate change is likely to have a significant impact on Viet Nam's energy system. All other things being equal, each additional degree Celsius is estimated to increase electricity consumption among households by 4.86%, and firms' energy demand by 4.31%. These significant effects, compounded with an expected 5–6% economic growth rate per annum, will put great pressure on the electricity generation sector in the long term.

On the supply side, projected changes in hydropower production across several river basins due to climate change have been investigated. Hydropower production displays a generally positive relationship with precipitation levels. However, the range of projections for annual as well as monthly hydropower generation impacts is wide and uncertain. In addition, while the climate models largely agree on an increase in future annual hydropower production across the basins, there are several months (mostly in the dry season), where the models disagree over whether there will be more or less hydropower production in future. The high uncertainty in our projections is a result of various uncertainties arising from using downscaled GCM simulations, and propagating them through the subsequent hydrological and hydropower modelling processes which challenge power, social and economic planning.

For the whole energy system, we find that climate change causes considerable negative effects on electricity demand, but brings positive effects on hydropower in terms of electricity production.

For hydropower production, electricity generation output will increase in comparison with BAU scenario, due to increased rainfall under climate change scenarios. However, this increase is negligible and similar in both scenarios RCP4.5 and RCP8.5, ranging from 0.04% to 0.13% of BAU's electricity generation output during the period 2017–2050. This increase in electricity generation output reduces demand for fuels for power generation, as well as decreased GHG emissions. However, all these decreases are small and negligible compared to the damage and losses caused by the climate change impacts on other areas.

Electricity demand is significantly increased from the BAU scenario due to the increase of temperature, ranging from 2.8% to 5.2% by 2050 under RCP4.5 and RCP8.5 scenarios, respectively. These increases result in corresponding increases of primary energy supply (due to the increase of input fuels for power generation) from 1.3% and 2.4%, as well as GHG emissions from power generation from 1.9% to 3.6% by 2050 under RCP4.5 and RCP8.5, respectively.

The total cumulative costs of climate change impacts on electricity demand in the 2017–2050 period range from US$ 4,227.5 million to US$ 7,675.3 million, with cumulative additional emissions of 161.9 MtCO2e and 288.3 MtCO2e under RCP4.5 and RCP8.5 respectively. This number will be greater if we take into account the impacts on other areas, such as commerce, transportation, and thermal power production. We leave these additional aspects to the end of the project.

6.2 Recommendations

As analysed above, the impacts of climate change on the energy system will increase electricity consumption for air conditioners, which is likely to lead to an increase in fuel consumption, costs and GHG emissions in power generation. The decreased use of electricity for air conditioners through the promotion of more efficient air conditioners and other electricity-efficient devices may mitigate these impacts of climate change. Research at the global scale has suggested that climate change has little or even a positive impact on hydropower generation [Kumar *et al.*, 2011]. Our quantitative assessment confirms a similar tendency for Viet Nam at a national scale. However, local impacts are shown to vary across the country. Hydrological processes in many basins are likely to be altered. In addition, the disagreement in results between different carbon emission scenarios and climate models highlights the risks associated with the larger uncertainty introduced by climate change, which challenges power, social and economic planning.

References

Abeberese, A. B. (2017). Electricity costs and firm performance: Evidence from India. *The Review of Economics and Statistics*, 99(5), 839-852. https://doi.org/10.1162/REST_a_00641

ADB (2013). Viet Nam Environment and Climate Change Assessment, Report, Asian Development Bank.

Bardazzi, R., Oropallo, F., & Pazienza, M.G. (2015). Do manufacturing firms react to energy prices? Evidence from Italy. *Energy Economics*, 49, 168-181. https://doi.org/10.1016/j.eneco.2015.01.014

Carew-Reid, Jeremy, Kempinski, J., & Clausen, A. (2010). Biodiversity and Development of the Hydropower Sector: Lessons from the Viet Namese Experience - Volume I: Review of the Effects of Hydropower Development on Biodiversity in Viet Nam. ICEM – International Centre for Environmental Management, Prepared for the Critical Ecosystem Partnership Fund, Hanoi , Viet Nam.

Christensen, L.R., Jorgenson, D.W., & Lau, L.J. (1973). Transcendental logarithmic production frontiers. *The Review of Economics and Statistics*, 55(1), 28-45. https://doi.org/10.2307/1927992

Ciscar, J.-C., & Dowling, P. (2014). Integrated assessment of climate impacts and adaptation in the energy sector. *Energy Economics*, 46, 531–538. https://doi.org/10.1016/j.eneco.2014.07.003

Cole, M., Elliott, R., & Strobl, E. (2014). Climate Change, Hydro-Dependency, and the African Dam Boom. *World Development*, 60, 84-98. https://doi.org/10.1016/j.worlddev.2014.03.016

Conevska, A., & Urpelainen, J. (2020). Weathering electricity demand? Seasonal variation in electricity consumption among off-grid households in rural India. *Energy Research & Social Science*, 65, 101444. https://doi.org/10.1016/j.erss.2020.101444

CRED (2015). The human cost of weather-related disasters (1995-2015). Centre for Research on the Epidemiology of Disasters (CERD).

Dang, V., Do, T., Nguyen, C., Phung, T., & Phung, T. (2013). Economic Development, Inequality and Climate Change in Viet Nam. Report. MPRA Paper 54190, University Library of Munich, Germany.

Deschenes, O., & Greenstone, M. (2011). Climate change, mortality, and adaptation: evidence from annual fluctuations in weather in the US. *American Economic Journal: Applied Economics*, 3(4), 152-185. DOI: 10.1257/app.3.4.152

Elliott, R., Nguyen-Tien, V., & Strobl, E. (2021). Power Outages and Firm Performance: A Hydro-IV Approach for a Single Electricity Grid.

FAO (2007). Digital Soil Map of the World.

FAO (2011). Climate change impacts on agriculture in Viet Nam. Report UNJP/VIE/037/UNJ.

FAO (2014). Rivers in South and East Asia (Derived from HydroSHEDS) Map.

Galvin, R., & Sunikka-Blank, M. (2018). Economic inequality and household energy consumption in high-income countries: a challenge for social science based energy research. *Ecological Economics*, 153(C), 78-88. https://doi.org/10.1016/j.ecolecon.2018.07.003

Gassman, P. W., Reyes, M. R., Green, C. H., & Arnold, J. G. (2007). The Soil and Water Assessment Tool: Historical Development, Applications, and Future Research Directions. *Transactions of the ASABE*, 50(4), 1211–1250. DOI: 10.13031/2013.23637

Goldberg, J., & Lier, E. (2011). Rehabilitation of Hydropower: An Introduction to Economic and Technical Issues. Water papers. World Bank, Washington, DC. © World Bank.

Ha-Minh, D., & Nguyen, H. S. (2017). Is electricity affordable and reliable for all in Viet Nam. https://hal.archives-ouvertes.fr/hal-01692453

Hansen, M., DeFries, R., Townshend, J., & Sohlberg, R. (1998). UMD Global Land Cover Classification, 1 Kilometer.

Hansen, M., DeFries, R., Townshend, J., & Sohlberg, R. (2000). Global land cover classification at 1 km spatial resolution using a decision tree classifier. *International Journal of Remote Sensing*, 21, 1331-1365. https://doi.org/10.1080/014311600210209

HEC (2007). *HEC-ResSim, Reservoir System Simulation User's Manual*, Version 3.0. US Army Corps of Engineers, Institute for Water Resources, Hydrologic Engineering Center, Davis.

Huu, T. P. (2015). Dilemmas of hydropower development in Viet Nam: between dam-induced displacement and sustainable development. EburonUitgeverij BV.

IFC (2015). Hydroelectric Power: A Guide for Developers and Investors. International Finance Corporation, World Bank Group.

Kumar, A., Schei, T., Ahenkorah, A., Rodriguez, R. C., Devernay, J.-M., Freitas, M., Hall, D., Killingtveit, A., Liu, Z., Branche, E., Burkhardt, J., Descloux, S., Heath, G., Seelos, K., Morejon, C. D., & Krug, T. (2011). Chapter 5: Hydropower, Report. In Edenhofer, O. (eds) IPCC Special Report on Renewable Energy Sources and Climate Change, 437-496. https://doi.org/10.1017/CBO9781139151153.009

Le, P. V. (2019). Energy demand and factor substitution in Viet Nam: evidence from two recent enterprise surveys. *Journal of Economic Structures*, 8, 35. https://doi.org/10.1186/s40008-019-0168-9

Lehner, B. (2013). HydroSHEDSTechnical Documentation Version 1.2.

Lehner, B. (2014). HydroBASINS Technical Documentation Version 1.c (with and without inserted lakes).

Lehner, B., & Grill, G. (2013). Global river hydrography and network routing: baseline data and new approaches to study the world's large river systems. *Hydrological Processes*, 27(15), 2171–2186. https://doi.org/10.1002/hyp.9740

Lehner, B., Verdin, K., & Jarvis, A. (2008). New Global Hydrography Derived From Spaceborne Elevation Data. *Eos, Transactions American Geophysical Union*, 89(10), 93–94. https://doi.org/10.1029/2008EO100001

Maximilian, A. (2018). Climate adaptive response estimation: short and long run impacts of climate change on residential electricity and natural gas consumption using big data. NBER Working Paper No. W24397.

MOIT (2021). National Master Plan for Energy Development in the Period 2021–2030 with Perspective to 2050.

MOIT (2021). Power Development Plan for the Period 2021–2030 with Perspective to 2045 (draft version 05/2021).

MONRE (2010). Viet Nam's second National Communication to UNFCCC. Ministry of Natural Resources and Environment (MONRE).

Moral-Carcedo, J., & Perez-Garcia, J. (2015). Temperature effects on firms' electricity demand: An analysis of sectoral differences in Spain. *Applied Energy*, 142(C), 407-425. https://doi.org/10.1016/j.apenergy.2014.12.064

Nguyen, M-H & Le, VC (2021), The impact of climate change on energy demand for Viet Nam, IREEDS working paper, 09-2021.

Nguyen-Tien, V., Elliott, R. J. R., & Strobl, E. A. (2018). Hydropower generation, flood control and dam cascades: A national assessment for Viet Nam. *Journal of Hydrology*, 560, 109-126. https://doi.org/10.1016/j.jhydrol.2018.02.063

Nguyen-Trinh, H. A., & Ha-Duong, M. (2015). Low Carbon Scenario for the Power Sector of Viet Nam: Externality and Comparison Approach. GMSARN International Journal 9, pp. 137–146.

Piman, T., Cochrane, T. A., & Arias, M. E. (2016). Effect of Proposed Large Dams on Water Flows and Hydropower Production in the Sekong, Sesan and Srepok Rivers of the Mekong Basin. *River Research and Applications*, 32(10), 2095–2108. https://doi.org/10.1002/rra.3045

Sailor, D. J., & Pavlova, A. A. (2003). Air conditioning market saturation and long-term response of residential cooling energy demand to climate change. *Energy*, 28 (9), 941-951. https://doi.org/10.1016/S0360-5442(03)00033-1

Slingo, J., & Palmer, T. (2011). Uncertainty in weather and climate prediction. *Philosophical Transactions of The Royal Society A*, 369, 4751-4767. https://doi.org/10.1098/rsta.2011.0161

Tilmant, A., Goor, Q., & Kelman, R. (2011). Optimal Multipurpose-Multireservoir Operation Model with Variable Productivity of Hydropower Plants. *Journal of Water Resources Planning and Management*, 137(February), 258–267. https://doi.org/10.1061/(ASCE)WR.1943-5452

Tram, V. N. Q., Liem, N. D., & Loi, N. K. (2014). Assessing Water Availability in Poko Catchment using SWAT model. KhonKaen Agricultural Journal 42(2), 73-84.

UNEP (1998). Handbook on Methods for Climate Change Impact Assessment and Adaptation Strategies.

UNIDO & ICSHP (2013). World Small Hydropower Development Report 2013 – Viet Nam. United Nations Industrial Development Organization (UNIDO) International.

USAID (2010). Asia Pacific Regional Climate Change Adaptation Assessment Final Report Findings and Recommendations. US Agency for International Development (USAID).

Uysal, G., Akkol, B., Topcu, M. I., Sensoy, A., & Schwanenberg, D. (2016). Comparison of Different Reservoir Models for Short Term Operation of Flood Management. *Procedia Engineering*, 154, 1385–1392. https://doi.org/10.1016/j.proeng.2016.07.506

World Bank (2011). Vulnerability, Risk Reduction, and Adaptation to Climate change Viet Nam.

World Bank & Viet Nam Ministry of Planning and Investment (MPI) (2016). Viet Nam 2035: Toward Prosperity, Creativity, Equity, and Democracy.

World Bank and MOIT (2019).Viet Nam – Getting on a Low-Carbon Energy Path to Achieve NDC Target.

World Bank (2016). Exploring a Low-Carbon Development Path for Viet Nam.

World Bank (2021). Viet Nam Overview.

Yalew, S. G., van Vliet, M. T. H., Gernaat, D. E. H. J., Ludwig, F., Miara, A., Park, C., Byers, E., Cian, E. D., Piontek, F., Iyer, G., Mouratiadou, I., Glynn, J., Hejazi, M., Dessens, O., Rochedo, P., Pietzcker, R., Schaeffer, R., Fujimori, S., Dasgupta, S., Mima, S., Santos da Silva, S. R., Chaturverdi, V., Vautard, R., & van Vuuren, D. P. (2020). Impacts of climate change on energy systems in global and regional scenarios. *Nature Energy*, 5, 794-802. https://doi.org/10.1038/s41560-020-0664-z

Chapter 6

Effects of climate variability on households, individuals and firms

COORDINATOR

Toan Nguyen [UQ]

AUTHORS

Phan Dang Duy Anh [ECARES - ULB]
Dang Thi Thu Hoai [CIEM]
Do Xuan Hong [NLU]
Diem Hoang [UDE]
Etienne Espagne [AFD]
Manh-Hung Nguyen [TSE]
Toan Nguyen [UQ]
Van Phan [UWE]
Pham Minh Thu [ILSSA]