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ICLEI Local Governments for Sustainability

100% RENEWABLES CITIES & REGIONS ROADMAP

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100 % RENEWABLES

ENERGY SYSTEM MODELING RESULTS FOR WEST NUSA TENGGARA, INDONESIA

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CHP	Combined heat and power plant
PV	Photovoltaic
WNT	West Nusa Tenggara
RE	Renewable energies
GIS	Geoinformation system
BAU	Business-as-usual
GDP	Gross domestic product

Foreword from the Country Manager of ICLEI – Local Governments for Sustainability Indonesia Office

ICLEI – Local Governments for Sustainability is committed to supporting Indonesia's efforts in its commitment to increase its clean energy share and to reduce greenhouse gas emissions. Indonesia has affirmed its commitment in the Nationally Determined Contribution (NDC), long-term strategy on climate change (The Ministry of Environment and Forestry/MoEF), and low-carbon climate-resilient development documents in cities and districts (Ministry of National Development Planning of the Republic of Indonesia/BAPPENAS).

As part of the global renewable energy transition, ICLEI launched the 100% Renewable Energy and Regions Roadmap Project, funded by the German International Climate Initiative (IKI). The Province of West Nusa Tenggara (WNT) and key ministries and departments in the national government have partnered with ICLEI to implement this initiative in Indonesia, with WNT as one of three deep-dive regions globally. With our extensive support, ICLEI has collaborated with Fraunhofer ISE to develop the WNT energy modeling to reach the goal of 100% renewable energy share in all sectors by 2050, in line with the region's ambitious net-zero target in the same year.

This energy modeling document provides scenarios that consider energy demand and the renewable energy (RE) potential in multiple sectors. A 100% RE share in primary energy supply is possible to achieve by 2050 by maximizing the potential of solar photovoltaic, biogas, wind power, and other RE sources, such as geothermal and hydropower plants. Further, this document will serve as one of the references in developing the roadmap towards WNT 100% Renewables 2050 and guiding local action strategies in addressing climate change. This initiative is expected to draw support from other parties who share the same objective: to achieve the ideals of clean and sustainable energy in the region.

ICLEI Indonesia Office proudly acknowledges the governments of West Nusa Tenggara Province, Mataram City, and Sumbawa Regency for their support. An enduring commitment to the project and continuous support have produced this study. Such a milestone would be impossible without the participation of community groups, universities, and many more enthusiastic collaborators. In closing, we would like to express our appreciation to the 100% renewable energy representatives from ICLEI Indonesia Office, Fraunhofer ISE, ICLEI Southeast Asia Secretariat, and ICLEI World Secretariat for their cooperation.

Ari Mochamad
Country Manager
ICLEI-Local Governments for Sustainability Indonesia Office

Preface from WNT Province Department of Regional Development Planning Head of Department

We are grateful that the energy modeling document for the West Nusa Tenggara (WNT) Province 100% Renewable Energy has been completed. On behalf of the WNT Provincial Government, I would like to express my gratitude and appreciation to ICLEI – Local Governments for Sustainability and Fraunhofer-Institute for Solar Energy Systems ISE team. This document will serve as a reference in the planning of new and renewable energy in the WNT Province, to be part of local action for climate mitigation strategies. Globally, this activity is an effort to support in achieving the targets of the Sustainable Development Goals (SDGs).

The 100% Renewable Energy (100% RE) scenario was developed by the experts which consist of relevant practitioners and academicians in the energy sector using modeling that considers various sectors of energy demand. Renewable energy potential is calculated based on GIS data, statistics, and other reliable data sources. The results of this modeling show that WNT Province's 100% RE target is possible to reach by implementing solar photovoltaic (69%), followed by biogas from food residue (18%), and wind power (10%). Technically, the 100% RE scenario has advantages when compared to the current scenario of using fossil fuels in daily business processes, which is 32% more expensive and 4.5 times higher carbon emissions.

A strategic step, which is a factor supporting the success of reducing the WNT Province's dependency on fossil fuels, is therefore needed for the implementation of the 100% RE scenario. These factors include technological capabilities in the regions, the availability of human resources with specialized expertise in the RE sector, effective and efficient work mechanisms, and adequate budget support.

Last but not least, we hope that this document can be a reference for the regional apparatus of the WNT Provincial Government, planners, and other related parties in the WNT Province, especially in optimizing the use of renewable energy sources for the welfare of the community. Hopefully, it will be useful for all of us in realizing the vision of "NTB *Gemilang*" – A bright Nusa (*Nusa Terang Benderang*) and the achievement of the SDGs.

Warmest regards,
Dr. Ir. H. Iswandi, M.Si.
WNT Province Department of
Regional Development Planning Head of Department

1 Summary

Achieving the Paris climate target of net-zero emissions in the second half of this century will require an unprecedented transformation of energy supply toward renewables in all sectors and all countries. In the project of 100 % Renewables Cities and Regions Roadmap (100%RE), three different countries around the world were selected to develop a plan for them how to achieve an energy system based on 100 percent renewables by 2050. These ambitious energy scenarios shall serve as lighthouses for other cities, provinces, or federal states to show how 100 percent renewable energies are possible in different parts of the world. Therefore, the countries span three different continents and have different boundary conditions for the implementation of renewable energies: Argentina in South America, Kenya in Africa, and Indonesia in Asia. This study covers one part of the project for one of the case studies: the development of 100 percent renewable energy scenarios for the target year 2050 for West Nusa Tenggara in Indonesia. West Nusa Tenggara is a province consisting of two large islands, Lombok and Sumbawa. The results of the scenario calculations are then used to develop further action plans and identify projects for the deployment of renewable energy transition. In order to develop 100 percent renewable energy (RE) scenarios, an energy system model is used (KomMod by Fraunhofer ISE). The deployment of fluctuating renewables and thus of storage technologies, the increase of sector coupling and restricted RE potentials, to name just a few, require the use of computer-aided modeling in order to get robust results. The modeling is performed in hourly timesteps to ensure supply security and includes all relevant demand sectors. In the specific case of West Nusa Tenggara these are cooling demand, electricity demand, cooking demand in households and commercial sector, heating and fuel demand in the commercial and industrial sector, as well as energy demand for transport on land and in water. All relevant demands are evaluated for today and projected to the year 2050 in different demand scenarios. RE potentials are calculated based on GIS data, statistics data, studies for West Nusa Tenggara as well as the whole of Indonesia when no specific data for West Nusa Tenggara is available. The whole input data assessment is done for the two islands separately. Solar photovoltaic has the highest possible potentials on both islands, followed by biogas from crop residues and then wind power. Other renewable energy sources (e.g. hydropower, geothermal power, or biogas from manure) have only minor potentials. Ten (10) different scenarios are calculated by varying three different features for the 100 percent RE scenarios: biomass and biogas fuel price, energy demand, and a coupling of the energy systems of the two islands versus a separated modeling for both. In addition, a business-as-usual (BAU) scenario is modelled to allow the comparison of costs and carbon dioxide emissions. A leading scenario has been chosen in workshops between ICLEI, Fraunhofer ISE, and local stakeholders. This scenario uses low fuel price, mean demand and considers the islands' energy systems as coupled. Photovoltaic is the main electricity supplier in this scenario with a share of 69 %, biogas comes second with 18 %, and wind power comes third with 10 %. Heating demand is mainly covered with biogas CHPs and excess heat from electrolyzers. Cooking demand is fully met with biogas stoves. With higher biomass and biogas fuel price, cooking and heating supply change drastically as now the electrification is the more feasible option. Instead of biogas stoves, electric stoves and heat pumps are used to cover cooking and heating demand. Coupling of the energy systems of the two islands is beneficial for several reasons: (1) it has economic advantages, (2) it increases supply security, and (3) allows a more evenly distribution of photovoltaic free field and wind power plants. But either coupled or decoupled: 100 percent RE is cheaper than the BAU scenario where major shares of energy demand are still covered by fossil fuels. The business-as-usual scenario is 32 % more expensive and has 4.5 times higher carbon dioxide emissions from fuel combustions than the 100% RE scenarios where the same demand projections are being used.

2 The 100% RE project and its case studies

In order to achieve the Paris climate protection target of net-zero emissions in the second half of this century, an unprecedented transformation of the energy supply toward renewable energies in all sectors is required.
Global electricity demand is projected to increase by 69 % until 2040 (Doman et al. 2016). This will exacerbate the challenge of meeting demand solely from renewable energy sources. In the twenty years from 1990 to 2010, electricity generation from coal decreased by only 3.5 %. Improvements in renewables and energy efficiency were largely offset by higher coal consumption in developing countries (REN21 2014). In other sectors, barriers were even higher: in 2015, renewable energy (RE) contributed to only 4 % of energy consumption in the transportation sector and 8 % in the heating and cooling sector.
The distortion of the energy market by fossil fuel subsidies is a major barrier to the widespread adoption of RE. Figures from the International Monetary Fund (IMF) from 2015 show that Argentina, for example, subsidizes fossil fuels to the tune of US$ 206.64 per capita, Indonesia to the tune of US$ 37.65, and Kenya to the tune of US$ 3.67 (Coady et al. 2015). In addition, fossil fuel prices do not reflect the health, environmental, and economic costs of using fossil fuels.
The potential of RE has been poorly tapped in the three target countries of this project Indonesia, Argentina, and Kenya; there is a lack of viable projects for the decentralized generation and use of RE (e.g., from wind, hydropower, geothermal, and biomass) (International Energy Agency 2021). Existing national frameworks do not or not yet sufficiently support local governments in the three target countries to test and demonstrate innovative and decentralized technologies, practices, and policies to increase the share of RE. For these reasons, this project supports cities and regions in Argentina, Indonesia, and Kenya in developing strategies for 100 percent RE supply until the year 2050, as well as raising awareness and engagement among shareholders. At the same time, it supports the assessment of local RE potential and project designs, as well as the development of eligible projects. To this end, the project provides tools and resources for a RE-based energy supply. The project promotes dialogue between various government levels, strengthens capacities, and stimulates the development of appropriate frameworks at national, regional, and local levels - with the aim of promoting the local potential for RE and energy efficiency. As an example, the project aims to demonstrate how local frameworks and projects contribute to achieving national contributions to the NDCs (Nationally Determined Contributions (United Nations Framework Convention on Climate Change)) and SDGs (Sustainable development goals).
In each country, one project city/region is designated as a lighthouse city/region (deep-dive cities/regions). This city/region will receive extensive support to build knowledge and competencies as well as consulting services to develop and implement its local strategy for 100 percent RE. The other two cities/regions will be involved in the exchange of experience, knowledge building, peer learning, and policy dialogue as so-called network cities/regions with fewer project resources. The deep dive regions/cities (in bold) and the network cities/regions are named in Table 1.

Table 1: Deep dive and network cities and regions in the three countries in the 100 % RE project

Argentina	Indonesia	Kenya
City of Avellaneda	**Province of West Nusa Tenggara**	**Kisumu County**
City of Rosario	City of Mataram	Mombasa County
City of La Plata	Sumbawa Regency	Nakuru County

Fraunhofer ISE’s part in the project is to calculate optimized 100 % RE scenarios for all deep dive regions/cities with the energy system model KomMod including all relevant demand sectors. The target year for the scenarios in which 100 % RE shall be achieved by the latest is

2050. Several possible energy systems are proposed in which renewables cover all relevant local energy demands, demonstrating how an energy supply based solely on renewables could be achieved. Questions that are answered in this report are:

- How might relevant energy demands develop by 2050, and how high is the electricity demand in 2050 compared to other countries? (Chapter 4.1.2)
- How high are the usable potentials for different kinds of renewable energy technologies? (Chapter 4.2)
- What technology mix achieves the least total system costs while at the same time supplying all energy demands with 100 % renewable energies? (Chapter 6.1)
- How are these technologies operated throughout the year? (Chapter 6.1.3)
- How much storage capacity is needed to use fluctuating renewables in the most optimal way? (Chapter 6.1.1)
- How high are the total system costs in different system configurations? (Including a business-as-usual scenario) (Chapter 6.2)
- What are the levelized costs of energy for the different technologies? (Chapter 6.2)
- What is the influence of a changing biomass fuel price on the results? (Chapter 6.1.2)

Based on these scenarios, pathways for the transformation of the energy system, the 100% RE local strategies and local implementation mechanisms for RE projects are developed for the deep-dive cities under the 100%RE project by February 2023. The 100 % RE scenarios shown in this report are the result of intensive cooperation of Fraunhofer ISE, ICLEI, and local stakeholders. Preliminary scenario results have been presented several times and discussions afterwards have helped to establish a common understanding of meaningful scenarios. The overall structure of the process is shown in Figure 1.

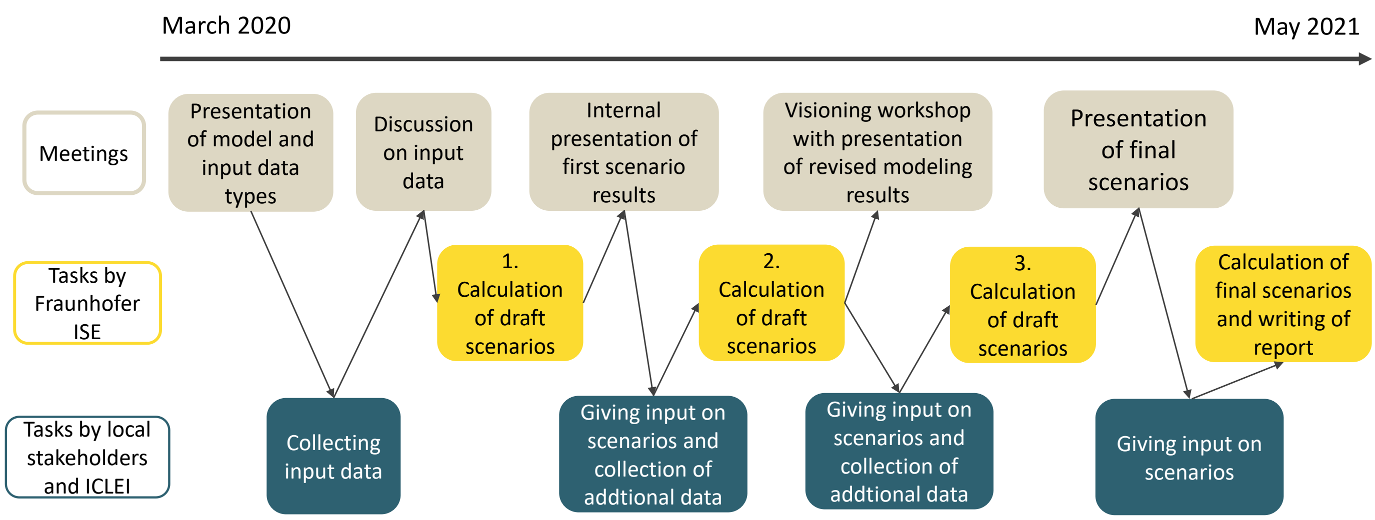


Figure 1: Structure of the process of energy system modeling between the different stakeholders

The outline of this report is as follows. Chapter 2 is giving a short overview about the project and the deep dive region of West Nusa Tenggara, Indonesia, which is the focus region of this report. In Chapter 3 a detailed description of the model is given including the scope of the model, its advantages, and its limitations. All used input data for the model as well as used sources and assumptions to calculate these input data are presented in chapter 4. Different scenarios are calculated to show the robustness of the different options, described in Chapter 5. The final scenario results are presented in Chapter 6 together with a transition plan for the leading scenario and a risk analysis linked with recommendations for how to overcome these risks. In Chapter 7 a short summary of the most important findings is given.

2.1 Energy supply and demand situation in the three countries

2.1.1 Argentina

In Argentina, the energy sector was privatized as part of the 1992 energy reforms. As a result of this restructuring, most energy production, transmission, and distribution fell into private hands. Only the state-owned nuclear power company and two hydroelectric plants still belong to the public sector (Pollitt 2008).

As one of the main producers of natural gas and oil in South America, Argentina meets about 75 % of its total electricity demand from fossil fuels. The share of renewable energy in electricity generation decreased from 36% to 25% between 1990 and 2019 due to a combination of rising electricity demand and rather constant renewable energy supply. The largest contributor to this share of renewables is hydropower, which covers about 20 % of electricity demand (in 2019). Excluding hydropower, renewable electricity generation has a share of only 5.3 % (in 2019).

Looking at the total primary energy consumption of Argentina, fossil fuels contribute about 91.7 % and RE 8.3 % (from Hydropower 3.5 %; biomass/waste 4.6 %; and geothermal, solar, wind 0.16 % (in 2018). (International Energy Agency 2021)

In Argentina, there are still quite a few tax breaks for companies investing in oil and gas production. However, Argentina also increased electricity prices at the end of January 2017 in order to reduce energy subsidies and narrow the budget deficit. This creates opportunities to promote decentralized RE, especially as forecasts predict growing demand for energy.

2.1.2 Indonesia

Perusahaan Listrik Negara is a state-owned company that controls power generation, transmission, and distribution in Indonesia. The power generation market is open to private and independent power producers, but they must sell their power to PLN. However, the National Bureau of Asian Research has made the following assessment: "Despite loud calls for infrastructure development along the value chain, PLN's limited capacity and poor liquidity, caused by rising generation costs and subsidies, have prevented any development." (Bravo et al. 2015) Clearly, reforms and a transformation of the energy sector in Indonesia are needed.

Indonesia faces the challenge of meeting its national climate change target in the energy sector on the one hand and meeting the increasing energy demand for the country's economic growth on the other. The country's archipelagic location also makes it difficult to distribute energy evenly.

Indonesia is currently heavily dependent on fossil fuels, which account for 64.2 % of total energy consumption. RE's share to date has come from geothermal, wind and solar (10.4 %), hydropower (0.8 %), biodiesel, and waste (14.5 %) (in 2018). (International Energy Agency 2021)

These existing renewable sectors have the potential for further expansion. However, given growing energy demand and national emission reduction commitments, these sectors need to be complemented by decentralized RE solutions such as those supported by this project.

2.1.3 Kenya

Kenya Power owns and operates most of the power transmission and distribution systems in Kenya. The government holds a majority stake of 50.1 % in this company and private investors hold a 49.9 % stake (Kenya Power 2015).

Kenya Electricity Generating Company Limited (KenGen) is the largest electricity-producing company in Kenya, managing about 80 % of the installed capacity for electricity production. The company uses various energy sources for electricity production, from hydropower to geothermal and wind. Due to the reform of the Kenyan power system in 1997, KenGen was decoupled from Kenya Power. Now 70 % of KenGen's shares are owned by the Kenyan

government. Both Kenya Power and KenGen are listed on the Nairobi Securities Exchange. (KenGen 2021)
An analysis of the national energy supply mix shows a heavy reliance on fuelwood and other biomass, which account for 63.5 % of total energy consumption. Oil has a 18 % share, coal 0.95 %, hydropower 1.2 % and Wind, geothermal and PV about 16.2 % (all in 2018).
Renewable energy sources have a high share of electricity generation in Kenya. In 2018, this was 83 %, with about 30 % hydropower, 40 % geothermal, 11 % wind, 1.7 % solar, and 1.4 % bioenergy (International Energy Agency 2021).
In 2018 75 % of the population had access to electricity, and the government has a stated goal of 100% access by 2030. Much of the progress in the last years can be attributed to solar home systems. (Alliance for rural electrification 2019)
Kenya currently has one of the most active markets for commercial solar photovoltaic (PV) systems compared to other developing countries. This increases the potential for access to affordable RE technologies. The government is waiving the 16 % VAT on all solar products to make them more attractive, especially for rural, sparsely populated, arid, and semi-arid areas. (Munyaka and Becker 2016)

2.2 Case study West Nusa Tenggara

West Nusa Tenggara (WNT) was chosen as the deep dive region for Indonesia. WNT is a province consisting of two larger islands, Lombok and Sumbawa, and smaller islands around them. Some key facts are summarized in Table 2.

Table 2: General information about West Nusa Tenggara

Location	Province of Indonesia, Coordinates: 8°35’S 116°7’E
Size	20,124.48 km², Sumbawa makes up 3/4 of it
Capital	Mataram (located on Lombok)
Currency	Indonesian Rupiah (exchange rate on 03.05.2021: 1 IDR = 0,0000574829 EUR)
Population	5,070,385 inhabitants and 1,407,554 households (mean household size of 3.6)
Climate	Tropical climate; mean annual temperature of 27 °C and ranges between 21 °C and 36 °C. West Nusa Tenggara has relatively little rainfall compared to the western region of Indonesia.
Main economic activities	Dominant primary sector economy: Food Crops Agriculture, Livestock, Fisheries, Tourism, Ore Mining, Food and Beverage Manufacturing, Tobacco Products Manufacturing, Wholesale and Retail Trade.
Grid electrification rate	99.55 %

74 % of WNT’s electricity demand is covered by the state-owned electricity company Perusahaan Listrik Negara (PLN), while 26 % is covered by independent power producers. Only for the part from PLN, the shares of different supply technologies are known as follow. 81 % is coming from Diesel generators, 18 % from steam power plants using mainly coal and 1 % is coming from renewable energies, mostly from hydro power plants (Islami and Aditya 2020).

3 Energy system modeling with KomMod

The energy system optimization model 'KomMod' identifies the cost minimal combination of supply technologies for an energy system, given specific goals and defined boundary conditions. KomMod takes the dynamics of the system into account by optimizing the entire energy system (electricity, heating/cooling, and energy for transport) over one year in hourly temporal resolution. This enables the detailed representation of fluctuating energy sources and analysis and consideration of the feasibility of each technology.
As input data, KomMod requires demand profiles for electricity and heat in hourly resolution for one year. Furthermore, economic and technological parameters for all considered technologies are required as well as detailed information on the potentials of the available energy sources. Information on climate data is also required. For consistency, all data is projected for the target year– in this study, the year 2050.
The model optimizes the supply side of the energy system to achieve the minimal total costs of the energy system while adhering to the given constraints, such as the target share of renewable energy generation or the restriction on energy import or export. Total costs include investments, operation and maintenance costs, as well as fuel costs, if applicable. The results provide data on the optimal capacity of each technology to be installed as well as an optimal hourly operation plan. Additionally, the temporal profile of import and export of electricity is calculated in case the local units are not capable of covering the energy demand at all times or are generating surpluses.
Mathematically the optimization is done by setting up a linear equation system which then is solved by the Simplex algorithm. Besides the physical and economic descriptions of each technology, there are some main equations forming the equation system. The central equation is named the objective function and defines the goal of the optimization. In this study, it aims to minimize the levelized total annual costs of the energy system. The most important physical equations are the energy balances for electricity and for heat for each temperature level. They combine the energy output, restrictions and conditions of each technology with the given demand in each sector. Accordingly, these equations incorporate the relevant occurring interdependencies. They assure that the given energy demand for each sector is covered in every hour of the year.

A graphical representation of the model is given in Figure 2. The energy sources used are depicted on the very left side of Figure 2, these are mainly renewable energy sources, but the utilization of fossil fuels is also possible. Wind energy, photovoltaics and hydro power resources and conversion are summarized in the figure and not shown separately. All other conversion technologies are depicted in the middle part of the figure. In the left column, all conversion technologies producing either heat, cold, or electricity out of the different resources are shown. In addition to combined heat and power (CHP) plants, which produce heat and electricity by converting different kinds of fuels like biomass, biogas, or even fossil fuels, there are boilers, heat pumps, power-to-heat and chillers using either heat (absorption) or electricity (compression) to produce cold.

In the middle column, different technologies producing or using synthetic fuels are depicted. Electrolyzers use electricity to produce hydrogen and excess heat from the exothermal process. This hydrogen can be either used directly in the transport sector or in industry, but it can also be stored and later converted to electricity again with fuel cells, or it can be used to produce other synthetic fuels like methane or methanol. To produce these synthetic fuels carbon dioxide is needed in addition to hydrogen. This carbon dioxide can be either extracted from the air via direct air capture or extracted from exhaust gases from combined heat and power plants. Both extraction processes as well as the synthesis processes need heat and have certain losses. Although producing methane and methanol is much more energy-intensive than producing hydrogen, still it has some advantages. Methane can be used in the same way as natural gas and therefore fed into a gas grid or used in a gas power plant.

Methanol is a liquid fuel which is easier to store and transport. Overall, hydrogen is quite hard to handle as it is very volatile. As it has a low density it must be compressed to at least 200 bars to be transported, and it is easily flammable.
In the last column, all storage technologies implemented in KomMod are depicted. These are electrical storages, mainly batteries, but hydro storages are also possible to be implemented here; heat and cold storages as well as fuel storages for hydrogen but also other fuels that have been produced and shall be used at a later time. In the very right of the figure, the different consumer types are shown. Normally these are households, commercial enterprises, industries, and the transport sector. It should be noted that for electricity all demands are summed up in the model to one demand time series that has to be covered at every hour of the year, because in the model the grid is seen as ideal and no transmission restrictions for any energy type are taken into account. For heat, different types of heating demands can be implemented in the model and they can be assigned to different technologies. For the specific case of West Nusa Tenggara besides commercial heating demand, cooking demand is prevalent. These demands are covered by different technologies and are therefore implemented in the model separately.

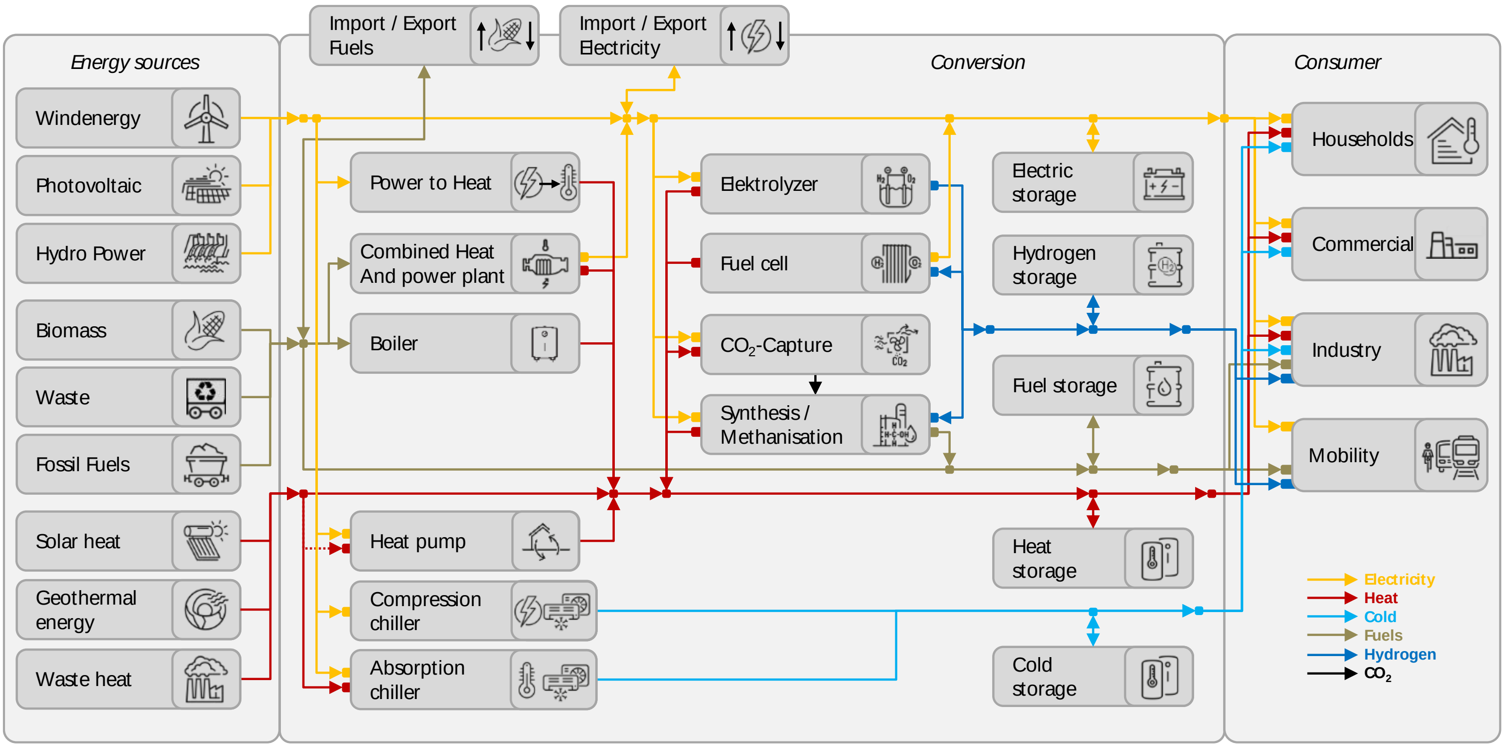


Figure 2: Graphical representation of the model KomMod with all technologies included

KomMod is minimizing and therefore considering total system costs. As described above this includes capital costs and operation and maintenance costs for all technologies as well as fuel costs, costs for the import and export of energy, if applicable as well as possible costs for carbon dioxide emissions. But there are costs of “real” energy systems which lie outside the scope of the model which is the reason why **the modeling results should be interpreted as stylized scenarios showing possible options for future energy systems**. Costs not considered in the model include network charges, grid expansion costs, and profits for energy providers.

4 Input data

Section 4.1 describes all energy demand projections in detail, including the applied time series. The potentials for all applicable kinds of renewable energy technologies are described in 4.2 while all used costs data is stated in chapter 4.3. In the last subchapter 4.4 the used weather data is presented.

4.1 Energy demands today and projections

Energy demand has to be projected to the year 2050, which is the target year of all calculated energy system scenarios. All relevant demand sectors are included in the scenarios, with exception of aviation (see chapter 4.1.5). Cooling demand is added to the electricity demand and its coverage is not optimized but given exogenously to the model (see chapter 4.1.4). It is assumed that cooling demand will be met with compression chillers. In the following subchapters, the demand projections for every demand sector are summarized with all used sources and calculation steps. In the last subchapter (4.1.6) a summary of the total energy demand today and in 2050 is given.

4.1.1 Macroeconomic developments

Energy demand in the different sectors is often correlated to the development of GDP, population or value added. By assessing the correlation between the sector-specific energy demand and the aforementioned indicators, future energy demand developments can be projected when the development of the indicators is known. Because of this, projections for population and GDP development are discussed below. Historical Population and GDP development are taken from BPS statistics of Nusa Tenggara Barat Province (2020). Population and GDP development until 2050 are included in Gubernur Nusa Tenggara Barat (2019). Both official development reports are compared with an extrapolation of the historic development. For population, the future development from Gubernur Nusa Tenggara Barat (2019) is taken, according to an extrapolation of the historic development. For GDP the official projection and an extrapolation of the historic development differ significantly. The two GDP developments are shown in Figure 3.
The official GDP development from Gubernur Nusa Tenggara Barat (2019) shows a much higher trend than the one extrapolating the historic development. The official projection of GDP predicts a growth of 10.5x from 2020 to 2050, whereas an extrapolation of the historic

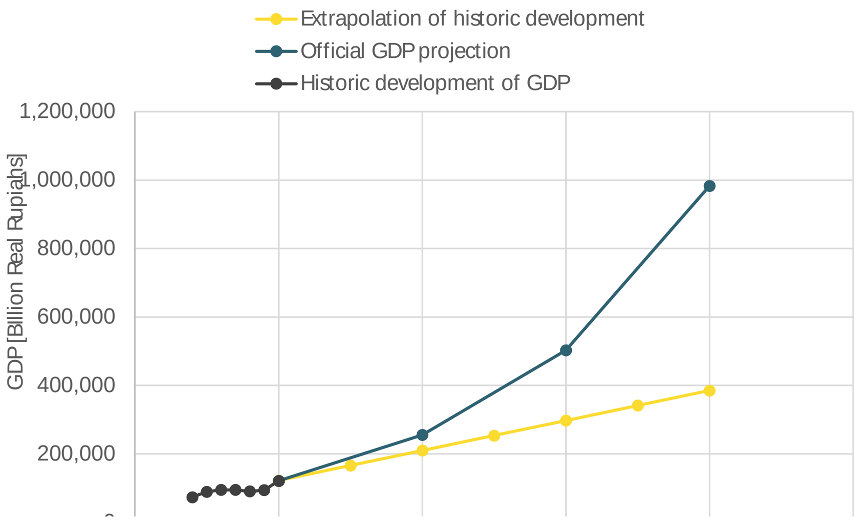


Figure 3: Historic data for GDP as well as two projections for future development until 2050

development predicts growth of only 4x in the same time period. The resulting developments for population, GDP (low and high) are given in Table 3. In the following chapters it will be described which developments are taken to make projections for the different demand categories.

Table 3: Values for 2019, 2020, 2030 and 2050 for population and two possible GDP developments

	2019	2020	2030	2050
Population [1000]	5070	5143	5491	6265
GDP high acc. To (Gubernur Nusa Tenggara Barat 2019) [Billion Real Rupiahs]	94,015	121,103	255,456	982,838
GDP low: extrapolation of historic development [Billion Real Rupiahs]	94,015	121,948	209,685	385,158

4.1.2 Electricity demand

The electricity demand is known for the years 2014-2019 for West Nusa Tenggara for the different demand sectors (Directorate General of Electricity 2016-2020). For several reasons the total electricity demand, instead of sector-specific demand, is projected to 2050. The shares of the different sectors are kept the same from today to 2050. This is a simplification, as demand can develop differently in the different sectors, due to growing GDP, population development and development of standard of living. Nevertheless, there are several reasons why keeping the shares of the sectors constant is still the most robust method. These reasons are:

- A mathematical correlation between the electricity demand and e.g. population or GDP is hard to calculate based on 5 data points, only trends can be assessed based on the given data
- As seen in Figure 4, electricity demand is dominated by household electricity demand which shows a rather linear trend while industrial and commercial electricity demands do not show such clear trends
- The electrical load curve is only given for the total electricity demand and is taken for the scenarios for 2050 without any adjustment. A decomposition analysis is not possible based on the given data. Therefore, leaving the shares of the sectors is a consistent method based on the given load curve.

The total electricity demand is therefore correlated to high and low GDP as well as population and the corresponding electricity demands are shown in Table 4.

Table 4: Projection of electricity demand calculated with both GDP developments and population development for the year 2050

	GDP high	GDP low	Population
Electricity demand in 2050 [GWh]	40,040	14,901	5,767
Increase of electricity demand compared to 2019 values [times 2019 demand]	23	8.66	3.35

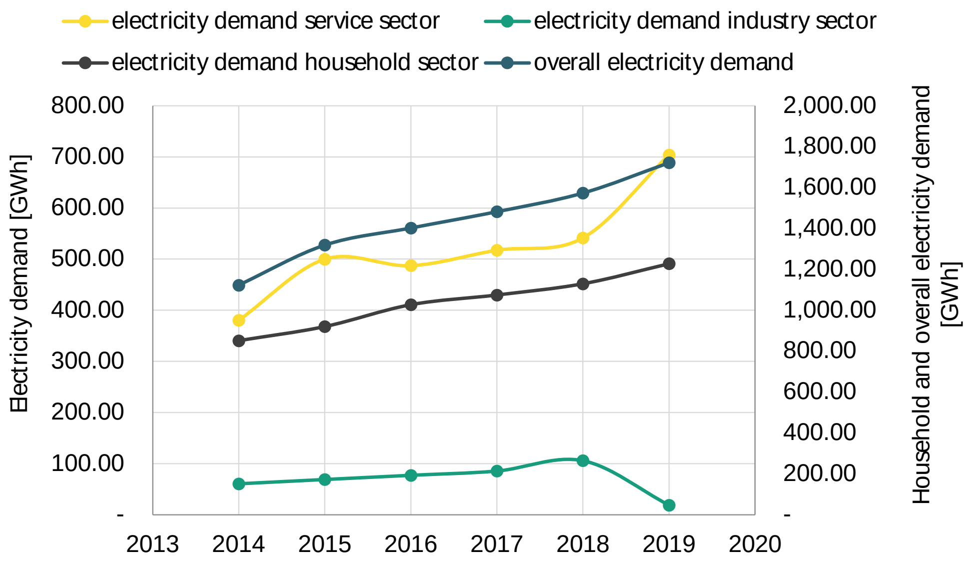


Figure 4: Electricity demand in the different sectors for the years 2014-2019

Comparing the specific electricity demands shall help to judge on a realistic increase of electricity demands until 2050. For this purpose, the specific electricity demands for 2050 are compared to the specific demands today for Germany and Thailand (see Table 5). Germany is used as a reference for an industrialized country with a high electricity demand and Thailand as a newly industrializing country in the same region of the world as Indonesia. As values for Thailand and Germany are for the present day, it should be questioned how electricity demand (transport and heating not included) shall develop until 2050 in these countries. For Germany it is normally projected that it will decrease (Sterchele et al. 2020) while for Thailand it is assumed instead that it will increase (Thailand Ministry of energy 2015).

Table 5: Specific electricity demands in West Nusa Tenggara today and in 2050 in comparison with specific electricity demands today in Germany and Thailand

	Specific electricity demand calculated with total demand	**Specific electricity demand calculated with residential demand**
	[kWh/cap]	[kWh/cap]
West Nusa Tenggara in 2019	385	242
West Nusa Tenggara in 2050 with demand correlated to population	1824	673
West Nusa Tenggara in 2050 with demand correlated to GDP low	4183	1633
West Nusa Tenggara in 2050 with demand correlated to GDP high	8195	4116
Germany in 2019 (Bundesministerium für Wirtschaft und Energie 2021)	6237	1558
Thailand with data from 2016 and 2018 (International Energy Agency 2018; International Renewable Energy Agency 2017c)	2372	545

If the trend for population development is taken to project electricity demand of West Nusa Tenggara, the specific electricity demand calculated with residential demand is in the same order of magnitude as the specific demand in Thailand while the specific demand calculated with the total demand is slightly lower than the demand in Thailand. If the low GDP development is taken to make a projection on the electricity demand of WNT in 2050, the specific demand calculated with the residential demand is comparable to German values. The specific demand calculated with the total demand is lower in WNT than in Germany. The specific demands calculated with the electricity demand projected with high GDP are way higher than the values from Germany and Thailand. The shares of the different sectors for the total electricity demand (see Figure 4) show that WNT has a low electricity demand in the industrial and commercial sector, tourism and agriculture are important branches of the economy. Germany and Thailand are both countries with a high share of energy-intensive industries which explains while the total specific electricity demand should be higher. The residential specific electricity demand is an indicator for the demand in households induced by electronic devices used and households connected to the grid which is correlated to the household's prosperity. Therefore, the two demand projections with population and low GDP are taken in the scenarios.

Time series of electricity demand are given for the two islands separately (PLN Regional of West Nusa Tenggara 2020). For Lombok data is available for the years 2011 until mid-2020 and for Sumbawa data is available for 2016 until mid-2020. For the scenario calculations, the time series for the year 2019 are used, as the most recent data should be the most representative one. A qualitative comparison of time series from several years from both islands found no major differences.

In Figure 5 the distribution of electricity demand for Lombok in deciles is shown. In this diagram electricity demand for all 52 weeks of one year is taken and it is calculated which percentage of the values for every hour of the week are in a certain range. The 0,5 decile, named q50, is the median, which means that 50 % of the values are below the shown value and 50 % are above. The same definition holds true for the other deciles. For example, the q30-70 means that 30 % of all values (the 30 % lowest ones) are below the shown respective area and 30 % are above (the 30 % highest ones). The load profile has a high peak on every day of the week at 7 PM. This is a rather typical pattern. At this time everyone comes home, switches on the lights as the sun goes down, and starts using different devices like television, computers, or rice cookers; in addition, electricity demand in restaurants will be at its peak at that time. Afterwards the electricity demand goes down and reaches its lowest value at 4 AM, when nearly everybody is asleep. A small peak can be seen in the morning hours when people who go to work or school wake up and prepare themselves to leave the house. Afterwards it goes down again and starts to rise during the day on a low level. The seven days of the week don't show a large difference, the 8 am peak is slightly lower at the weekends as fewer people go to work or school. The pattern for Sumbawa doesn't show a great difference, but the same behavioral patterns can be investigated (see Figure 6).

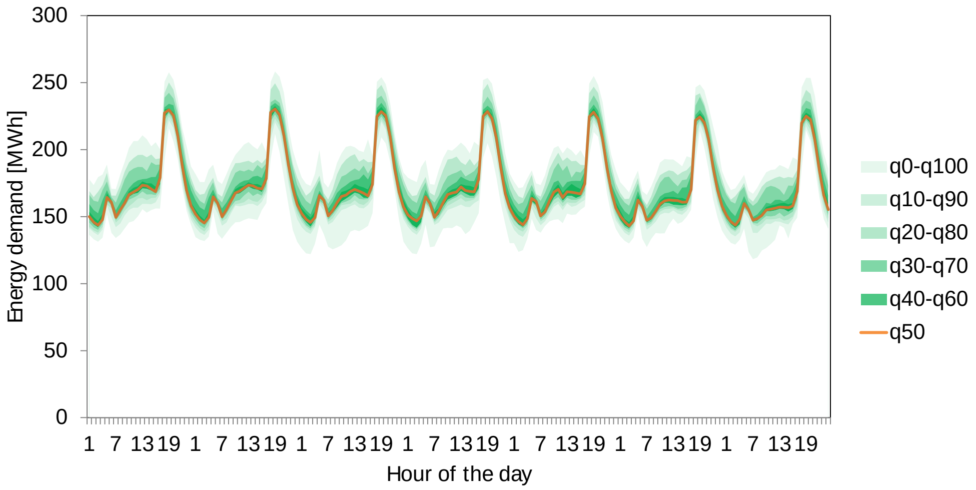


Figure 5: Distribution of the electricity demand in Lombok shown in deciles (Monday until Sunday)

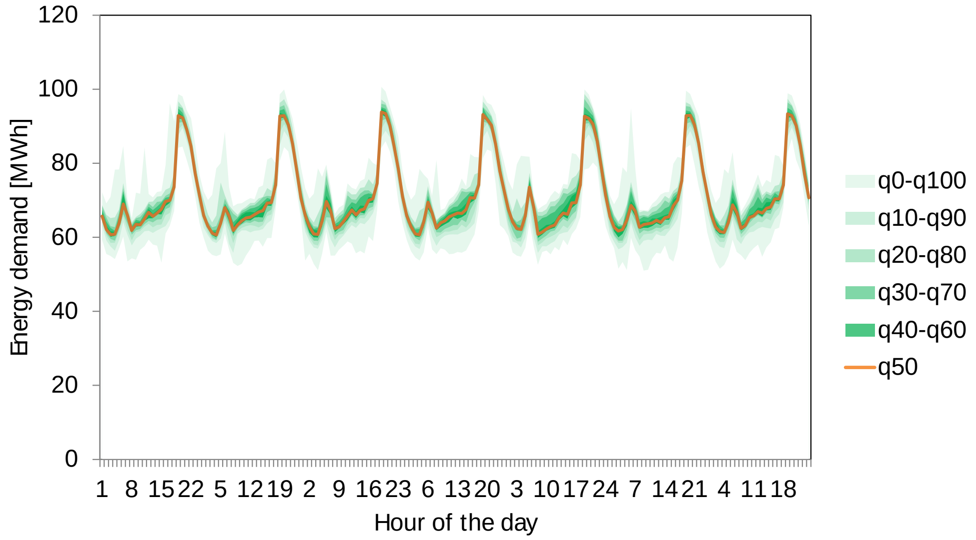


Figure 6: Distribution of the electricity demand in Sumbawa shown in deciles (Monday until Sunday)

4.1.3 Cooking, heating and commercial and industrial fuel demand

In the household sector there is no heating demand, only cooking demand. Outside temperatures are high all year round, and there is no need for space heating. For cooking three different fuels are used today: biomass, gas, and oil. Biomass is the most important cooking fuel with a share of 63 %, the share of gas is 36 %, and oil plays only a minor role (values for the year 2019) (BPS statistics of Nusa Tenggara Barat Province 2020). The scenario calculations require the useable energy demand for cooking, not the primary energy demand for cooking fuels, as fuel transitions and efficiency improvements shall be taken into account. Because of that, the useable energy demand for cooking is calculated using mean efficiencies for the different stove types for the present day. These efficiencies are taken from Morelli et al. (2017). The specific final energy demand for cooking per capita is then calculated. It is further assumed that the per capita useable energy demand for cooking in households will stay constant until 2050. Useable energy demand for cooking is dependent on duration of cooking and amount of stoves used during cooking. Keeping the useable energy demand the same means cooking habits will not change drastically in the next 30 years. This leads to a total useable energy demand for cooking that is rising with population increase.

Cooking, heating, and fuel demand in the commercial sector is assessed via detailed data on fuel demand in different commercial branches (Rosmaliati 2020). The different fuel types are linked to different usage forms according to Table 6. The useable energy demand is calculated from the fuel demand with mean efficiencies for today. For cooking demand, these efficiencies are taken from Morelli et al. (2017), for heating demand an efficiency of 80 % is assumed. For fuel demand in machinery and vehicles no conversion to useable energy is done as processes are manifold and efficiencies are hard to assess. By not assuming any efficiency progresses for machinery and vehicles in the commercial sector the demand will likely be overestimated.

Table 6: Fuel demands in different commercial subsectors and calculated final energy demand

Subsector	Usage form	Fuel demand in 2019 [GWh]	Calculated useable energy demand in 2019 [GWh]
Commercial food and beverages			
Diesel	machinery and vehicles	12	12
Kerosene	cooking	39	18
LPG	cooking	987	483
charcoal	cooking	247	49
Sum		**1285**	**562**
Commercial: rest			
Diesel	machinery and vehicles	6	6
Kerosene	heating	259	207
LPG	cooking	241	118
charcoal	cooking	654	131
Sum		**1160**	**462**
Agricultural and other fuel demand (for machinery and vehicles)			
Premium (gasoline)	machinery and vehicles	1297	1297
Diesel	machinery and vehicles	474	474
Sum		**1771**	**1771**

Starting from present day final energy demands, the future demands are calculated by correlating the demand to GDP development. For the high demand scenario, the high GDP increase is taken; for the low demand scenario, the low GDP increase. This will lead to an overestimation of demands, as a high GDP increase shows very high values for 2050 (see chapter 4.1.1 and 4.1.2). The resulting useable energy demand for cooking and heating in the different sectors is shown in Table 7.

Table 7: Resulting useable energy demands for cooking, heating and fuels in households, commercial and industrial sector

	Useable energy demand in 2050 high demand scenario [GWh]	**Useable energy demand in 2050 low demand scenario [GWh]**	**Additional remarks**
Household cooking demand	271	271	
Commercial cooking demand	7065	2769	
Commercial heating demand	2009	781	
Commercial and industrial fuel demand for machinery and vehicles	13874	5436	Assumption that ¼ is heating demand, 3/8 can be electrified and 3/8 is covered by synthetic fuels

Because of temporal resolved modeling, time series for all demands are needed. Cooking times are taken from Durix (2015), which states reference cooking times for Indonesia: morning cooking takes about 65-80 minutes and evening cooking takes about 30 minutes and nearly no cooking is happening for lunch. It is assumed that energy demand for cooking is equally distributed over all days of the year. The cooking time series for one day for Lombok is shown in Figure 7.

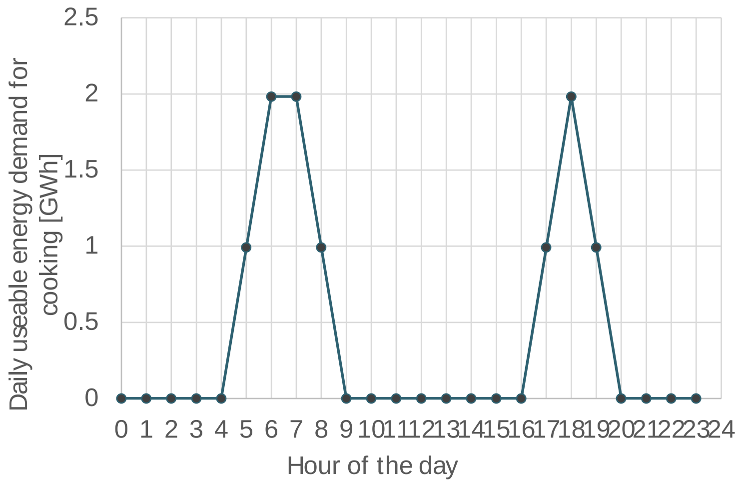


Figure 7: Daily cooking time series for Lombok in 2050

Industrial and commercial heating demand is equally distributed over all hours of the year while fuel can be produced at any time of the year and only the yearly amount of fuel needed is given to the model.

4.1.4 Cooling demand

Cooling demand is playing a minor role today but projections from International Energy Agency (2019) state that it will increase significantly in the future as general household welfare increases. Figure 8 shows a projection for the number of air conditioning units in households and in the commercial sector through 2040 for Indonesia and the rest of South East Asia. For simplicity, the 2040 values are taken for 2050. The increase of units from 2017 (the base year of the diagram) and 2040 is calculated. Further, a mean efficiency of air conditioning units today of 3 is assumed, rising to 5.5 in the high demand scenario and to 8 in the efficiency scenario based on information from International Energy Agency (2019). This results in the electricity demands for cooling shown in Table 8.

Table 8: Electricity demand for cooling today and in the two demand scenarios

	Electricity demand for cooling 2017 [GWh]	**Electricity demand for cooling high demand scenario in 2050 [GWh]**	**Electricity demand for cooling low demand scenario in 2050 [GWh]**
Households	109	849	583
Commercial sector	87	380	262

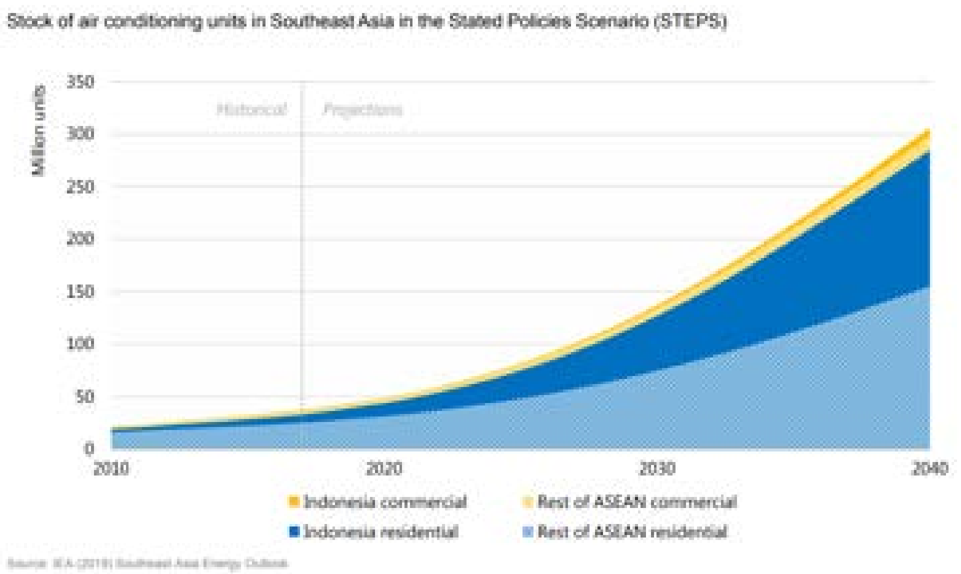


Figure 8: Stock of air conditioning units in Indonesia and the rest of south east asia historic and projections (International Energy Agency 2019)

The time series of electricity demand for cooling is based on the method of cooling degree days. For this method, a certain indoor temperature is given that people would like the buildings to be cooled down to, and a certain outside temperature is defined above which people start to use cooling devices. Both temperatures are set to 25 °C. The resulting electricity demand time series for cooling for Sumbawa in 2050 is shown in Figure 9. Cooling demand is prevalent all year as West Nusa Tenggara does not experience strong seasons, but it can be seen that cooling demand is a little bit lower in the summer months, because of slightly lower outside temperatures.

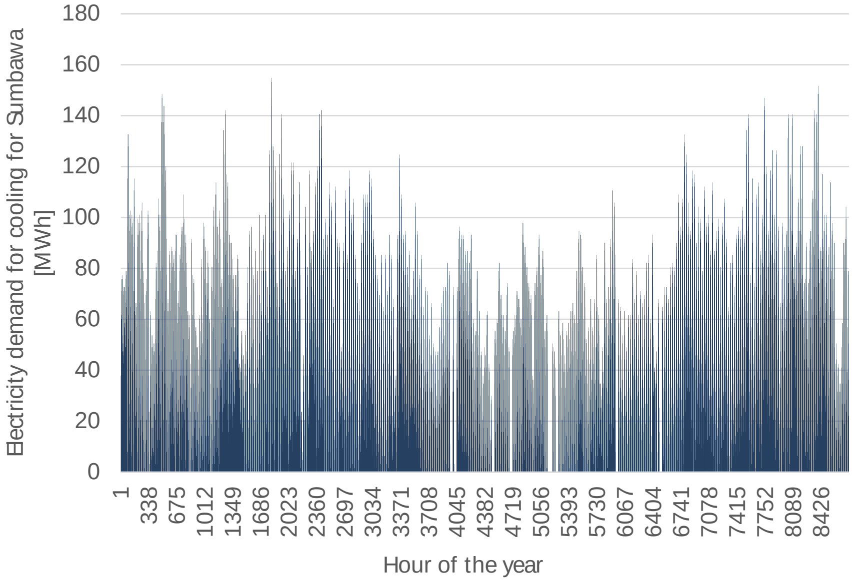


Figure 9: Yearly time series for electricity demand for cooling for Sumbawa in the year 2050

Figure 10 is the same type of diagram as Figure 5 and Figure 6, where the diagram type is explained in detail. It is evident that demand is usually zero in the night when the sun is not shining, and temperatures decrease. During the day, at around 2 pm, cooling demand reaches its peak.

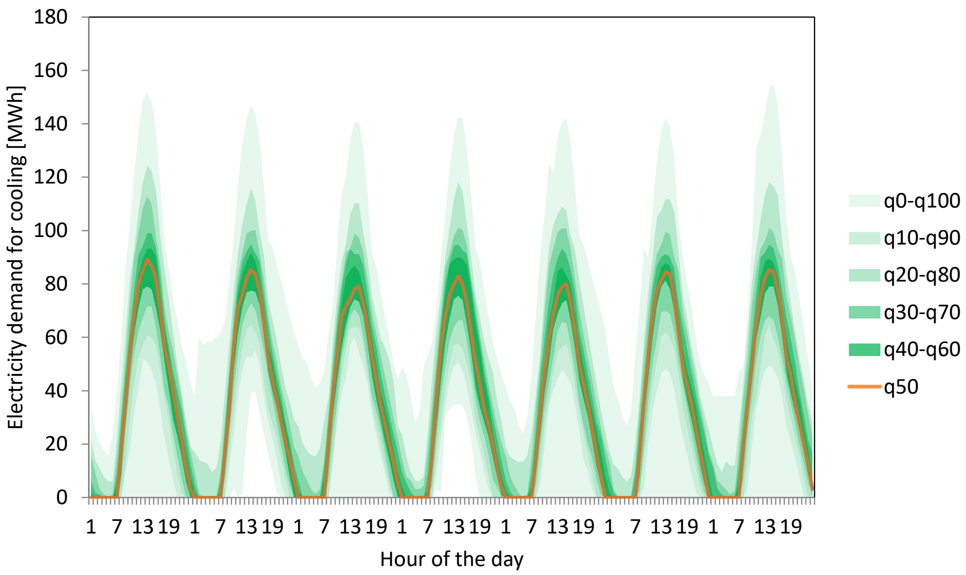


Figure 10: Distribution of the electricity demand for cooling in Sumbawa in 2050 shown in deciles (Monday until Sunday)

4.1.5 Energy demand for transport sector

Detailed information on the fuel demand of different vehicle types for the fuels: diesel gasoline and jet fuel (avtur) is available for the years 2014 until 2019 (Rosmaliati 2020). Jet fuel is only used in aviation and this subsector is excluded from the analysis. The calculation of the future final energy demand of the transport sector is based on the assumptions that the share of demand of the different vehicle types stays the same from today until 2050. For the assessment of the overall fuel demand of the transport sector in 2050, no WNT specific data is available but data for the whole of Indonesia is used. Three different sources state projections for fuel demand in the transport sector, these projections are summarized in Table 9.

Table 9: Summary of different sources stating future energy demand in transport sector in Indonesia

	Fuel demand today [TWh]	**Fuel demand in 2050 BAU scenario [TWh]**	**Fuel demand in 2050 efficiency 1 scenario [TWh]**	**Fuel demand in 2050 efficiency 2 scenario [TWh]**
Biofuels policy in Indonesia: Overview and status report (Kharina et al. 2016) (no distinction for different vehicle types)	2015: 560	2932	-	
Indonesia energy outlook 2016 (Prasodjo et al. 2016)	2015: 491	**2329**	1795	**1328**
Indonesia energy outlook 2019 (Suharyati et al. 2019)	2018: 480	1387	1209	1191

Kharina et al. (2016) and Prasodjo et al. (2016) state a quite similar increase of transport energy demand, being 5.23 times higher than in the base year for the former and 4.74 times higher for the latter. The more recent study from Suharyati et al. (2019) states a much lower value for 2050 and an increase by 2.89 times. It is important to consider which types of vehicles are assumed to be used in 2050 as the final energy demand is dependent on the type of vehicle and drive train concept. In all three projections, vehicles using fossil fuels or biofuels are assumed to be used in 2050 and electric vehicles have a negligible share. To project the increase of vehicles in BAU scenario and efficiency scenario for transport sector, two scenarios from Prasodjo et al. (2016) are taken. The resulting final energy demand of a scenario where fossil or synthetic fuels are solely used in the transport sector for West Nusa Tenggara is 22,179 GWh in the high demand scenario and 13,522 GWh in the low demand scenario. As 100 % RE shall be reached with the scenarios calculated in this study, the resulting final energy demand using fossil fuels in the transport sector is then adapted to a scenario where vehicles use either electricity or hydrogen. Table 10 presents the share of the different drive train concepts in 2050 in the scenarios. The used final energy demands of the different vehicles types and drive train concepts are presented in Appendix B.

Table 10: Share of different drive train concepts for vehicles in 2050

	Share of electric vehicles	**Share of hydrogen vehicles**	**Share of vehicles using synthetic fuels**
Car	100 %	0 %	0 %
Motorcycle	100 %	0 %	0 %
Truck and bus	50 %	50 %	0 %
Navigation	0 %	0 %	100 %

For cars and motorcycles, it is assumed that they will drive 100 % electric in 2050. Direct usage of electricity for vehicles should always be preferred if possible, as the efficiency is

much better when using electricity directly instead of first converting it to hydrogen and then back to electricity in the vehicle. The largest constraint for direct usage of electricity is the need for charging which leads to the need for charging infrastructure.
Motorcycles usually drive short distances and therefore it can be assumed that the charging process can be executed mostly at home. Cars normally are used to drive larger distances which could lead to the necessity of charging infrastructure. But as West Nusa Tenggara consists of two islands, distances are limited naturally. Trucks and busses have a much higher specific energy demand because of their higher weight. This limits the drivable distance of electric trucks and busses and makes regular charging necessary. Because of that, a share of 50 % of hydrogen vehicles is assumed. Boats and ships are assumed to use synthetic fuels and electricity directly each by 50 % in 2050. It is still discussed which range must be achieved by electric trucks and busses to ensure economically feasible operation. Electric busses and trucks have the advantage that energy demand is lower, as they can use electricity directly, while hydrogen trucks and busses have a higher range but energy demand is higher. Assuming 50 % hydrogen trucks in Avellaneda in 2050, the estimation of energy demand is to the safe side.

Hydrogen and synthetic fuels can be produced at any time of year and stored until needed, so no time series is given to the model. For electric vehicles, a simple charging time series is taken which is shown in Figure 11. For this time series, it is assumed that most vehicles are charged in the evening hours when people come home and vehicles are not used anymore.

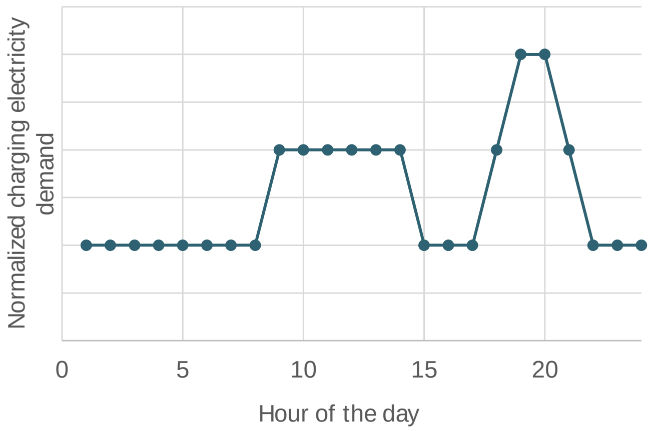


Figure 11: Normalized charging electricity demand for electric vehicles for West Nusa Tenggara in 2050

4.1.6 Demand today and in 2050

The total final energy demand of all included demand sectors is 10,119 GWh today (see Figure 12). The largest share is fossil fuel demand in the transport sector with 50.7 %. In 2050 in the high demand scenario total demand is 47,247 GWh and therefore 4.66 times higher than today. In the low demand scenario, total demand is 20,410 GWh and therefore 2.02 times higher than today. In 2050 transport energy demand is covered with electricity and hydrogen and has a share of 16.7 % of total final energy demand in the high demand scenario and of 22.2 % of total final energy demand in the low demand scenario. In 2050, Electricity demand has the largest share with 31.5 % in the high demand scenario closely followed by commercial fuel demand with 29 %. The increase of commercial demands is dependent on the two GDP projections (see chapter 4.1.1). In particular, the high GDP increase can be rated as very ambitious, leading to an increase in commercial fuel demand by 7.63 times. The share of the different demand sectors does not stay the same between present day and future scenarios, as the methods to project the different demands are different for every sector. (See chapter 4.1.2 to 4.1.5). In Appendix A, a table showing all demands today and in 2050 can be found.

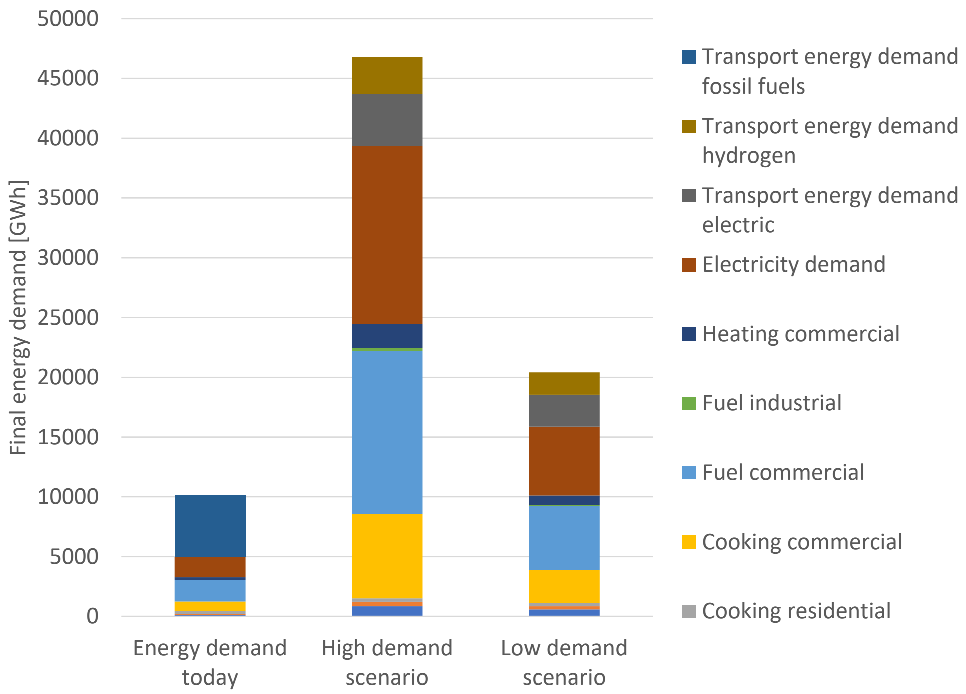


Figure 12: Final energy demand today and in the two demand scenarios in 2050

As already stated above, the highest share in final energy demand today is the transport sector with 50.7 % or 5133 GWh. Commercial and industrial sector comes second with 34.7 % (Figure 13).

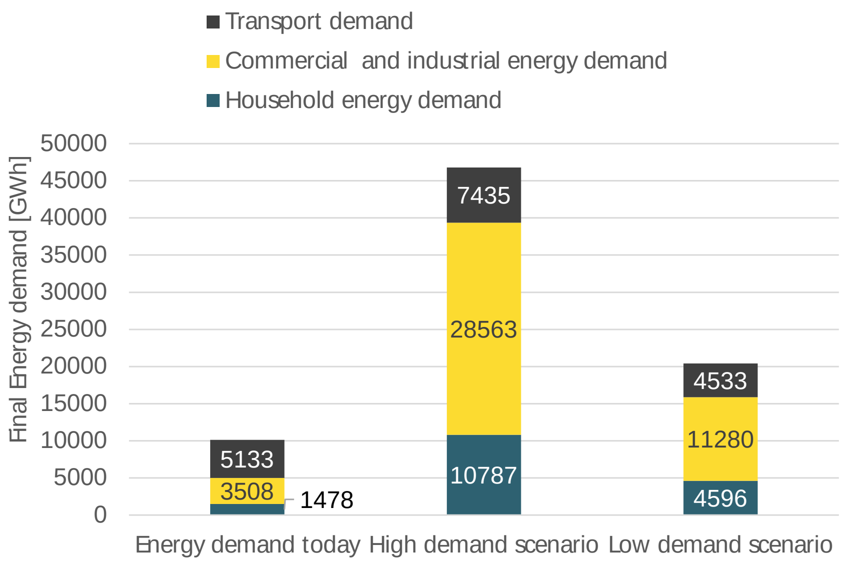


Figure 13: Energy demand today and in the two demand scenarios divided by sectors

Electricity demand in the commercial and industrial sector is small with 605 GWh or 5.9 % of total final energy demand. But the commercial fuel demand is much higher with 1788 GWh. Households have a larger electricity demand than the commercial sector of 1116.5 GWh but only a small fuel demand for cooking of 253 GWh. In the future scenarios, the commercial and industrial sector has the largest share with 60.4 % in the high demand scenario and 55.3 % in the low demand scenario. This increase can be attributed to two reasons in particular.

First, the correlation of fuel, heating, and cooking demand in commercial sector to GDP increase and second the increase in efficiency in the transport sector as vehicles with electric drive trains consume less energy per driven km than vehicles with gasoline and diesel engine.

4.2 Renewable energy potentials

In the following chapter data processing for the evaluation of all different renewable energy potentials are described in detail.

4.2.1 Wind energy and Free field photovoltaic potential

The assessment of the potential for solar photovoltaic power plants and wind power plants is based on GIS data (Regional Planning Agency of West Nusa Tenggara 2020) for West Nusa Tenggara disaggregating for thirty different land-use types as shown in Table 11.

Table 11: Land use types in West Nusa Tenggara and their area on the two islands Lombok and Sumbawa

	WNT	**Lombok**	**Sumbawa**
	area [km²]	area [km²]	area [km²]
Building	581.49	422.41	159.08
Bush	1593.07	194.08	1398.99
Canal	0.33	0.00	0.33
Coastal area sand	28.21	9.52	18.69
Domestic airport	1.53	0.56	0.97
Dry primary forest	4212.70	758.27	3454.43
Dry secondary forest	6149.55	810.40	5339.15
Free field	1.20	0.00	1.20
Grassland	3037.33	594.33	2443.00
International airport	5.36	5.36	0.00
Irrigated rice field	1537.33	280.95	1256.38
Lake	11.71	10.87	0.84
Mining	24.88	0.00	24.88
Mixed plant	86.68	49.68	37.00
Non-irrigated rice field	1493.47	1231.92	261.55
Open field	72.64	2.00	70.64
Open field on caldera	0.64	0.00	0.64
Plantation	166.12	135.97	30.15
Pond	132.40	16.03	116.37
Port	1.86	0.54	1.32
Reservoir	25.28	13.17	12.11
River	54.15	7.69	46.46
Savana	341.41	1.16	340.25
Sediment coast	3.48	0.39	3.09
Sediment river	0.06	0.00	0.06
Swamp	6.37	0.36	6.01
Swamp grass	1.96	0.00	1.96
Tidal rice field	0.16	0.00	0.16
Wet primary forest	0.78	0.78	0.00
Wet secondary forest	94.62	21.95	72.67

Total	19,666.79	4,568.39	15,098.40

For free field photovoltaic (PV) and wind power plant installations, the following land use types are assigned as suitable: free field, grassland, open field, and savanna. As other usages of these areas will be present, 10 % of these areas are assumed suitable for the installation of these two technologies. For PV it is further assumed that the elevation of the PV modules leads to a factor of 0.5 from usable area to module area of PV. The efficiency per unit area is 200 W/m². For wind power plants, the distance between two power plants is 5 times the rotor diameter in the wind speed direction and 3 times the rotor diameter in the direction across the wind direction. With these values, an ellipsoid around every wind power plant can be calculated and based on that the number of wind power plants installable in a certain area. The chosen wind turbine is an Enercon E-160 EP-5 with a rotor diameter of 160m and a capacity of 4.6 MW (Enercon 2021). With these specifications, installable capacities result in the values shown in Table 12.

Table 12: Resulting installable capacities for photovoltaic and wind power plants for Lombok and Sumbawa

	Usable area for photovoltaic and wind power plants installations [km²]	**Installable capacity photovoltaics [MW]**	**Installable capacity wind power plants [MW]**
Lombok	183	18,274	2,793
Sumbawa	163	16,258	2,485

4.2.2 Photovoltaic rooftop potential

For the assessment of rooftop potential, the GIS data is used; in addition, it gives information about the building area on the two islands, which is correlated to the rooftop area. (See Table 11). It is assumed that the usable rooftop area considering a possible elevation of the modules on flat roofs as well as unusable areas on all roofs is 20 % of the rooftop area. Furthermore, it is assumed that the orientation of the roofs in the different cardinal directions is equally distributed. Therefore 25 % of the usable rooftop area is assigned to each cardinal direction, namely south, north, east, and west. This leads to the installable capacities shown in Table 13.

Table 13: Building area, usable rooftop area for the installation of PV and installable capacity of PV in each cardinal direction

	Building area [km²]	**Usable rooftop area in each cardinal direction [km²]**	**Installable capacity in each cardinal direction [MW]**
Lombok	21.1	4.22	4224
Sumbawa	8	2	1591

4.2.3 Biomass energy potential

Different types of biomasses are theoretically existent in West Nusa Tenggara, but not all of them are taken into consideration as fuel in the presented scenarios. Via GIS data the forest area is known for the two islands, but as wood is also used for other purposes, it is not included as a possible fuel in the scenarios. Agriculture is an important sector in WNT and mainly three crop types are cultivated: corn, coconut, and rice. The crops themselves are used for food production and shall not be used as fuel, but non-edible residues from processing the crops can be used either as input material for biogas production or directly burned in combined heat and power plants (chapter 4.2.3.1). Manure from livestock is also available for use in biogas production (chapter 4.2.3.2).

4.2.3.1 Crop residues

The usable amounts of crop residues are known for the years 2014 until 2018 (Rosmaliati 2020). The amounts of harvested crops are highly dependent on external conditions like the weather and do not show any clear trend for the given years, which makes extrapolation difficult. From internal discussions, it is known that the year 2018 was rather special and the harvest amounts were unusually high. Because of this, the amounts of 2017 harvest are taken for the assessment of biomass potential. As harvest is fluctuating between the years, the development of the agricultural sector is not known and a part of the crop residues might be used for other purposes, only 75 % of the crop residues are taken into account when calculating the usable amount of biomass. Whether biomass shall be burned directly or first be converted to biogas or even bio-methane depends on different factors. Direct combustion of biomass is the easiest option. On the other hand, the power plants are rather large and should be located close to the location of the harvest of biomass. Converting first to biogas is the better option if the fuel will be transported to another location, as the energy content is much higher and the power plants are much smaller in size. Refinement to bio-methane would even allow the resulting gas to be fed into an existing gas grid (which does not exist in WNT) or to bottle the gas to sell it for household use. All three biomass types are theoretically suitable for the production of biogas. The calorific values of the solids and possible methane yields are presented in Table 14.

Table 14: Calorific values of the solids and possible methane yields from corn, rice and coconut

	Calorific content of solids [kWh/kg]	Reference	Methane yield from solids [kWh/kg]	Reference
Rice husks and straw	4.2-4.44	(Gravalos et al. 2016)	4.56	(Gummert et al. 2020)
Coconut	7.63	(CleanTech 2017)	2.77-3.83	(Prabhudessai et al. 2013)
Corn	4.72	(Lizotte et al. 2015)	2.05-4.50	(International Renewable Energy Agency 2017b)

To keep the scenarios simple and allow easy trading and transport of biomass products, it is assumed that all crop residues are converted to biogas. **To find the best solution for different application cases for West Nusa Tenggara, feasibility assessments of specific projects shall be carried out in the future.** The resulting energy contents of biogas from different crops residues are shown in Table 15.

Table 15: Usable energy content of crop residues for Lombok and Sumbawa

	Biogas from corn [GWh]	Biogas from Rice husks and straw [GWh]	Biogas from Coconut [GWh]
Lombok	501	4381	58
Sumbawa	2210	31064	12

4.2.3.2 Manure

Sumbawa and Lombok both have manure from livestock potential from different kinds of animals. The animal types, their numbers as well as the resulting energy content of the biogas are shown in Table 16. It should be noted that only 75 % of the manure potential is assumed to be usable due to potential losses during collection or other usages.

Table 16: Number of livestock and usable energy content of biogas from manure for Lombok and Sumbawa

	Number [-] Lombok	Number [-] Sumbawa	Usable energy content biogas Lombok [GWh]	Usable energy content biogas Sumbawa [GWh]	Methane yield per livestock unit including used Reference [m³/a]
Sheep	9,080	18,228	1.79	3.58	26.3 (Scarlat et al. 2018)
Horse	8,255	44,430	23.95	128.90	388 (Fachagentur nachwachsende Rohstoffe e.V. 2021)
Buffalo	24,764	79,747	22.22	71.56	124 (value for male bovine from (Scarlat et al. 2018))
Goats	143,632	214,177	28.25	42.12	26.3 (Scarlat et al. 2018)
Cattle	94,929	157,215	131.32	217.48	185 (Fachagentur nachwachsende Rohstoffe e.V. 2021)

The number of different kinds of livestock is taken from Dahlanuddin et al. (2011) and is therefore already 10 years old, more recent data was not available.

4.2.4 Waste potential

The waste potential is correlated to the population and calculated with the information that each person is producing 0.7 kg of waste per day (Environmental Agency of West Nusa Tenggara 2019). This waste can be used as fuel in a waste power plant. As the exact composition of the waste is not known, an average heating value of 2.8 kWh/kg is assumed. This leads to the amounts of waste presented in Table 17. For the scenarios, it is assumed that waste is burnt directly in a waste power plant and not converted to biogas.

Table 17: Waste potential for Lombok and Sumbawa

	Waste potential [t]	Waste potential [GWh]
Lombok	1,116,735	3126
Sumbawa	484,081	1355

4.2.5 Hydro energy potential

The hydro energy potential splits up in the run of river potential and hydro storage potential. The information about the installable capacities is taken from (Islami and Aditya 2020). For the implementation of the hydro storage potential in the model, additional information about the storage potential of the upper reservoirs is needed. Information on one specific potential hydro storage site is available where the storage capacity of the upper reservoir lies between two and three hours (Danish Energy Agency 2019). As no further information is available this storage capacity is taken for all possible hydro storage sites. In addition, the dry season has to be taken into account, when the rivers as well as lakes contain too little water to use either run of river hydro power plants or hydro storage. Both technologies can therefore only be used in the time from November until May. The installable capacities are shown in Table 18.

Table 18: Hydro potential for Lombok and Sumbawa

	Hydro run of river potential [MW]	Hydro storage potential [MW]	Hydro storage potential [MWh]
Lombok	8.91	79.25	198.125
Sumbawa	4.82	119.5	298.75

4.2.6 Geothermal energy potential

There are several potential deep geothermal power plant locations on the two islands for producing electricity. More detailed information can for example be found in Islami and Aditya (2020). The aggregated potential for the two islands is shown in Table 19. In addition, shallow geothermal energy can be used with heat pumps to cover heating demand in the commercial and industrial sectors. In this case only a small temperature hub is needed and it is sufficient to either dig a hole of a few dozen meters to use it with an earth probe or to install an earth collector in 1-2 meters depth.

Table 19: Deep geothermal potential in Lombok and Sumbawa

	Deep geothermal potential [MW]
Lombok	70
Sumbawa	75

4.2.7 Summary of renewable energy potentials

A summary of the primary energy supply calculated with expected full load hours is presented in Figure 14. The largest potential is for solar electricity from PV. The rooftop potential is higher in Lombok as it is more densely populated. Free field potential usable for wind power as well as PV is nearly the same on the two islands. It is important to note that wind power and PV free-field compete for the same areas and the full potential of both technologies can therefore not be implemented. Biomass potential is much higher in Sumbawa because of more agriculturally used areas. Potentials for biogas from manure, waste potential, hydro and geothermal potential are rather small on both islands.

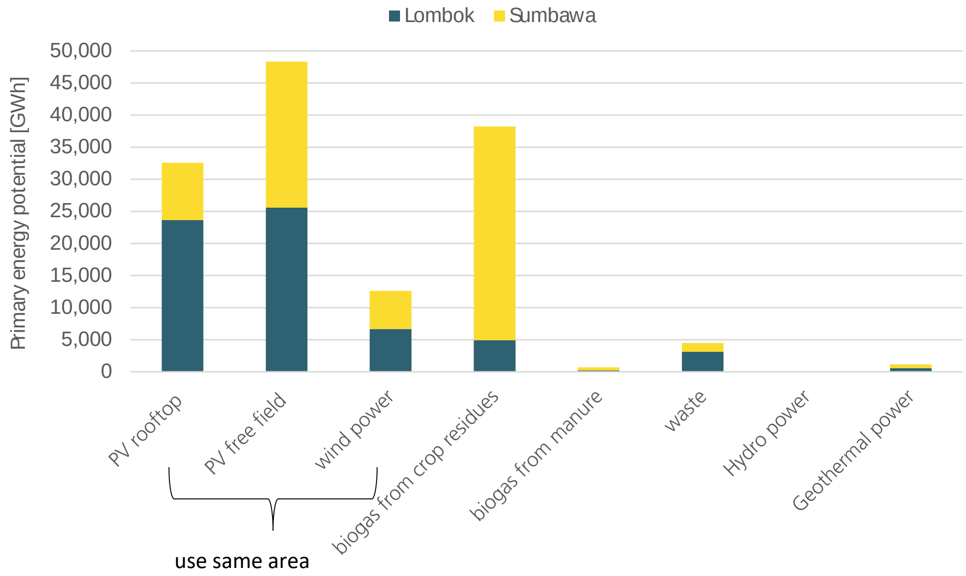


Figure 14: Primary energy supply potential of all renewable energy resources

4.3 Technology and cost data

4.3.1 Technology specific data

All technological specifications of the different power plant types are summarized in Table 20. Technology-specific data is taken from several references. An attempt was made to take most data from the same references, which are Sterchele et al. (2020) and Ram et al. (2019). Data was then cross-checked with other references. However, all data for all technologies are not available in Ram et al. (2019) and Sterchele et al. (2020) and therefore other references have been used as well. Recently a study from Danish Energy Agency has been published (Danish Energy Agency 2021) stating cost data specifically for Indonesia. The data has been compared with all data used for this study. For two power plant types where the data used was quite different, it has been updated with information from Danish Energy Agency (2021). These power plant types were geothermal power plants and waste power plants.

Table 20: Technology specific data for the scenarios

	Full load hours	Efficiency	Investment costs [€2021/kW] ([kIDR2021/ kWh])	O&M costs [% Investment]	Lifetime	References
Photovoltaics	1287-1417	200 W/m², inverter: 98 %	508 (8,679)	2	30	(Sterchele et al. 2020; Ram et al. 2019)
Wind power plants	2357	Depends on wind speed	1117 (19,084)	2	25	(Ram et al. 2019; Sterchele et al. 2020; Perner et al. 2018)
Biogas power plants	0-8000	El: 40% Th: 45%	1818 (31,060)	3.8	30	(Ram et al. 2019; International Energy Agency)
Waste power plants	0-8000	El: 40% Th: 45%	4663 (79,669)	3.5	20	(Danish Energy Agency 2021)
Geothermal power plants	0-7000	-	2324 (39,706)	1.3	20	(Danish Energy Agency 2021)
Hydro power Plants	0-4000	92 %	3350 (57,236)	2	50	(Ram et al. 2019; Anciaux et al. 2018)
Coal power Plants	0-7000	El: 42 % Th: 20 %	1571 (26,841)	1.3	50	(Ram et al. 2019)
Gas power Plants	0-7000	El: 63 % Th: 20 %	811 (1,384)	2.5	35	(Ram et al. 2019)
Heat pumps	0-8000	COP: 4	1218 (20,810)	1	20	(Sterchele et al. 2020)
Biomass boilers	0-8000	85 %	209 (3,571)	3	20	(Sterchele et al. 2020)
Biogas stoves	0-8000	45 %	354 (6,048)	3.8	20	(JIQ magazine on climate and sustainability 2016)
Electric stoves	0-8000	80 %	282 (4,818)	2	20	(Jeuland and Pattanayak 2012)
Electrolysis	0-8000	El: 64 %	471	3	20	(Perner et al. 2018)

		Th: 20 %	(8,047)			
Methanol synthesis	0-8600	81 %	4.4 [€/(kg/h)] 75 [IDR/(kg/h)]	3	20	(Hank et al. 2020; Perner et al. 2018; Schmidt et al. 2016)
Methanisation	0-8000	79 %	523 (8936)	3	20	(Perner et al. 2018)
Direct Air capture	0-8000	el: 50 %* th: 300 %	15,000 (256,278)	2	20	(Fasihi et al. 2019)
CO_2 sequestration from power plants	0-8000	el: 10 %* th: 75 %	49,200 (840,595)	3	20	(Graham et al. 2018)
Hydrogen storage	-	Dis/charge: 0.1 % Self-discharge: 0.01 %	165 [€/kg] (2,819 [IDR/kg])	2.5	20	(Sterchele et al. 2020)
Hydro storage	-	98 %	1728 [€/kWh] (3041 [IDR/kWh])	3	50	(Ram et al. 2019)
Batteries	-	Self-discharge: 0.03 %	101 [€/kWh] (1726 [IDR/kWh])	1	15	(Sterchele et al. 2020)
Thermal storages		Self-discharge: 0.09 %	101 [€/kWh] (1726 [IDR/kWh])	1.3	20	(Sterchele et al. 2020)

*Efficiency is the specific electric and thermal energy that is needed for sequestration

4.3.2 Fuel costs

Despite capital as well as maintenance costs for the different technologies' fuel costs are an important input parameter that can have a major influence on the results. Fuel costs make up a large share of the overall costs when fuel-consuming power plants supply high shares of energy in the energy system scenario. Because of this, biogas fuel costs are varied in the scenarios to account for insecurity in fuel price prediction. For further information on this variation, refer chapter 5.3. In the 100% RE scenarios only fuel prices for biomass, waste, manure, and biogas are needed. In the business-as-usual (BAU) scenario (see chapter 5.5) different fossil fuels are still in use; their prices are also given in Table 21. Values for today are taken from official statistics, projections are taken from (Suharyati et al. 2019).

Table 21: Fuel prices today and projections for 2050

Fuel	Fuel price today	Fuel price in 2050	References
Biomass	0.0029265 €/kg 50 IDR/kg	Low: 0.05853 €/kg; 1000 IDR/kg High: 0.23412 €/kg; 4000 IDR/kg	Today: (Danish Energy Agency 2019) 2050: Internal discussions
Waste and manure	-	Same price as for biomass taken	No information available
Biogas	-	Low: 0.024 €/kWh; 410 IDR/kWh High: 0.071 €/kWh; 1213 IDR/kWh	Biomass feedstock price plus biogas production costs from (International Renewable Energy Agency 2017a)
Natural Gas	0.0379 €/kWh; 648 IDR/kWh	0.051 €/kWh 863 IDR/kWh	Today: (Adi et al. 2018) Projection: (Suharyati et al. 2019)
Hard coal	0.00553 €/kWh 94.5 IDR/kWh	0.008 €/kWh 136.7 IDR/kWh	Today: (Perusahaan Listrik Negara 2019) Projection: (Suharyati et al. 2019)
LPG	0.0428 €/kWh 730 IDR/kWh	0.0564 €/kWh 963 €/kWh	Today: (Adi et al. 2019) Projection: (Suharyati et al. 2019)
Ethanol	-	Same price as LPG	No information available

4.4 Climate data

Climate data is given to the model in the same time resolution as the demand time series, which is hourly. The source for the climate data is Meteonorm (Meteonorm). All weather stations in and around West Nusa Tenggara are visible in Figure 15 (blue dots). Weather time series from all stations are compared to assess possible particularities of weather and climate data from these stations. For solar irradiation and outside temperature, the data from all stations show quite similar values. For temperature, the relative standard deviation is 0.68 % and for solar irradiation it is 4.6 %, but for wind speed, it is 23 %. As it is assumed that wind power plants are installed on the best suitable places, the highest wind speed data from all stations is used, which is wind speed data from the station in Bali. For Lombok, temperature and solar irradiation are taken from the same station, while for Sumbawa, the solar irradiation and temperature from the station Sumbawa Besar are taken.

Figure 15: Weather stations in and around West Nusa Tenggara

Temperatures in West Nusa Tenggara are high throughout the year with a mean temperature of 27.24 °C (Lombok weather data). The sum of global solar irradiance on a horizontal plane is 2048 kWh/m². The time series (Figure 16) shows that irradiation is a little bit less in summer, when there is rainy season, than in winter. Wind speed histogram at rotor height of the implemented wind power plant is depicted in Figure 17. According to that data, WNT is a suitable site for wind power plants with medium wind speed. Therefore, the implemented wind power plant is a wind turbine specialized on lower wind speeds (Enercon 2021). The resulting total full load hours of the implemented wind power plant are 2439 h.

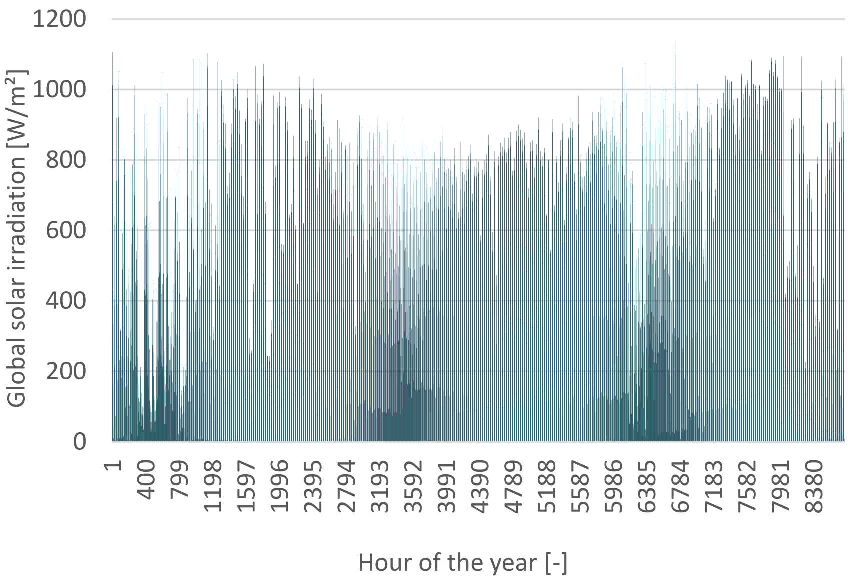


Figure 16: Global solar irradiation on a horizontal plane for Lombok with data from (Meteonorm)

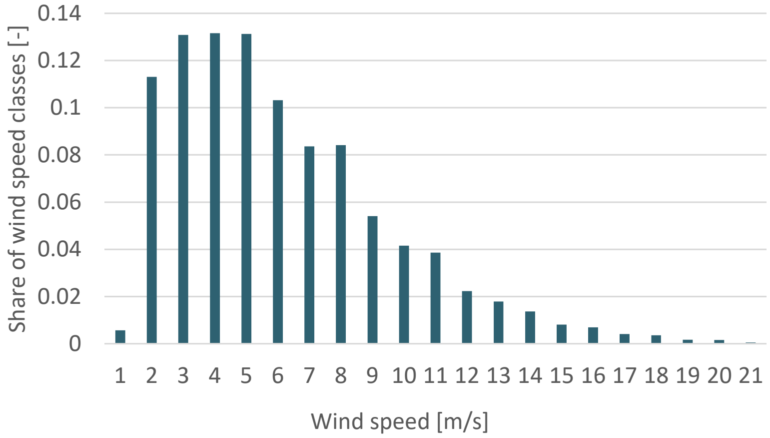


Figure 17: Wind speed histogram for the used wind data in the height of the rotor at 120 m (Meteonorm)

5 Overview of Scenarios

In this chapter, first all considered technologies in the different scenarios are described (chapter 5.1) as well as an explanation of all calculated scenarios (chapter 5.2 - 5.5).

5.1 Considered technologies

The different technologies implemented in the model (see Figure 2) are assigned to different energy demand sectors that they can supply to (Figure 18). The technologies are chosen according to their potential use in West Nusa Tenggara. Some of the technologies shown in Figure 2 are therefore not implemented; these are solar heaters, power to heat, chillers, and cold storages. Cooling demand is considered in the model but added to electricity demand directly. Power to heat and solar heaters could supply to heat demand, but their usage has been tested at the beginning of the modeling process and their deployment wasn't economically feasible.

Demand sector	**Supply technologies**					**Storage technologies**
Electricity	Wind energy	Hydro-power	CHP using Biomas and waste	Geothermal energy	Photo-voltaic	Batteries and hydro storage
Commercial and industrial heat	CHP or boiler using Biomass and waste	Heat pumps	Electrolysis			Heat storage
Cooking	biogas stove crop residues, manure	Electric stove				
Synthetic fuels	Methanol Synthesis, Methanisation	Needed: CO2 seques-tration				
Hydrogen	Electrolysis					Hydrogen storage

Figure 18: Display of supply technologies implemented in the model to meet the different demand types

Electricity demand can be covered with wind power plants, hydropower plants, photovoltaic, geothermal energy, and CHPs using biomass, biogas, and waste. To balance electricity supply from fluctuating renewables, Lithium-Ion batteries and hydro storages can be used. Commercial and industrial heat can be supplied by combined heat and power plants which produce electricity and heat simultaneously as well as excess heat from electrolyzers. This implies **that these plants have to be installed close to industrial sites with heating demands**, as transporting heat requires a heating grid and is only economically feasible for short distances. In addition, commercial and industrial heating demands can be met with heat pumps and boilers burning biogas. Cooking demand has to be covered directly in the households or commercial sites with either biogas or electric stoves. Demand for synthetic fuels is prevalent in the industrial and commercial sector because it is assumed that not all processes can be electrified in the future. Two different kinds of synthetic fuels are assumed to be used in 2050, synthetic methane as gaseous fuel and synthetic methanol as liquid fuel. Synthetic methane is produced via methanisation, and methanol via methanol synthesis. In the transport sector, it is assumed that either vehicles are using electricity directly in battery-electric cars or hydrogen is first converted to electricity in hydrogen-electric cars. The drive train is electric in both vehicle concepts. Hydrogen is produced out of electricity via electrolyzers.

5.2 Variation of energy demand

For most of the demand sectors except household cooking, two different demand projections have been constructed as input for the scenarios. Out of the high and low demand scenario, a mean demand scenario is calculated. The scenarios are calculated by default with the mean demand scenario. In addition, high demand scenarios are calculated to assess the influence of higher demand on installed capacities, usage of potentials, and costs.

5.3 Variation of fuel price

While costs for technologies change rather slowly and can usually be predicted quite well based on economy of scale, fuel costs are dependent on many boundary conditions like available resources, current production capacities, demand for that fuel in different parts of the world, and therefore politics as well as the economy in all countries using that fuel, etc. As the scenarios show, with 100 % RE the energy system is independent from fossil fuels like gas and coal and only biomass is used. Biomass is not traded internationally or even nationally but is used locally. This makes prices easier to predict. Today crop residues are cheap in West Nusa Tenggara as crop residue potential is high. But if crop residues are used in the future to produce biogas and be burned directly to supply electricity and heat, prices will most probably rise as the value increases. In addition, the costs for collection, transport, labour, profit, etc. must also be included in that price. For biogas, the costs for production also have to be included. These can be calculated based on the capital and maintenance costs of biogas digesters. For the assessment of biogas production costs, prices from (International Renewable Energy Agency 2017a) are taken. The price stated in IRENA lies between 0.0183-0.0325 €/kWh (313-555 IDR/kWh). These prices don't include any feedstock costs. The lower threshold for feedstock costs in 2050 was given to ISE by ICLEI and is 0.05853 €/kg (1000 IDR/kg); the upper threshold is four times the low feedstock costs (own assumption). High feedstock costs and high biogas production costs are added to a high fuel price for biogas, low feedstock and low production costs are added up to a low price for biogas. For waste, only the feedstock costs are set as fuel price.

5.4 Variation of spatial coupling

Today the two islands are not connected by any electricity grid with any other islands surrounding them, but Lombok as well as Sumbawa are producing all needed electricity on site. The shortest distance between the two islands is around 15 km, so a connection is easily possible. This is why scenarios are calculated where the two islands have disconnected energy systems and each island has to supply itself, and scenarios are calculated where the two islands are connected via an electricity grid and in addition trading of biogas is also possible. As 70 % of the inhabitants live in Lombok, but Sumbawa has much higher potentials of crop residues this could be beneficial.

5.5 Business as usual scenario

Total system costs are one of the results from energy system modeling (see chapter 3) including all costs for investment, operation and maintenance, fuels, and potential costs for carbon dioxide emissions. But there are also many cost types not included in such a stylized energy system model, such as network charges, grid expansion costs, or profits for energy providers. Energy transport is ideal and therefore loss-free which leads to an underestimation of installable capacities of power plants. Because of this, the total costs of different scenarios can be used to compare them with each other but are not suitable to compare them to "real" total costs of an energy system. Because of that, a business-as-usual scenario is calculated where the energy supply in 2050 is according to the plans of the local government (Gubernur Nusa Tenggara Barat 2019). The shares of different energy supply technologies in this scenario are given in Table 22.

Table 22: Share of different energy supply technologies in the business-as-usual scenario for 2050

	Cooking	Electricity	Transport -ation	Commercial and industrial heating demand	Commercial and industrial fuel demand
LPG	0.88				
Biomass	0.11				
Biogas	0.01				
RES		0.5			
Gas power plants		0.25		CHP plants	
Coal power plants		0.25		CHP plants	
Diesel			0.5		like for transportatio n
Gasoline			0.29		
Biofuel			0.13		
Ethanol			0.08		
Other technologies				Boilers and heat pumps in addition to CHP plants	

5.6 Overview

Table 23 gives an overview of all scenarios that have been calculated and are presented in this report. All scenarios are calculated for the target year 2050. The scenario family is constructed around the leading scenario which has been agreed on by relevant stakeholders during the workshop where the pre-final scenarios have been presented. The leading scenario is the first one in Table 23 where a coupling of the two islands is assumed as well as the mean demand scenario and a low fuel price. For comparison, two scenarios are modelled: one coupled scenario with high fuel price and mean demand as well as one scenario with high demand and low fuel price. For the decoupled energy systems, this means that all scenarios have to be calculated for Sumbawa and Lombok separately. The rest of the boundary conditions are set the same as for the coupled scenarios. In addition, one business-as-usual scenario as described in chapter 5.5 is modelled

Table 23: Overview over all calculated scenarios

Scenario name	Coupled/ decoupled	High/ low fuel price	High/ mean demand	100 % RE /BAU supply
WNT, mean demand, low fuel price	coupled	low	mean	100% RE
WNT, mean demand, high fuel price	coupled	high	mean	100% RE
WNT, high demand, low fuel price	coupled	high	BAU	100% RE
Lombok, mean demand, low fuel price	Decoupled: Lombok	low	mean	100% RE
Lombok, mean demand, high fuel price	Decoupled: Lombok	high	mean	100% RE
Lombok, high demand, low fuel price	Decoupled: Lombok	high	BAU	100% RE
Sumbawa, mean demand, low fuel price	Decoupled: Sumbawa	low	mean	100% RE
Sumbawa, mean demand, high fuel price	Decoupled: Sumbawa	high	mean	100% RE
Sumbawa, high demand, low fuel price	Decoupled: Sumbawa	high	BAU	100% RE
WNT, business as usual	coupled	low	mean	BAU supply

6 Results

6.1 Leading scenario: coupled energy system, mean demand, low fuel price

From the six different scenarios that have been calculated (nine when the two islands are counted separately in the decoupled scenarios, see Table 23) one has been chosen as the leading scenario. This is the scenario where both islands are coupled, mean demand projection is assumed, and fuel prices are low. A coupling of the two islands is seen as realistic until 2050 and therefore this specification is taken here. By taking the mean demand scenario, a commitment to efficiency measures shall be shown. The low fuel price is taken for the leading scenario because with the high fuel price biogas is only playing a very minor role in energy supply, which is rated as unrealistic. The leading scenario will be presented in detail in chapter 6.1.1, while the comparison with high fuel price scenario is done in chapter 6.1.2. A detailed discussion of the operation of the different power plants during the year is done in chapter 6.1.3. In chapter 6.2 a comparison of all calculated scenarios is conducted. Chapter 6.3 is presenting a transition plan from today until 2050 to reach the leading scenario while in chapter 6.4 a risk analysis is performed, linked with recommendations for how to overcome the most common risks when transforming to RE.

6.1.1 Energy supply

Figure 19 shows how electricity demand is covered with the different technologies in the leading scenario. The total electricity demand to be covered in this scenario is 18,507 GWh. This electricity demand consists of the electricity demand in the different sectors: (1) electricity demand for cooling, (2) demand in the transport sector for vehicles using electricity directly, hydrogen and synthetic fuels, (3) cooking demand that is covered with electric stoves and (4) electrification of heating and fuel demand in the commercial and industrial sector. The largest electricity supplier is photovoltaic with 69 %; of that, free field photovoltaic has the larger share with 51 %. The second-largest supplier is combined heat and power plants using biogas from crops with 18 %, while wind power plants are covering 10 %. Only minor electricity amounts are supplied by geothermal and hydropower plants, although their potential is fully used.

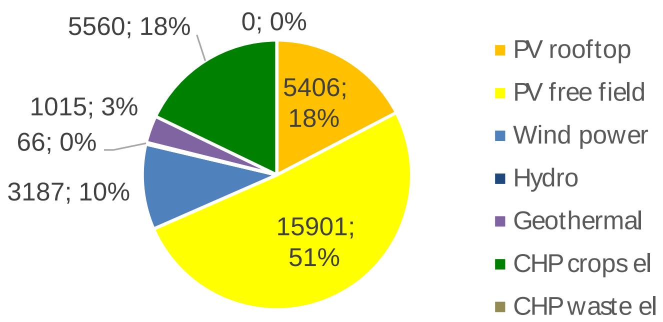


Figure 19: Results for the coupled energy system, mean demand, low fuel price for electricity supply in 2050 in GWh

Some of the implemented technologies in the model for electricity production are not installed in this scenario; these are waste CHPs and fuel cells. The levelized costs of energy for waste CHPs are shown in Figure 28 and, as they are higher than the levelized costs of energy for biogas CHPs, they are only installed when the potential for biogas from crop residues is already fully used. Fuel cells use hydrogen and convert fuel energy back to electricity and heat. This process is associated with losses but has the advantage that storing hydrogen has a higher efficiency, especially in the long term, than storing electricity in batteries. But in the presented scenarios, batteries are used as storage option; as short-term storage is sufficient to balance supply and demand, batteries are therefore the cheaper option.

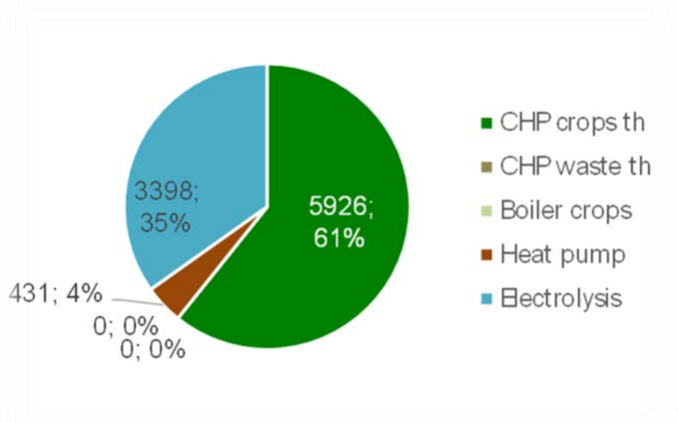


Figure 20: Results for the coupled energy system, mean demand, low fuel price for commercial and industrial heating supply in 2050 in GWh

In addition to the heating demand in the commercial and industrial sector, heating demand for CO_2 sequestration has to be covered, totalling in 5939 GWh, in addition to commercial and industrial heating demand of 3812 GWh. The heating demand is met with three different kinds of supply technologies (Figure 20). The largest share comes from the combined heat and power plants with 61 %, and the second largest share is excess heat from electrolyzers. A small portion of 4 % is covered by heat pumps. It should be noted that the usage of CHPs and electrolyzers to cover heating demand implies that **heating demand is located close to these supply technologies**. As already described above waste CHPs are not installed because of higher costs than for biogas CHP. In addition, also biogas-burning boilers are not used.

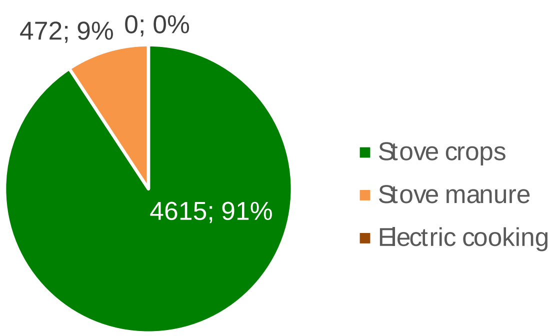


Figure 21: Results for the coupled energy system, mean demand, low fuel price for cooking demand in households and commercial sector in 2050 in GWh

Cooking demand is fully met with stoves using biogas, with 91 % coming from crops and 9 % from manure. Electric cooking is not used with low fuel prices (Figure 21).

Figure 22 shows the energy flow (Sankey) diagram for the leading scenario. On the left-hand side, the different power plant types are depicted, that are used in the leading scenario and produce electricity or heat. On the right-hand side, the different energy demand types are presented. In this energy flow diagram, flows are distinguished between cooling demand, electricity demand, energy demand in the transport sector, industrial and commercial heating demand and cooking demand. Electricity supply adds up to 31,134 GWh including electricity demand for cooling, for appliances in the different sectors, in transport, for heating purposes in commercial and industrial sector as well as for the production of hydrogen, which is presented in the middle of the energy flow diagram. Hydrogen is either used directly in transport sector, but it is also processed further to produce synthetic fuels (Methane and Methanol). CO_2 sequestration is not depicted in the figure but is included in the synthesis process. Also, in the middle of the figure heat pumps can be found which take geothermal energy and electricity to produce heat for commercial and industrial sector. Not all losses are shown in this picture,only the ones from electrolysis, synthesis and battery storage. The power plant processes shown in the left of the figure also have losses when converting fuel energy into electricity and heat, but for the sake of simplicity this part has been left out.

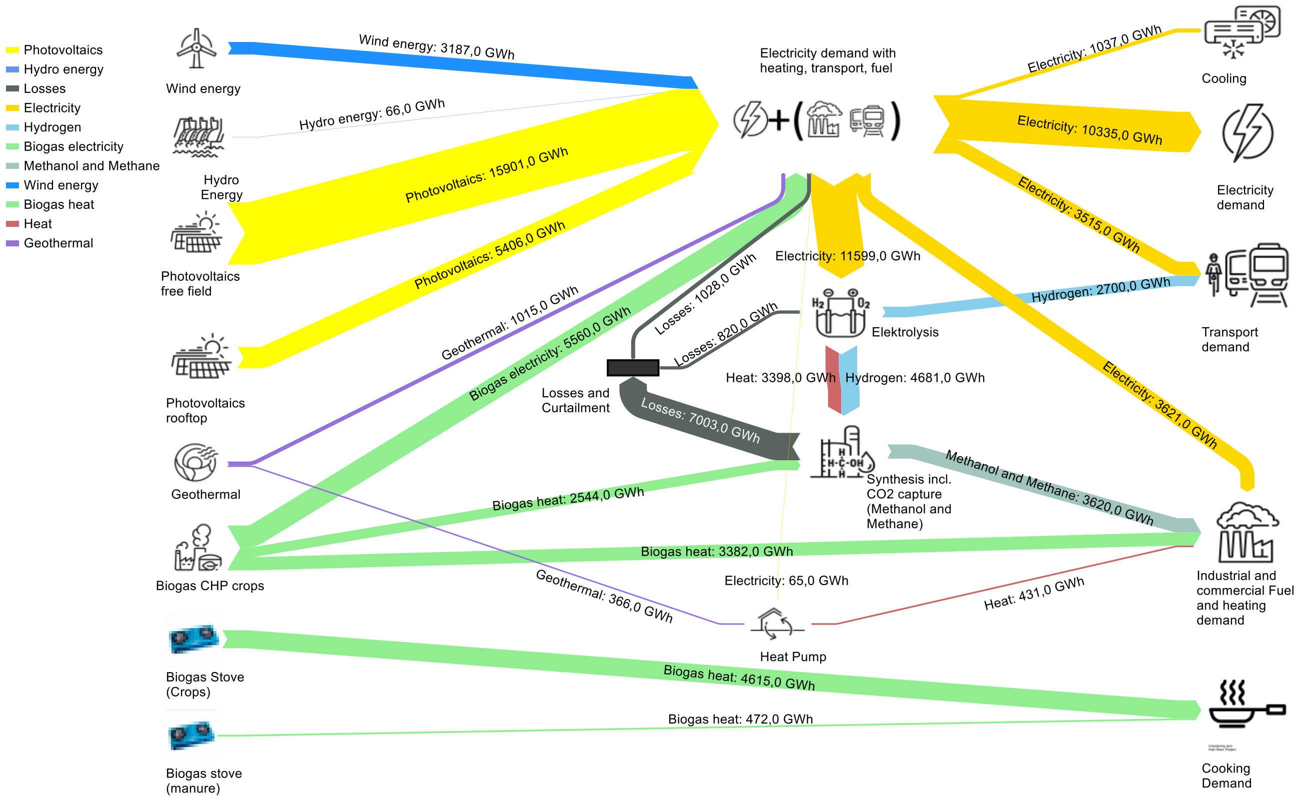


Figure 22: Energy Flow diagram of the leading scenario

The largest installed capacity of all supply technologies is PV free-field and PV rooftop. This is the supply technology with the largest amount of supplied energy and at the same time the lowest full load hours of around 1300 h-1400 h per year. (See Figure 23 and Figure 24). Batteries are also installed to a high extent as the majority of electricity supply comes from fluctuating resources (PV and Wind).

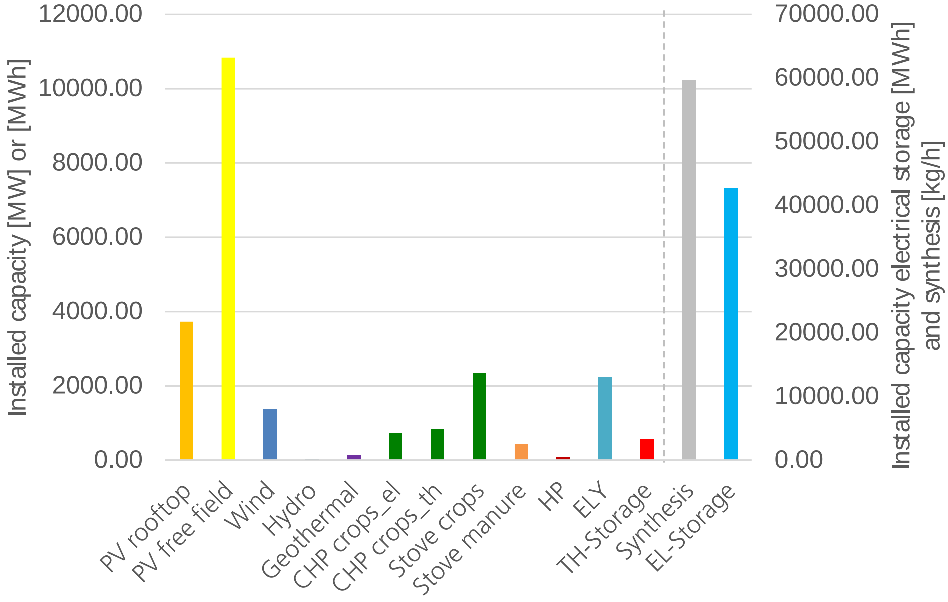


Figure 23: Installed capacities of all installed technologies in the leading scenario in 2050 (coupled energy system, mean demand, low fuel price)

Thermal storages are used to store heat from CHPs, electrolyzers, and heat pumps for later use. They are installed at a capacity of 558 MWh. The potential for geothermal and hydro energy is small but used to the full extent which leads to an installed capacity of 145 MW of geothermal power plants and 14 MW of hydropower plants. The highest full load hours are reached by synthesis plants that produce methane and methanol quite constantly throughout the year (Figure 24). As capital costs of these plants are high, they need to be operated with high full load hours to be economically feasible. The second highest full load hours are reached by combined heat and power plants (7381 h) who run as baseload all year. As the heating demand is also implemented as constant time series, supply and demand fit together well and only small thermal storage capacity is needed (see also chapter 6.1.3).

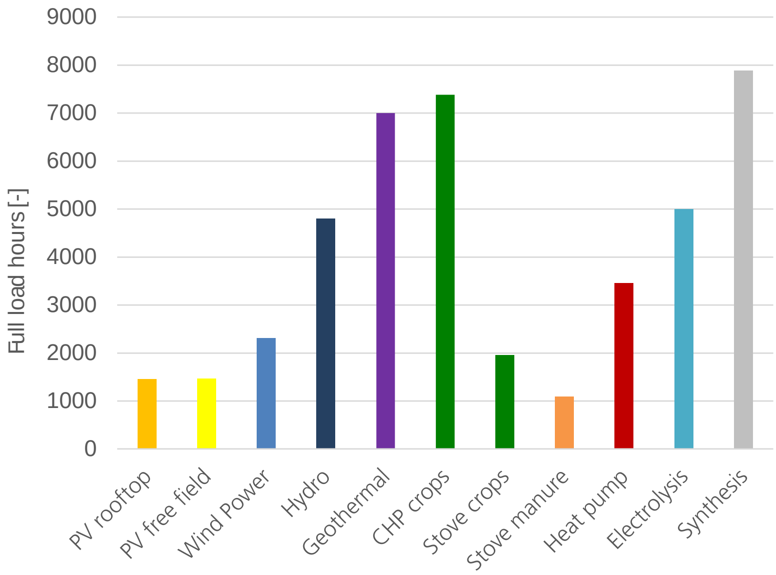
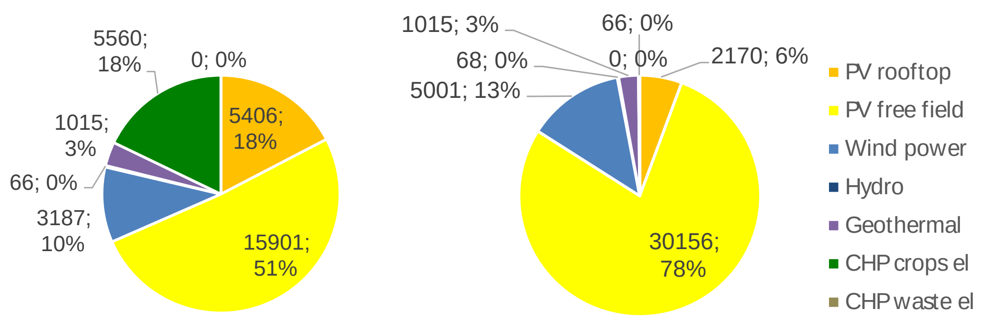


Figure 24: Full load hours of all installed technologies in the leading scenario in 2050 (coupled energy system, mean demand, low fuel price)

6.1.2 Comparison with high fuel price scenario for coupled energy system and mean demand

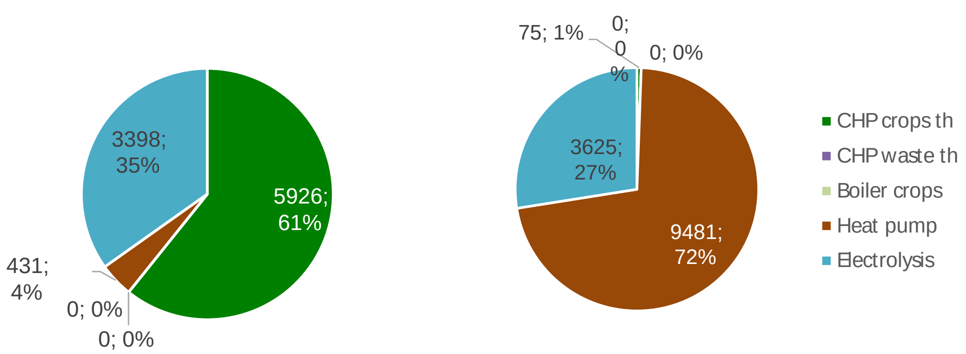
The diagram on the left side in Figure 25 shows the electricity supply structure in the leading scenario while the diagram on the right side shows the electricity supply with the higher biogas fuel price. The higher fuel price for biogas is 3 times the lower fuel price. With higher fuel price the costs of CHPs are not economically feasible, and the share of PV increases further increasing compared to the low fuel price scenario. The share of PV reaches 84 %. This leads to the need of an even higher storage capacity of 70 GWh compared to 41 GWh in the low fuel price scenario. CHPs are installed with a capacity of 280 MW but are only supplying 66 GWh of electricity to shave demand peaks in times with low solar irradiation and wind speed. The total electricity demand is higher in the high fuel price scenario as heat pumps and electric heating are used to a larger extent (see also Figure 26 and Figure 27).



Low fuel price High fuel price

Figure 25: Comparison of coupled scenario with mean demand with low and high fuel price for electricity supply, absolute values in GWh

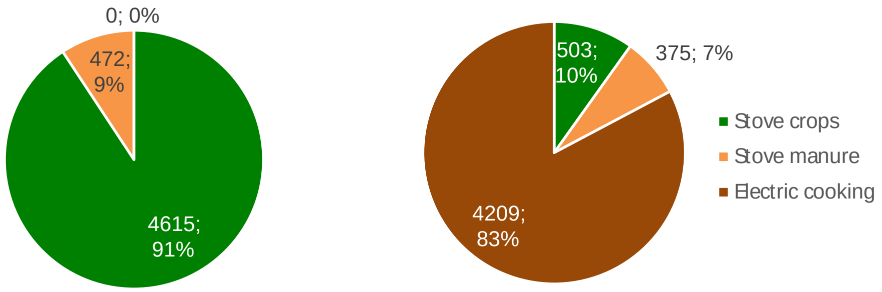
The heating supply structure is changing. As little CHPs are installed, heat pumps come into play and supply 72 % of heating demand. 27 % is supplied by excess heat from electrolyzers while 1 % is supplied by CHPs. Heating demand for CO2 capture is higher in the scenario with higher fuel price. CO2 can be either captured with direct air capture or from CHPs burning biogas (see chapter 3). Direct air capture is the more energy-intensive process and needs more heat than extraction from exhaust gases from biogas CHPs.



Low fuel price High fuel price

Figure 26: Comparison of coupled scenario with mean demand with low and high fuel price for heat supply, absolute values in GWh

In the low fuel price scenario, cooking demand is covered entirely by biogas stoves. This supply structure changes drastically to 83 % electric cooking and 17 % of biogas cooking with high fuel price.



Low fuel price High fuel price

Figure 27: Comparison of coupled scenario with mean demand with low and high fuel price for cooking supply, absolute values in GWh

The levelized costs of electricity (LCOE) and heat (LCOH) are important indicators to understand which technologies are the most economically feasible in the two different scenarios (Figure 28). These costs are defined as the total costs for the supply technologies consisting of yearly capital, operation, and fuel costs divided by the total amount of supplied electricity or heat per year.

With low fuel price LCOEs of all technologies are in a range between 0.028 €/kWh (481 IDR/kWh) for PV and 0.066 €/kWh (1128 IDR/kWh) for hydropower. Biogas CHPs have an LCOE of 0.0423 €/kWh (723 IDR/kWh). With high fuel price the LCOE of biogas CHPs increase to 0.1057 €/kWh (1806 IDR/kWh). As electricity from PV and wind is fluctuating, batteries are needed to store excess electricity for later use. The battery costs should be therefore added to the LCOE of PV and wind. This increases the LCOE of PV to 0.044 €/kWh (752 IDR/kWh) and of wind to 0.063 €/kWh (1076 IDR/kWh). In the low fuel price scenario, LCOE for PV with battery and CHP are therefore the same. But the LCOE of CHPs is also dependent on generated and more importantly used amount of heat. Capital, operating, and fuel costs are distributed between electricity and heating supply to calculate LCOH and LCOE. If the heating supply is less, specific costs per kWh electricity and heat rise. As heating demand in WNT is rather low, as it is only prevalent in the commercial sector, **it is important that heat from CHPs is used efficiently to ensure a low LCOE and LCOH.** LCOH is lowest for heat pumps, as efficiency is quite high, because of high underground temperatures and electricity costs are low with for example 0.028 €/kWh for PV. With low fuel price, electric cooking is the most expensive cooking technology, but with high fuel price, it is the cheapest one. This explains the radical shift in energy supply for cooking (see Figure 27).

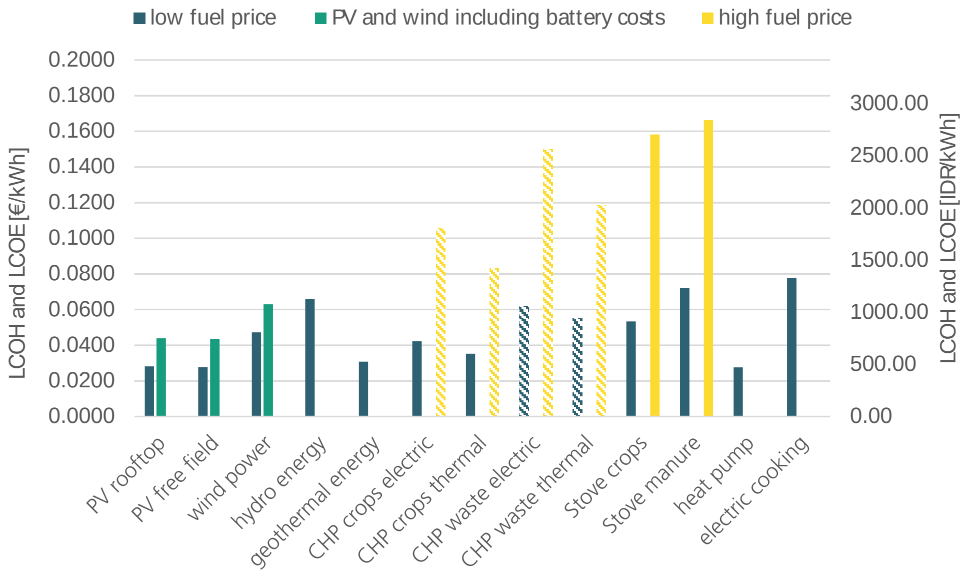


Figure 28: Levelized costs of electricity and heat with low and high fuel price, striped bars show theoretical costs with 7000 full load hours

6.1.3 Time series evaluation

An assessment of the temporal resolved results of the scenarios helps to understand how the different power plants are operating throughout the year and how storage technologies help to balance power generation from fluctuating renewable technologies. Figure 29 shows power generation and demand for one week in June 2050 for the leading scenario; the figure can be found in a higher resolution in Appendix D. Demand is shown with lines, with a red line indicating net demand (demand given to the model exogenously) and a blue line indicating gross demand (demand calculated during optimization for heating purposes and production of synthetic fuels). CHPs (in green) run as baseload with an output of around 650 MW. PV (in yellow) reaches its maximum output at around 12 am with 8000 MW. This is much higher than the gross demand with around 4500 MW. Excess electricity is stored for use in the nighttime when no electricity from solar is produced. This could cause challenges for the future electricity grid when this excess electricity will be fed into the grid all at once. To reduce network load, decentral installation of battery storages could be one option. Especially on large free field photovoltaic power plants, battery storages can be build up next to the plant, electricity can be stored directly and be fed into the grid in the evening hours when it is needed. It is also an option for rooftop PV systems that households own their own battery storage in addition to the PV systems and store excess electricity by themselves for later use. As KomMod does not model any networks, no quantification of grid load can be given here, but this must be part of a more detailed planning process for grid expansion, if the share of PV power plants in the electricity system of WNT will rise in the future.

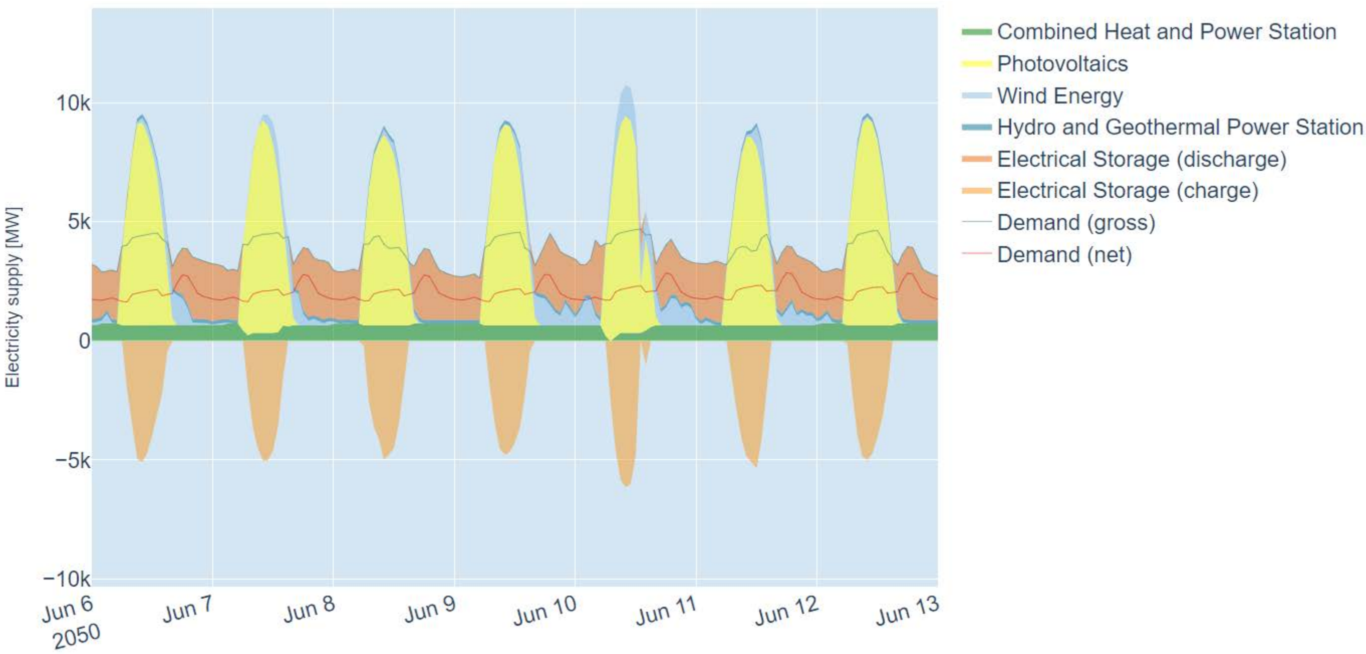


Figure 29: Time series for one week in June 2050 for electricity supply and demand for the leading scenario

Wind energy output is much less than produced electricity from solar. In the shown week, notable amounts of electricity from wind are produced in three nights and are a good supplement to solar electricity which is only produced in the daytime.

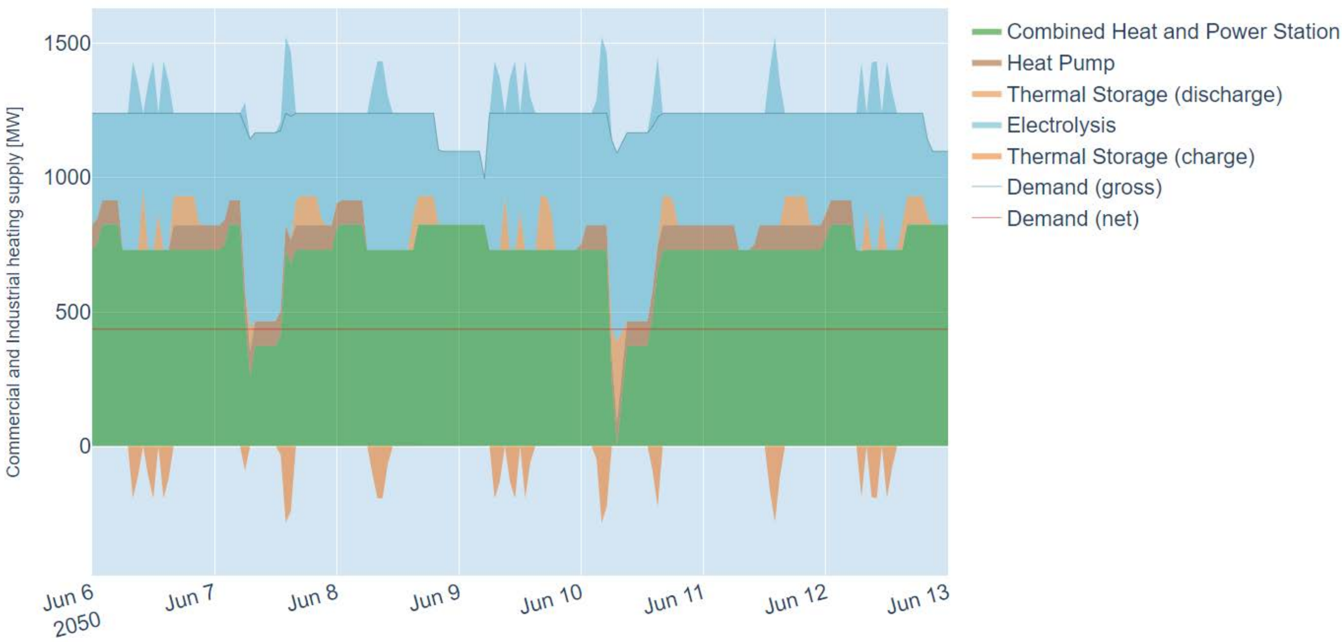


Figure 30: Time series for one week in June 2050 for heating supply and demand for the coupled scenario with mean demand and low fuel price

The heating supply for commercial heating demand in the same week is shown in Figure 30. Like in Figure 29, the demand is shown with a red line for net demand and with a blue line for gross demand (net demand is constant see Chapter 4.1.3). In this case, gross demand is including heating demand for direct air capture to extract CO_2 for the production of synthetic fuels. Heating demand for direct air capture is higher than commercial heating demand leading to a total heating demand in that week of around 1200 MW. As known from the analysis of electricity supply and demand, CHPs run as baseload and are producing electricity and heat at the same time. As thermal efficiency is slightly higher than electrical efficiency the output of CHPs is 825 MW maximum. But it can also be seen that output is often less than that. As not all produced heat is needed but electricity is, heat output must be regulated. In practice, this would mean that heat exchangers are needed to cool down the water used in the power plant process to not have major efficiency losses. A large part of the heating demand is also covered with excess heat of electrolyzers that produce hydrogen. As electrolysis is an exothermal process, heat is being produced as a by-product when converting electricity to hydrogen. Small amounts of heating demand are covered with heat pumps. Thermal storages are used, but only to a small extent, especially compared to battery usage. This week shows a rather typical behaviour, although there are of course times with less solar electricity production and/or higher wind energy output. When electricity production is lower in times with less sunshine, the production of hydrogen and synthetic fuels is lowered or even stopped in order to decrease electricity demand (see figures in Appendix E).

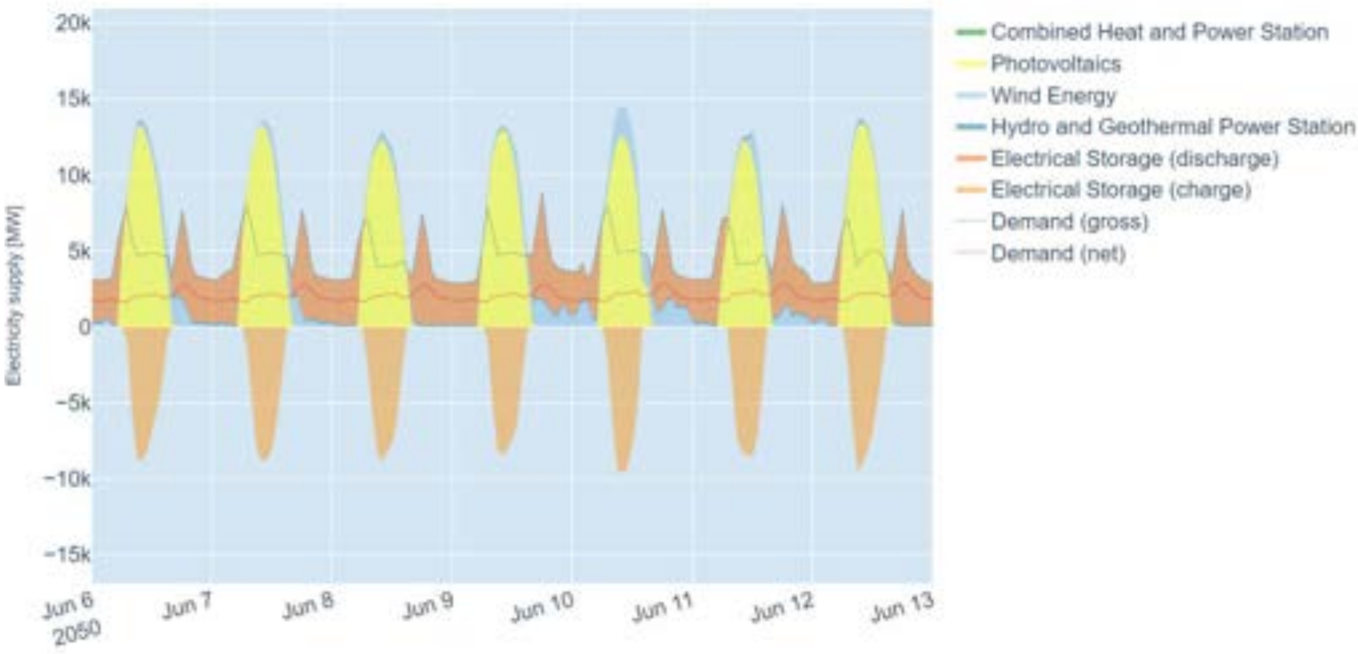


Figure 31: Time series for one week in June 2050 for electricity supply and demand for the coupled scenario with mean demand and high fuel price

Figure 31 shows the same week for the scenario with higher biomass fuel price where CHPs are only used for covering some peak demands. In the analysed week in June, no CHPs come into play. Electricity supply is mainly coming from solar energy which has an even higher output than in the leading scenario, with around 13 GW. Wind power output is a little bit higher than in the leading scenario to replace CHPs. As PV output is higher,more excess electricity is being produced, and no baseload CHPs are running, a higher battery capacity is installed, and more electricity is stored for use at night. The peak in gross demand in the morning hours comes from cooking demand which is mainly covered with electric cooking devices. (See Figure 32) Additionally, this gross demand peak due to cooking demand is also observable in the evening. Annual cooking demand is met with 83% electric cookers and 17 % biogas cookers. As can be seen in Figure 32, the installed capacity of electric cookers is high enough to meet the peak in cooking demand of 2787 MW. Still biogas cookers are used, for example, on June 9th instead of electric cookers. This operation shows the stylized modeling results, which cannot always depict real-world behaviour of (in this case) single households. In reality every household has one cooking device and will always use that one. Therefore, even though the total cooking demand can often be met by the total electric cooker supply (as seen in Figure 32), in reality a certain segment of the population (household/commercial) will use biogas stoves instead of electric cooker. In the model, there is one cooking demand time series and all installed cooking devices can cover this demand.

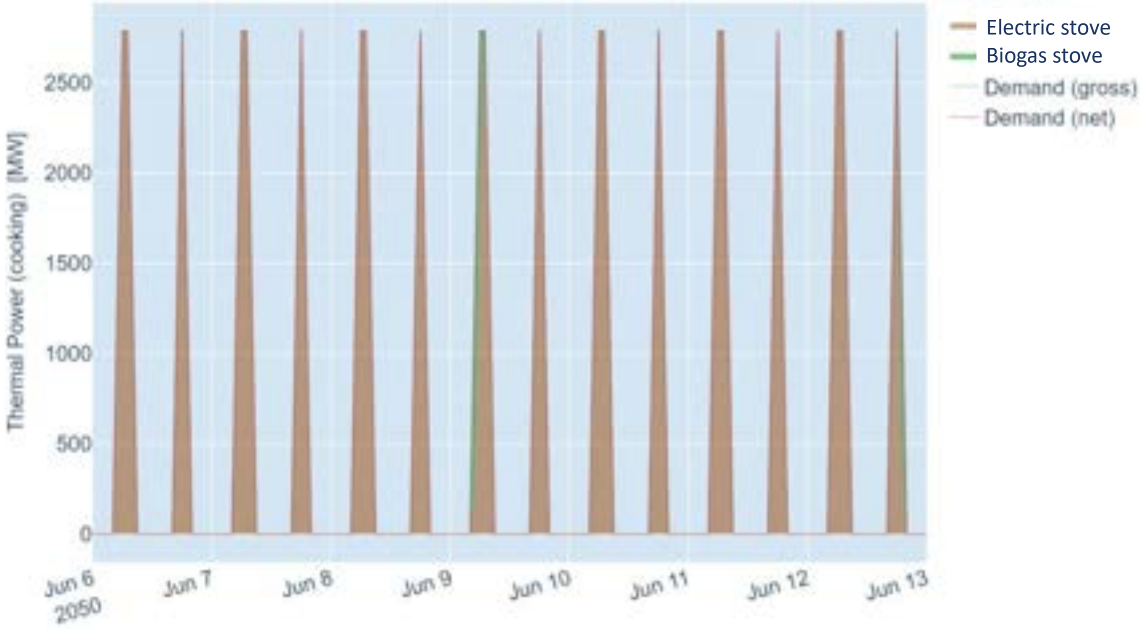


Figure 32: Time series for one week in June 2050 for cooking supply and demand for the coupled scenario with mean demand and high fuel price

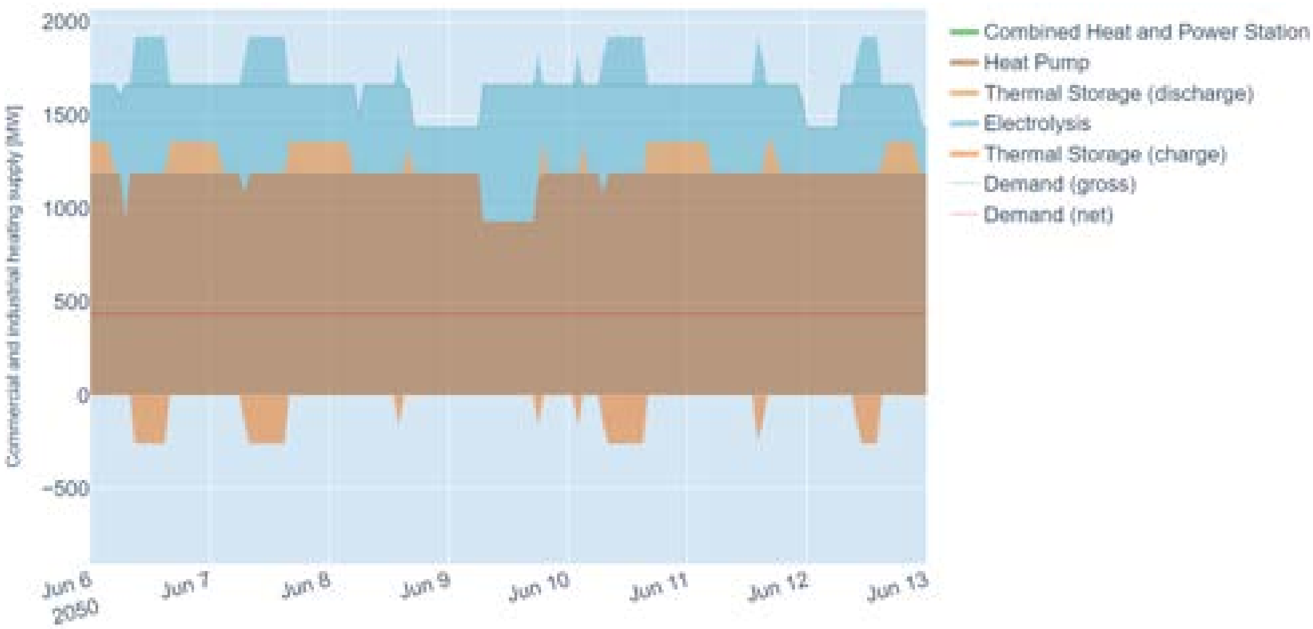


Figure 33: Time series for one week in June 2050 for heating supply and demand for the coupled scenario with mean demand and high fuel price

As described in chapter 6.1.2, heating demand for CO2 capture is higher in the scenario with higher fuel price. This is why the share of heat from electrolyzers is decreasing. Heat pumps meet the highest share of heating demand. They run quite constant the whole year as do the electrolyzers.

6.2 Comparison of all scenarios

Overall, 10 scenarios have been calculated. Three scenarios for the coupled energy system, three plus three for the decoupled energy system, and one business as usual (BAU) scenario for the coupled energy system. All results in table format can be found in Appendix C. In Figure 34 the electricity supply in all scenarios is shown. In all 100 % RE scenarios, PV covers the largest share of electricity demand with the highest share: in the mean demand scenario with high fuel price for Lombok with 86 %, and with the lowest in the mean demand scenario with low fuel price for Sumbawa with 65 %. In the business-as-usual (BAU) scenario, 50 % of the electricity demand is covered with coal and gas power plants by definition, while 50 % comes from renewable energies. From this 50 %, PV covers 73%, the rest comes from wind power, hydro, and geothermal. The electricity demand is different in all scenarios, as it depends not only on the choice of high or mean demand scenario, but also on additional electricity demands for heating and cooking. This is the reason why the electricity demand is not the same in the mean demand scenarios with high and low fuel prices. In the low fuel price scenarios, the electricity demand is lower, as CHPs cover parts of the heating demand and therefore less electricity is needed for heat pumps and electric cookers.

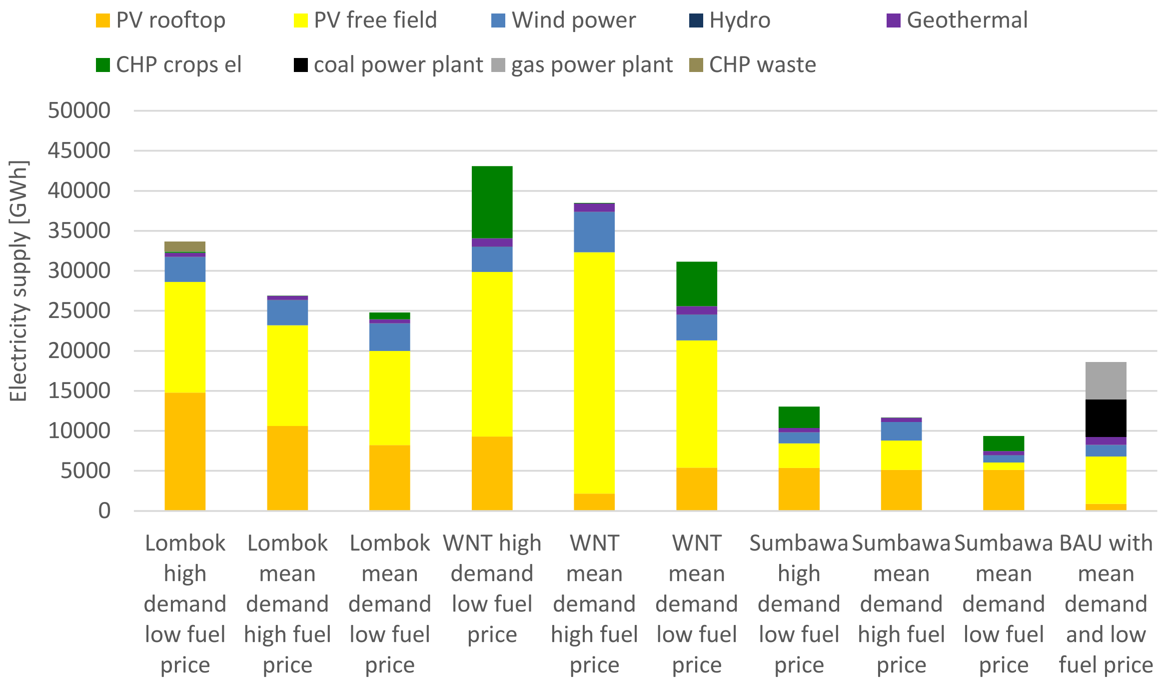


Figure 34: Comparison of electricity supply in all scenarios

Heating demand for the commercial sector and CO_2 capture is covered mainly with heat pumps in five (5) scenarios and mainly with CHPs in four (4) scenarios (Figure 35). With low fuel price, CHPs cover the largest share of heating demand in all scenarios except Lombok, as biomass potentials are restricted and mainly used to cover cooking demand. In the business-as-usual scenario, heating demand is mainly covered with heat from coal power plants.

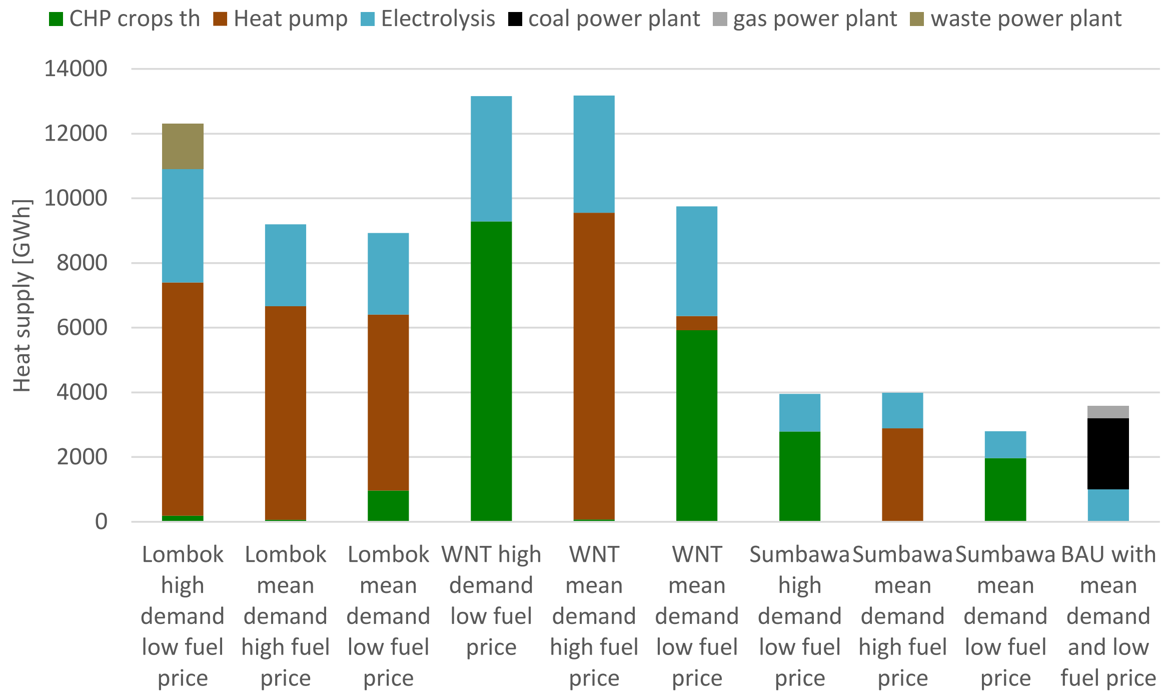


Figure 35: Comparison of heating supply in all scenarios

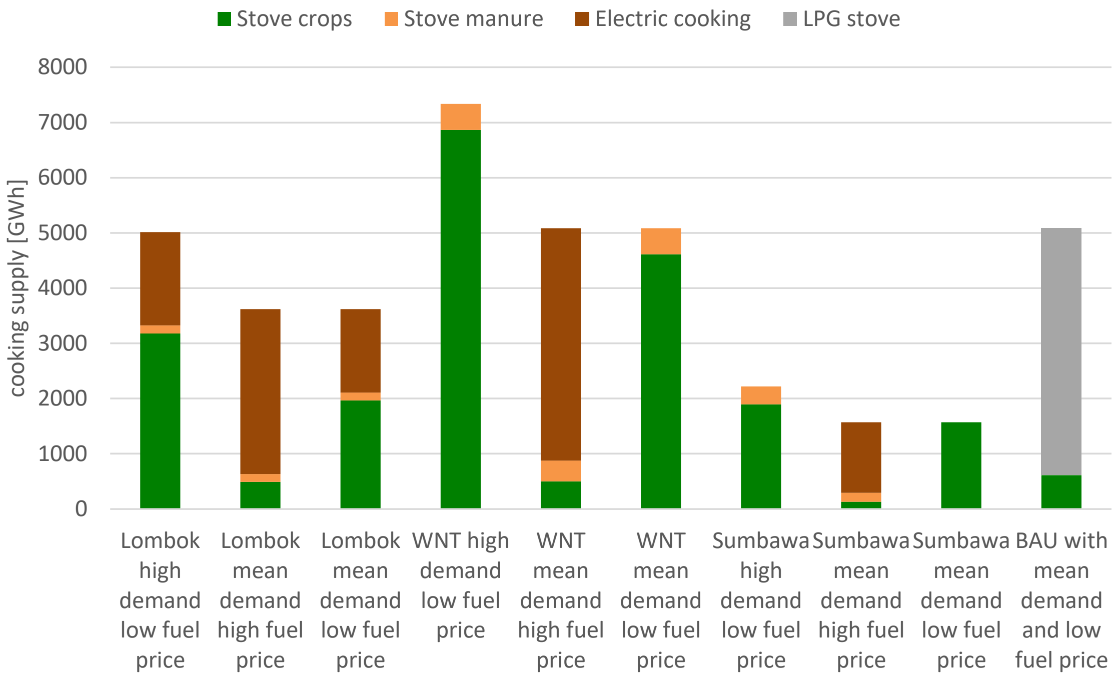


Figure 36: Comparison of cooking supply in all scenarios

With high fuel price, electric cooking covers the larger shares of cooking demand in the coupled as well as in the decoupled scenarios (see
Figure 36). With low fuel price, the higher share is coming from biogas stoves. In two scenarios electric cooking is not used at all: the coupled scenario and decoupled scenario for Sumbawa both with low fuel

price. In the business-as-usual scenario, LPG covers 88 % of cooking demand by definition, while the rest is mainly covered with solid biomass stoves using crops and 1 % is covered with biogas stoves.
100 percent RE can be reached in all calculated scenarios even with high demand scenarios. An assessment of the used potentials helps to understand if demand could be even higher in the future and 100 percent RE would still be possible. In the coupled scenarios, highest usage of wind power and PV potentials is given with mean demand and high fuel price, as usage of biomass is more expensive than wind power and PV in combination with heat pumps and electric cookers (Figure 37). In this scenario nearly no biomass is used (see Figure 38). Highest deployment of PV and wind power potentials is 88 %, in the decoupled scenario with high demand for Lombok. In the same scenario, biomass potentials are used by 100 % (Figure 38). This means that in a decoupled energy system, demand in Lombok cannot be much higher than in the high demand scenario as the limit for the RE potentials is nearly reached. In Sumbawa, potentials are much higher yet demands are lower, as only 30 % of the whole population lives in Sumbawa. Apart from lower costs (see Figure 39), this is one reason why coupling the energy systems of the two islands could be beneficial as it also increases supply security, especially for Lombok. As Sumbawa is much larger (3/4 of the area of WNT), a coupling would also allow a more even distribution of PV and wind power plants in the best locations.

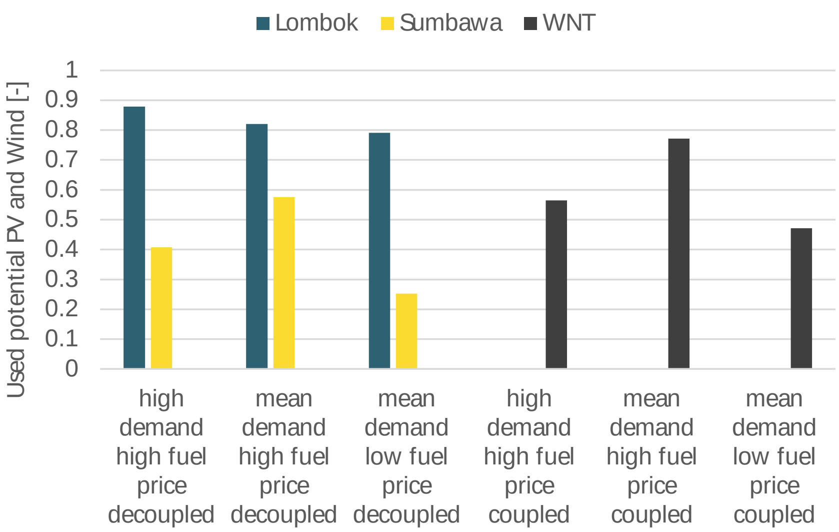


Figure 37: Used potentials PV and Wind in all 100% RE scenarios normalized to the maximum potential

Table 24 shows the land use of wind power plants, free field PV, and rooftop PV. Free-field potentials are used to their full extent in all scenarios in Lombok leading to a land use share of 4 % of the whole area of the island. In Sumbawa, meanwhile, only between 0.2 and 0.6 % of the area is used.

Table 24: Land use of Wind power plants, free field PV and rooftop PV in all scenarios

Scenario	Used free field area for Wind and PV [km^2]	Share on overall area of the islands [%]	Used rooftop area [km^2]	Share on overall rooftop area [%]
WNT, mean demand, low fuel price	198.6	1.0	18.6	16
WNT, mean demand, high fuel price	344.8	1.8	11.2	10
WNT, high demand, low fuel price	228.8	1.2	31.8	27
Lombok, mean demand, low fuel price	181.9	4.0	28.9	34
Lombok, mean demand, high fuel price	181.9	4.0	36.8	44
Lombok, high demand, low fuel price	181.9	4.0	52.4	62
Sumbawa, mean demand, low fuel price	31.6	0.2	17.5	55
Sumbawa, mean demand, high fuel price	94.7	0.6	17.5	55
Sumbawa, high demand, low fuel price	60.8	0.4	18.6	58
WNT, business as usual	80.1	0.4	3.3	3

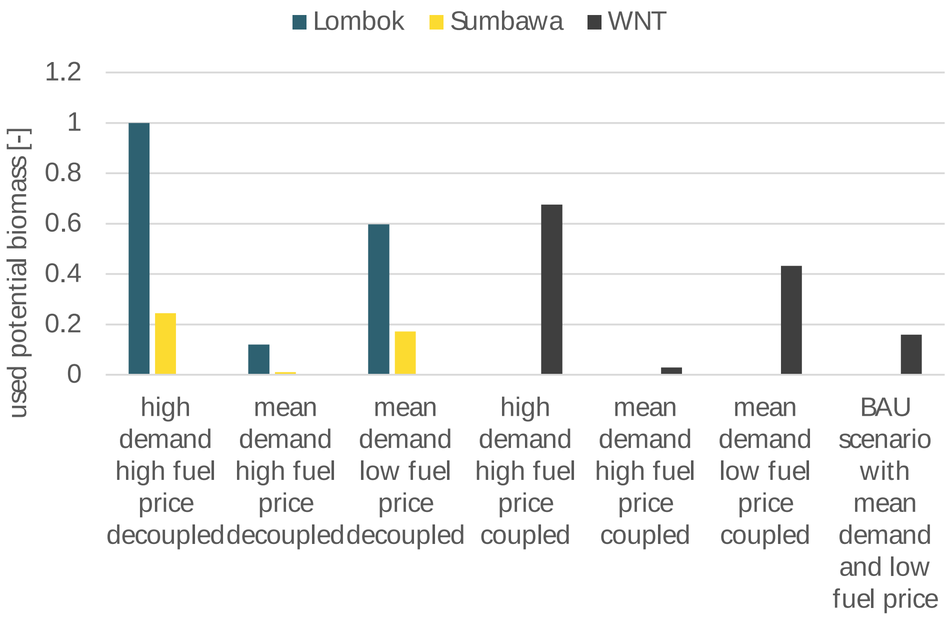


Figure 38: Used potentials biomass in all 100% RE scenarios

Figure 39 shows the overall system costs in all scenarios, normalized to the costs of the leading scenario which is also the cheapest system configuration. With mean demand and low fuel price but a decoupled energy system, the costs are 5.9 % higher. With higher fuel price, the costs are 16 % higher; furthermore, coupled and decoupled energy systems have nearly the same costs. This means that a coupling of the two systems has an economic advantage with lower fuel price, but not with higher fuel price. This is due to restricted biomass potentials in Lombok.
With high fuel price biomass is used only to a minor extent as it is more expensive than PV and wind power electricity in combination with heat pumps and electric cooking (see Figure 28). PV and wind power potential in Lombok and Sumbawa are high enough that the maximum potential is not reached in any of the scenarios (see also Figure 37). With low fuel price, it is economically more feasible to use biogas CHPs; however, as the potential in Lombok is restricted, wind power and PV still have to be used to a higher extent than in Sumbawa or in the coupled energy system. This makes the Lombok energy system more

expensive compared to Sumbawa, or the coupled energy system, given the low fuel price scenario. The business-as-usual scenario is calculated with mean demand and low fuel price and is 32 % more expensive than the leading scenario. That means that under the given boundary conditions, an energy system based on 100 % renewable energies is cheaper than an energy system which is still mainly based on fossil fuels.

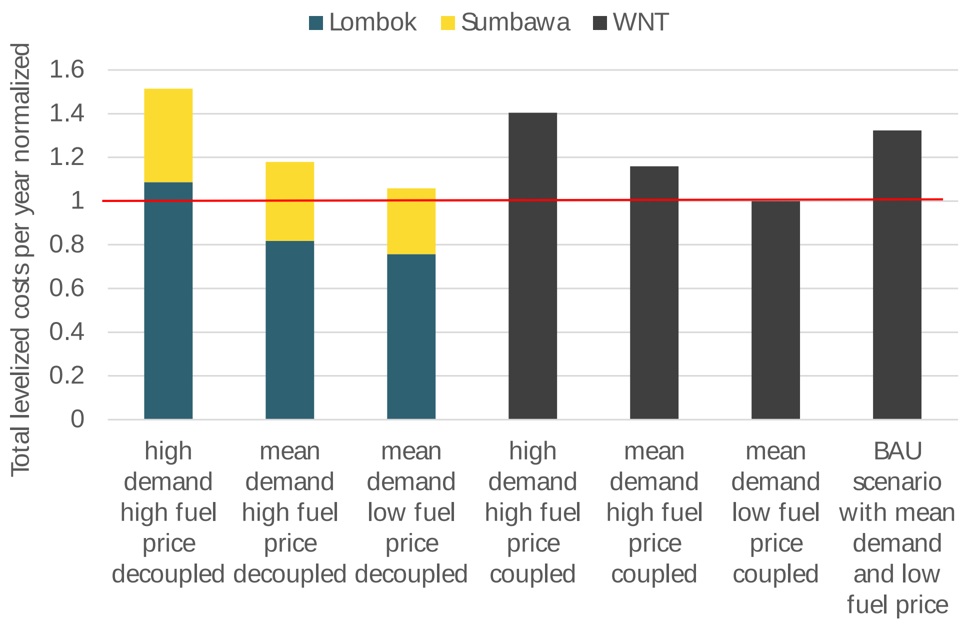


Figure 39: Total system costs in all scenarios normalized

The direct CO2e emissions in all scenarios are depicted in Figure 40. Direct CO2e emissions are only emissions from burning fuel, no carbon dioxide equivalents from the production of different power plants are included. This leads to the result that CO2e emissions are higher in the lower fuel price scenarios, where more biogas is used. Biogas has lower CO2e emissions than, for example, natural gas but due to transport of biomass, leakage in the biogas production process, etc. they are not zero. The direct CO2e emissions from burning fuels are 4.5 times higher in the business-as-usual scenario than in the leading RE scenario. In the leading RE scenario the per capita CO2e emissions are 0.53 tonnes and in the business-as-usual scenario they are 2.4 tonnes.

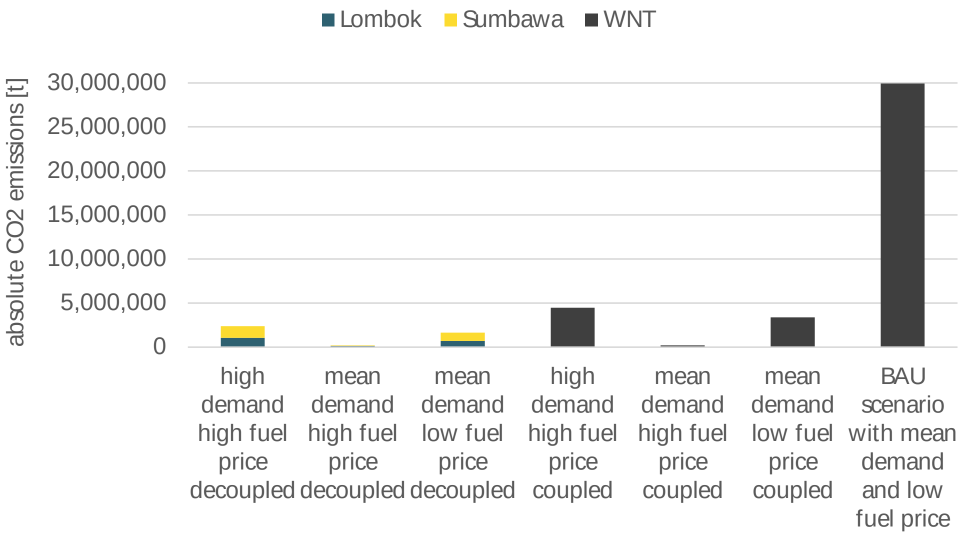


Figure 40: Direct CO2e emissions in all scenarios

6.3 Transition Plan

The elaboration of a detailed transition plan will be part of the ongoing project, but some first insights into possible transformation pathways of WNT's energy system shall be given here already. It is considered to be very important that the right investment decisions are made from on the present day. Therefore, ideally no further investments in fossil technologies should be made, as these investments would eventually be stranded. This means that private households, in addition to commercial and industrial units, must be incentivized to invest into renewable energy technologies like biogas stoves and PV power plants.

Figure 41 shows one possible pathway for electricity generation to reach the leading scenario in the year 2050. Today the share of renewable electricity generation is small, with only a few photovoltaic systems and hydro power plants installed. As electricity demand is projected to rise by 15 times in the mean demand scenario (including electricity demand for fuels, heating and transport demand) until 2050 new power plant capacities have to be installed quite soon on the two islands to cover growing electricity demand. As photovoltaic is an easily scalable and decentral technology it is recommended to start with the expansion very soon. Biogas CHPs can also be installed in the next two to three years, as soon as biogas production plants have been built up. Biomass residues are available in large amounts at cheap prices today, and biogas CHPs can therefore directly replace diesel generators. Wind power plants need longer planning processes as suitable locations have to be found by analyzing wind speed, potential risks for certain birds and other threats to nature. These processes should start now, so that the commissioning of first wind parks could realistically be achieved by the year 2028. Also, geothermal power plants need longer planning horizons, so electricity production from geothermal power plants could only start in the year 2030. Existing diesel generators can be held as back up in the next years as maintenance costs are rather low and costs are strongly driven by fuel prices. As it can be seen in Figure 41, electricity demand rises quite slowly until 2030. Trom that year on the increase is steeper as electricity demand for transport sector and the production of synthetic fuels also rises more and more.

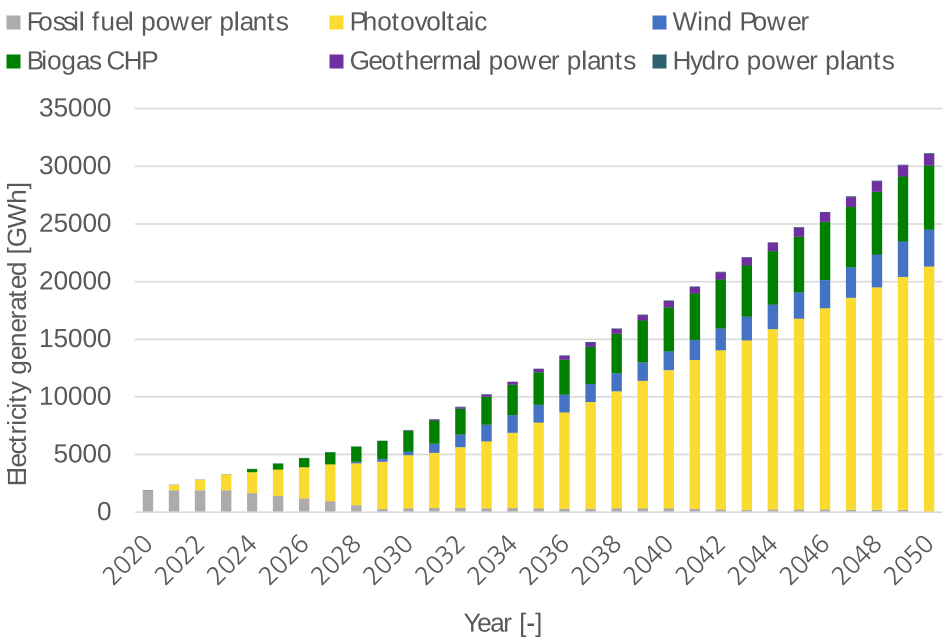


Figure 41: Generated electricity in the years 2020-2050 in the leading scenario

Figure 42 shows the share of different drive train concepts from today until 2050, aggregated for all vehicle types. The first vehicles that are assumed to be electrified are small ships and boats mainly traveling short distances, as this technology is mature and easily available at the present. Also, electric motorcycles are currently available in Asia and shall be diffusing into the market as soon as possible. For electric cars, deployment is seen realistic from the year 2025 on, but the share of total vehicles increases slowly at first. Hydrogen vehicles are seen only realistic from the year 2032 onwards, as today not many different manufacturers produce hydrogen busses, trucks, or ships and prices are still high. Simultaneously with the adoption of the new vehicles, charging and refueling infrastructure must be installed on the two islands.

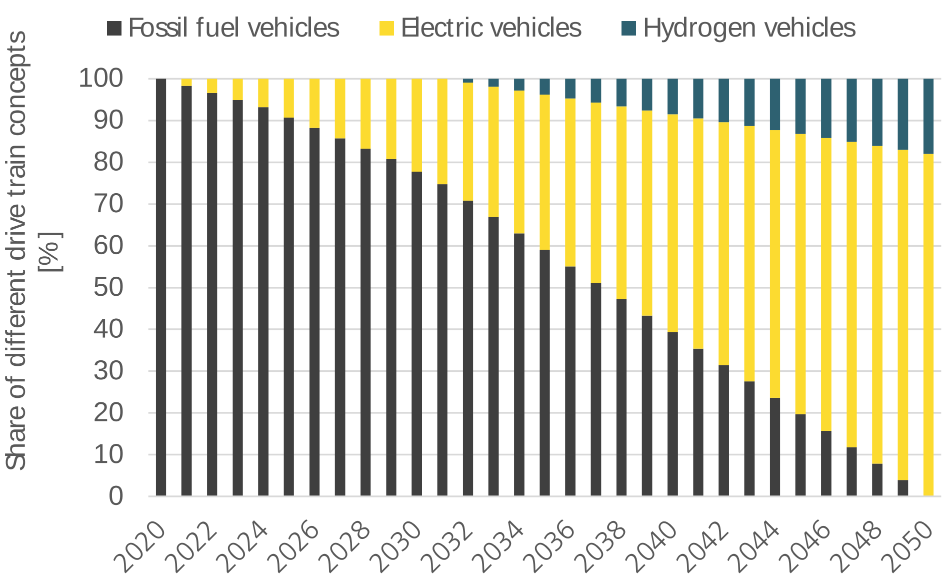


Figure 42: Share of different drive train concepts over all vehicle types in the leading scenario from 2020 until 2050

Fossil fuels for covering heating demand in commercial and industrial sector are only needed until the year 2026 (see Figure 43). From that time on, CHPs produce enough heat to cover heating demand. From the year 2028 on, the start of hydrogen production for transport sector and production of synfuels is assumed and electrolyzers produce excess heat as well. As electricity and fuel demand is high compared to heating demand, because space heating is not prevalent in WNT due to the climate, electrolyzers and CHPs produce more heat than is needed and excess heat has to be curtailed. This is depicted by negative heating supply in Figure 43.

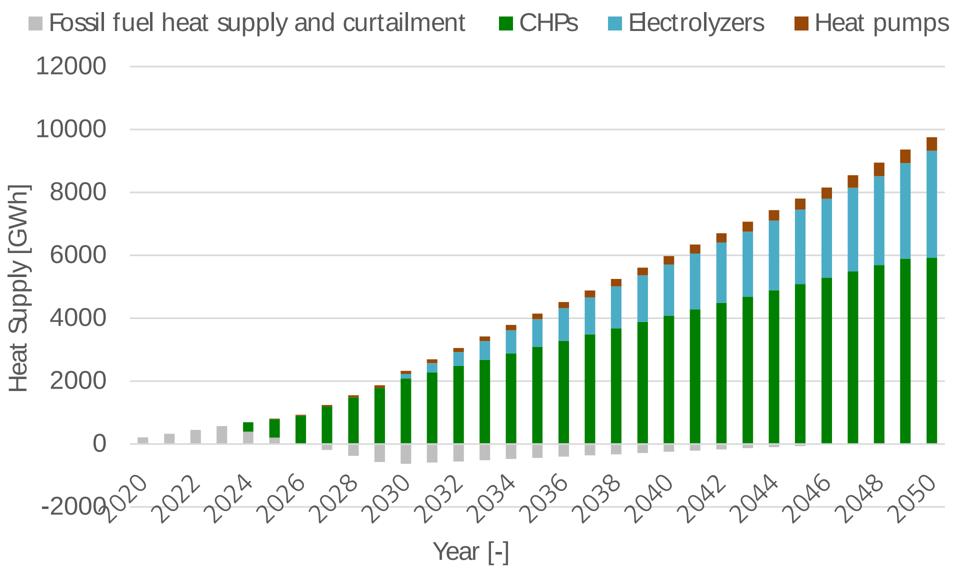


Figure 43: Share of different heat supply technologies on overall heat supply in the leading scenario from 2020 until 2050

Today's cooking technologies (mainly biomass and gas) should be replaced with modern biogas stoves, which have a higher efficiency and generate less harmful smoke. As lifetimes of cooking stoves is rather short (up to 10 years), they can simply be replaced when they have reached the end of their lifetime (see Figure 44). Additional stove capacity should directly be based on renewable energies. This means that biogas production from crop residues shall start as soon as possible, so that biogas is available for deployment in biogas stoves as well as biogas CHPs. Cooking supply and therefore demand is increasing from today until the year 2050 in the household as well as the commercial sector. In the household sector increase is correlated to increase of population, while in the commercial sector it is correlated to increase of GDP, which will be mainly dependent on increase of tourism on the two islands.

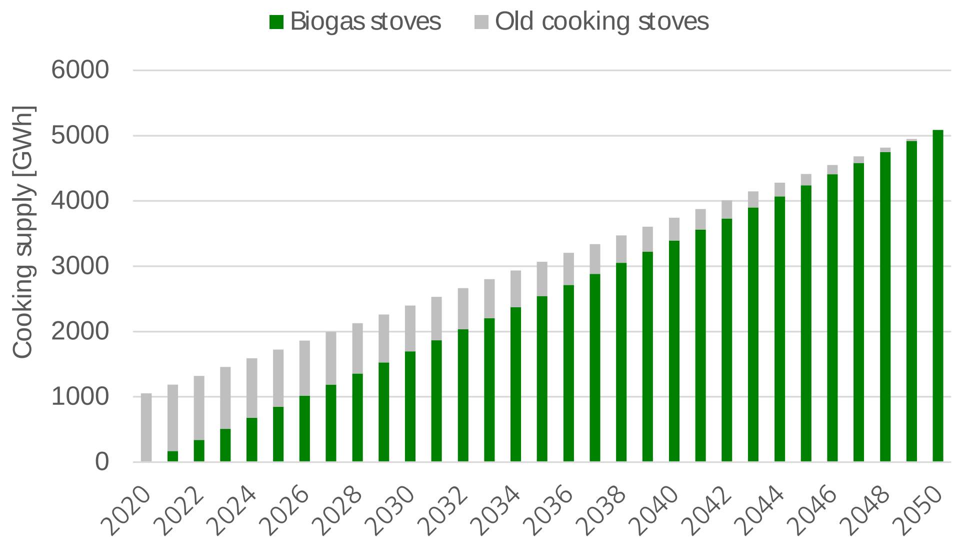


Figure 44: Share of biogas and old cooking stoves on overall cooking supply in the leading scenario from 2020 until 2050

Hydrogen is needed around the years 2030-2032 for transport and synthetic fuel demand in commercial and industry sector and therefore the first electrolyzers shall be installed at that time, as well as synthesis plants and technologies to capture carbon dioxide for the production of synthetic fuels (see Figure 45).

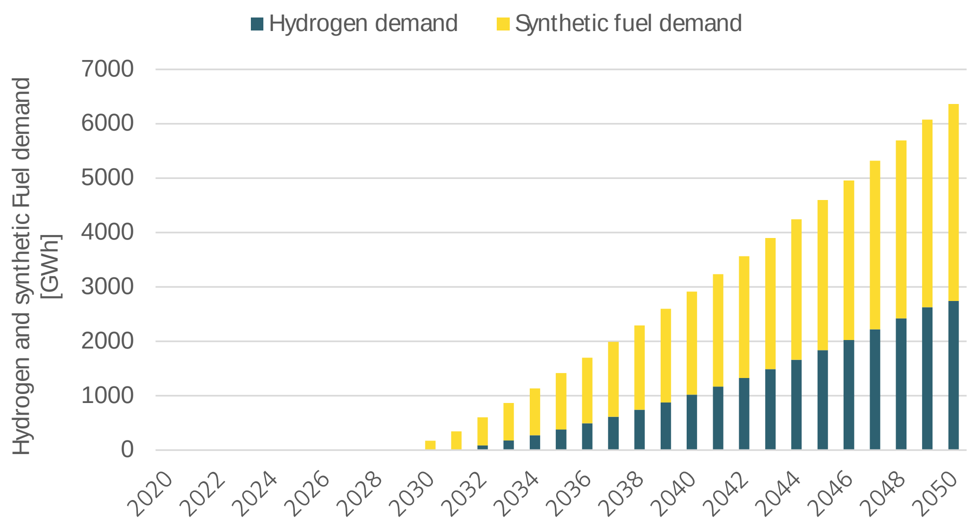


Figure 45: Hydrogen and synthetic fuel demand in the leading scenario from 2020-2050

Their share of overall fuel demand in the commercial and industrial sectors will be small at first. The onset of synthetic fuel production can be scheduled sooner or later depending on the availability of mature and economically feasible technology, but hydrogen will be needed in the transport sector as soon as the first hydrogen busses and ships are being used. In the model, carbon dioxide capture can be either done from biogas CHPs or via direct air capture. Sequestration from thermal power plants is cheaper and therefor recommended. This means that the production of synthetic fuels shall be close to biogas CHPs, which is logical, as heat and fuels will be used in commercial and industrial sector. As the amount of carbon dioxide from the capture of CHPs is not sufficient, direct air capture is also used, which is an energy intensive process at the present day. The choice of the most suitable processes for CO_2

sequestration in the specific case of West Nusa Tenggara shall be further evaluated and is dependent on the technical and economic development of the different carbon dioxide capture processes.

6.4 Risk analysis and Recommendations

Electricity supply:

- Supply security is more difficult to ensure when fluctuating renewables take high shares of overall electricity production. In the model supply security is ensured by modeling with a high time resolution and endogenous calculation of needed storage capacity. But nevertheless, the needed storage capacity is dependent on parameters like the availability of installed storage and the longest period in which little to no renewable energy from fluctuating renewables is produced due to low wind speed and low solar irradiation (a condition known as "Dunkelflaute"). In the model two kinds of electric storage technologies were implemented: battery storages and pumped hydro storages using lake water. As water levels of the lakes are too low in the dry season, pumped storage is not feasible option, as it could only be used half of the year. Another possibility would be pumped storage using sea water. First potential analyses for West Nusa Tenggara are being conducted at the moment. A diversification of storage technologies can help to increase supply security and therefore it is recommended to conduct further analyses on different storage options.
- PV deployment is high in all scenarios that have been calculated and it is a technology that can easily be scaled up. The promotion of the installation of PV power plants is therefore recommended. Prices are already quite low today, but subsidies could help to make the installation of PV even more attractive, also for households and commercial enterprises. PV can be installed decentralized and therefore also help more remote areas to have access to clean, affordable, and secure electricity supply
- Especially for wind power plants, a detailed assessment of possible sites is inevitable. It is recommended to conduct feasibility studies including detailed measurements of wind speeds in the near future to determine the best locations and start the planning process. To ensure a successful process and the detection of the most suitable sites as well as a high acceptance of the technology all stakeholders should be included in the planning process: people living nearby, environmental organizations who know about potential threads for birds nesting close to the potential sites, the local electricity supply company, the grid operator, and the local government.
- In this study, for the sake of simplicity, biogas was assumed to be the only source of bioenergy for all scenarios. Whether direct burning of biomass or the conversion of biomass to biogas is a better option for West Nusa Tenggara shall be assessed via detailed feasibility studies.
- Produced Biogas shall soon start to be used, both in biogas cooking stoves in households as well as in biogas CHPs replacing diesel generators. To produce biogas, biomass residues must be collected and brought to biogas production facilities. It is beneficial if biomass must only be transported for short distances as the calorific value is low before the biogas production process and transport costs should be kept at a minimum to keep biogas price low. The best locations for biogas production should be found by taking into account the areas used for agriculture, as well as the locations of usage of biogas in households and CHP plants, which should be located close to commercial and industrial sites because of the usage of heat.
- Less energy demand in the future directly leads to a less expensive energy system, as lower capacities of power plants are required to be installed and less fuel is needed. Projections of energy demand show that demand will most probably

increase in the future, due to several reasons, such as growing welfare and therefore the use of more appliances in the households, and similar trends in the commercial sector. Efficient appliances, and the efficient operation thereof, can be promoted or even subsidized.

Transport sector:

- If electric and hydrogen vehicles shall be used in the future, charging infrastructure must be planned accordingly. As distances on the two islands are rather short, charging for electric motorcycles in particular can be done mostly at home. But for cars fast charging stations in the cities as well as on the main connecting roads will be necessary.
- One important issue to be resolved is the availability and price of electric and hydrogen cars in Indonesia. Today electric and hydrogen cars are more expensive than fossil fuel driven cars and many countries have subsidies to increase their market diffusion. Furthermore, the availability of hydrogen and electric cars on the secondhand car market is currently nonexistent, which could be a potential obstacle to their uptake in Indonesia.
- The projection used for the development of energy demand in transport sector has the underlying assumption that the ownership of individual motor vehicles will increase in the next 30 years. Expansion of public transport as well as car sharing options can reduce the projected increase in energy demand in the transport sector.

Cooking supply

- One risk for the adoption of new cooking technologies is the lack of acceptance by the potential users, namely households and commercial facilities (restaurants, hotels). Informing about the new technology is therefore important. As biogas stoves with higher efficiency have higher investment costs which could make them unaffordable for lower income households, subsidies and/or microcredits can help people to adopt these new technologies.
- The usage of biogas stoves is highly dependent on the availability of biogas. Therefor the expansion of biogas production must be a key priority in the next years. (See also the risks and recommendations for electricity supply)

Fuels and heating supply in commercial and industrial sector

- Heating and fuel purposes in commercial and industrial sector are diverse and highly dependent on the specific processes that are being conducted. Before deciding on the optimal fuel and heating supply option for the different facilities, their needs must be understood and the possibility for an individual consultation should be given to companies, so that each can find customized solutions based on renewable energies. Consulting programs for commercial and industrial facilities about energy saving measures and usage of renewable energies can be implemented for that purpose.
- Demand development until 2050 in commercial sector has been correlated to increase in GDP and demand increase is therefore high. It is highly recommended to help companies in the commercial sector to implement energy saving measures to decouple economic growth and energy demand.
- The usage of excess heat from electrolyzers and CHPs relies on spatial proximity and therefore it is recommended to build up CHP power plants and electrolyzers close to commercial and industrial sites.

7 Conclusions

This study is able to show that, given certain boundary conditions, 100 percent renewable energy for West Nusa Tenggara is possible for the following sectors: electricity, heating, cooking, fuel demand in commercial and industry sector, as well as transport on land and water. The most important findings of the study are:

- 100 percent renewable energy is possible in all demand scenarios. For the decoupled energy system for Lombok, the potentials are used to a very high extent that would make a further increase in demand hard to cover.
- Coupling the energy systems of the two islands has economic advantages and increases supply security, as Sumbawa has higher biomass potential and lower energy demand than Lombok.
- Photovoltaics is the technology with the highest electricity supply in all 100 % RE scenarios, varying from 65 % to 86 %, with the lowest levelized costs of energy of all technologies at 0.028 €/kWh (480 IDR/kWh). As PV and wind power supply fluctuating electricity, batteries are needed to balance between supply and demand. If battery costs are added to levelized costs of electricity for PV, the LCOE increases to 0.044 €/kWh (752 IDR/kWh)
- Wind power is installed in all scenarios, covering between 7 % and 20 % of the demand in the 100 % RE scenarios.
- Geothermal power plants and hydropower plants are focus technologies of the Indonesian government; therefore, their potentials are fully utilized in all scenarios. However, their potential is rather small, only accounting for around 2-3 % of the electricity supply for the coupled energy system.
- Variations in biogas fuel price lead to changes in the structure of energy supply, especially for covering heating and cooking demand. While with high fuel price heating and cooking demand is mainly covered by heat pumps and electric cookers, with low fuel price the former is mainly covered by CHPs and the latter is mainly covered with biogas stoves. With higher fuel price, CHPs cover only minor shares of electricity supply and the share of PV rises compared to the scenarios with lower fuel price
- One scenario was chosen as a leading scenario. The implementation of this scenario should now be promoted in West Nusa Tenggara. The leading scenario consists of a coupled energy system with mean demand and low fuel price
- The business-as-usual scenario represents an energy system with much lower ambitions for RE deployment, with 50 % renewables for electricity supply but nearly no deployment of RE for cooking supply and in the transport sector. This scenario is 32 % more expensive and CO_2e emissions are 4,5 times higher than in the leading scenario.

Recommendations for the transition of the energy system of West Nusa Tenggara to 100 % renewables are described in chapter 6.4. The most important recommendations are:

- PV deployment is high in all scenarios that have been calculated and it is a technology that can easily be scaled up. The promotion of the installation of PV power plants is therefore recommended. PV can be decentralized and therefore also help more remote areas to have access to clean, affordable, and secure electricity supply.
- Energy efficiency shall be promoted throughout all sectors to decouple energy demand and economic growth in the long-term. This will lead to a less expensive energy system and less deployment of resources. Consultation programs can help to promote energy efficiency in households and commercial and industrial facilities. In transport sector the promotion and expansion of other modes of transport, for

instance public transport, as well as new concepts like car charging, can lead to energy savings.

- Today energy supply is mostly coming from coal and diesel power plants. As energy demand will grow and installed power plants will eventually reach the end of their lifetime, new power plant capacities will have to be installed in the next years. New installed capacities should consist only of renewable power plants. In the first years PV and biogas CHPs should be installed, followed later by wind and geothermal power plants.
- Especially for wind power plants, a detailed assessment of possible sites is essential to the installation of new plants. It is recommended to conduct feasibility studies in the near future, including detailed measurements of wind speeds, to determine the best locations and start the planning process. In addition, for the use of synthetic fuels it is recommended to conduct further analyses, so that decisions can be made about which kind of synthetic or biofuels can replace fossil fuels in the future.

8 APPENDIX

A. Table of final energy demands today and in 2050

	Energy demand today	High demand scenario			Low demand scenario		
All values in [GWh]	WNT	Lombok	Sumbawa	WNT	Lombok	Sumbawa	WNT
ec for cooling residential	109	592	257	849	407	176	583
ec for cooling commercial	87	265	115	380	182	79	262
cooking residential	253	189	82	271	189	82	271
cooking commercial	800	4929	2137	7065	1932	837	2769
fuel commercial	1788	9522	4127	13649	3731	1617	5349
fuel industrial	22	157	68	225	61	27	88
heating commercial	207	1402	608	2009	549	238	787
electricity demand	1721	10396	4506	14902	4023	1744	5767
transport energy demand electric	0	3047	1321	4367	1858	805	2663
transport energy demand hydrogen	0	2462	1067	3530	1305	566	1870
transport energy demand fossil fuels	4714						
navigation energy demand fossil fuels	419	0	0	0	0	0	0
Sum	9700	32960	14287	47247	14238	6172	20410

B. Specific energy demands of vehicles with different drive train concepts

	Final energy consumption of fuel vehicle [kWh/100 km]	Final energy consumption of electric vehicle [kWh/100 km]	Final energy consumption of hydrogen vehicle [kWh/100 km]
Motorcycles	32 (Böke 2007)	4 (Böke 2007)	
Car	45 (Mauch 2009)	20 (Wikipedia 2021)	29 (Mauch 2009)
Bus and truck	291 (Schmied and Mottschall 2014)	115 (Bünnagel 2020)	300 (Kupferschmid and Faltenbacher 2019)

C. Energy supply and installed capacities of all technologies in all scenarios in 2050

Leading scenario: Coupled system, mean demand, low fuel price

	Capacity [MW]	Generation [GWh]	Generation [kt]	Full load hours [h]
PV rooftop	3728	5406		1450
PV free field	10833	15900		1468
Wind power	1381	3187		2308
Hydro power	14	66		4800
Geothermal power	145	1015		7000
CHP Biogas crops el	733	5560		7382
CHP Biogas crops th	825	5925		
CHP waste el	0	0		0
CHP waste th	0	0		0
Heat pumps	91	431		3451
Stove biogas crops	2357	4615		1958
Stove biogas manure	431	472		1095
Electrolysis	2247	3398	223	5001
Methanol Synthesis	38966 kg/h		329	8447
Methanisation	20744 kg/h		141	6818
Electrical storage	42702 MWh	9981		
Thermal storage	558 MWh	289		

Coupled system, mean demand, high fuel price

	Capacity [MW]	Generation [GWh]	Generation [kt]	Full load hours [h]
PV rooftop	2232	2170		925
PV free field	20517	30156		1470
Wind power	2137	5001		2341
Hydro power	14	68		4917
Geothermal power	145	1015		7000
CHP Biogas crops el	280	66		237
CHP Biogas crops th	315	75		
CHP waste el	0			
CHP waste th	0			
Heat pumps	1190	9481		5804
Stove biogas crops	755	503		666
Stove biogas manure	638	375		587
Electric cooking	2787	4209		1522
Electrolysis	2247	3398	223	5001
Methanol Synthesis	39525 kg/h		329	8328
Methanisation	19958 kg/h		141	7086
Electrical storage	42702 MWh	9981		
Thermal storage	558 MWh	289		

Coupled system, high demand, low fuel price

	Capacity [MW]	Generation [GWh]	Generation [kt]	Full load hours [h]
PV rooftop	6353	9282		1461
PV free field	13837	20580		1487
Wind power	1383	3116		2253
Hydro power	14	66		4800

Geothermal power	145	1015		7000
CHP Biogas crops el	1189	9040		7273
CHP Biogas crops th	1338	9289		
CHP waste el	0			
CHP waste th	0			
Heat pumps	0			
Stove biogas crops	3589	6865		1913
Stove biogas manure	431	472		1095
Electric cooking	0			
Electrolysis	3311	3872	310	4306
Methanol Synthesis	56046 kg/h		473	8439
Methanisation	29995 kg/h		203	6775
Electrical storage	58621 MWh	13685		
Thermal storage	0 MWh			

Decoupled system, Lombok, mean demand, low fuel price

	Capacity [MW]	Generation [GWh]	Generation [kt]	Full load hours [h]
PV rooftop	5785	8225		1416
PV free field	8064	11746		1457
Wind power	1549	3438		2220
Hydro power	9	41		4560
Geothermal power	70	490		7000
CHP Biogas crops el	304	861		2828
CHP Biogas crops th	342	965		
CHP waste el				
CHP waste th				
Heat pumps	720	5438		5502
Stove biogas crops	1240	1965		1584
Stove biogas manure	147	146		990
Electric cooking	992	1509		1534
Electrolysis	1649	2528	156	4908
Methanol Synthesis	27045 kg/h		230	8490
Methanisation	13136 kg/h		99	7511
Electrical storage	41151 MWh	9558		
Thermal storage	1426 MWh	389		

Decoupled system, Lombok, mean demand, high fuel price

	Capacity [MW]	Generation [GWh]	Generation [kt]	Full load hours [h]
PV rooftop	7355	10593		1437
PV free field	8837	12588		1424
Wind power	1431	3140		2195
Hydro power	9	40		4451
Geothermal power	70	490		7000
CHP Biogas crops el	225	52		229
CHP Biogas crops th	253	58		
CHP waste el				
CHP waste th				
Heat pumps	835	6608		5767
Stove biogas crops	743	9		658
Stove biogas manure	249	146		586
Electric cooking	1983	5		1517

Electrolysis	1647	2529	156	4912
Methanol Synthesis	27668 kg/h		230	8299
Methanisation	13955 kg/h		99	7070
Electrical storage	50469 MWh	11672		
Thermal storage	1498 MWh	394		

Decoupled system, Lombok, high demand, low fuel price

	Capacity [MW]	Generation [GWh]	Generation [kt]	Full load hours [h]
PV rooftop	10471	14770		1293
PV free field	9417	13854		1471
Wind power	1342	3080		2295
Hydro power	9	39		4405
Geothermal power	70	490		7000
CHP Biogas crops el	254	166		652
CHP Biogas crops th	286	186		
CHP waste el	167	1251		7460
CHP waste th	188	1402		
Heat pumps	935	7210		5619
Stove biogas crops	2557	3181		1244
Stove biogas manure	192	146		761
Electric cooking	1374	1690		1239
Electrolysis	2452	3511	216	4585
Methanol Synthesis	39018 kg/h		330	8456
Methanisation	20047 kg/h		142	7072
Electrical storage	58173 MWh	13563		
Thermal storage	1651 MWh	450		

Decoupled system, Sumbawa mean demand, low fuel price

	Capacity [MW]	Generation [GWh]	Generation [kt]	Full load hours [h]
PV rooftop	3498	5131		1467
PV free field	711	925		1301
Wind power	375	879		2344
Hydro power	5	24		4934
Geothermal power	75	525		7000
CHP Biogas crops el	242	1884		7510
CHP Biogas crops th	272	1964		
CHP waste el	0			
CHP waste th	0			
Heat pumps	0			
Stove biogas crops	860	1569		1825
Stove biogas manure	0			
Electric cooking	0			
Electrolysis	728	837	67	4251
Methanol Synthesis	11704 kg/h		100	8505
Methanisation	6213 kg/h		43	6883
Electrical storage	11872 MWh	2772		
Thermal storage	0 MWh			

Decoupled system, Sumbawa mean demand, high fuel price

	Capacity [MW]	Generation [GWh]	Generation [kt]	Full load hours [h]
PV rooftop	3498	5120		1464
PV free field	2955	3656		1237
Wind power	997	2323		2331
Hydro power	5	21		4390
Geothermal power	75	525		7000
CHP Biogas crops el	25	2		79
CHP Biogas crops th	28	2		
CHP waste el				
CHP waste th				
Heat pumps	361	2888		5844
Stove biogas crops	179	130		728
Stove biogas manure	251	160		640
Electric cooking	860	1278		1499
Electrolysis	696	1095	67	5041
Methanol Synthesis	11820 kg/h		100	8421
Methanisation	5844 kg/h		43	7318
Electrical storage	22425 MWh	5114		
Thermal storage	647 MWh	185		

Decoupled system, Sumbawa high demand, low fuel price

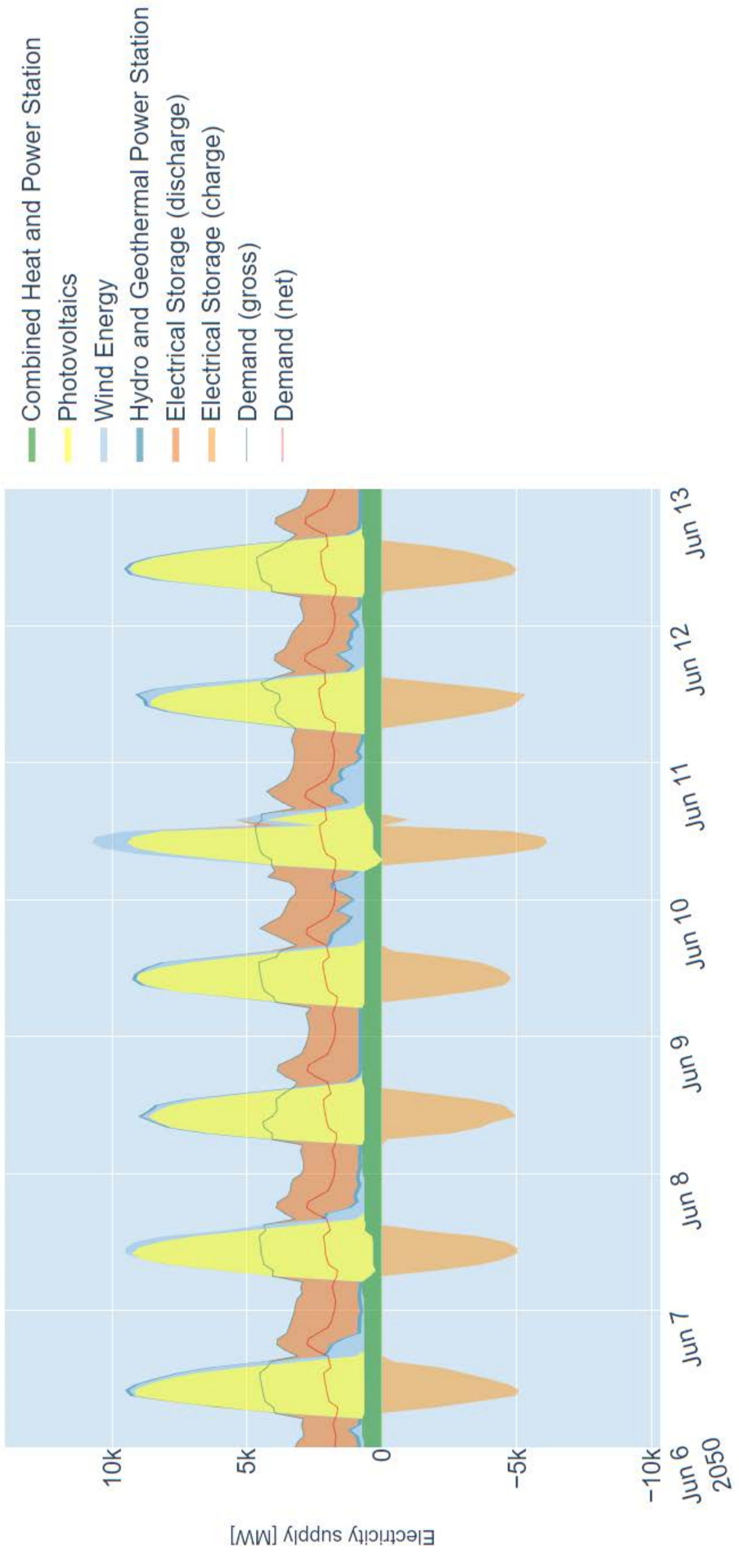
	Capacity [MW]	Generation [GWh]	Generation [kt]	Full load hours [h]
PV rooftop	3718	5386		1365
PV free field	2265	3037		1341
Wind power	584	1371		2348
Hydro power	5	24		4909
Geothermal power	75	525		7000
CHP Biogas crops el	341	2686		7563
CHP Biogas crops th	384	2789		
CHP waste el	0			
CHP waste th	0			
Heat pumps	0			
Stove biogas crops	918	1893		2062
Stove biogas manure	298	326		1095
Electric cooking	0			
Electrolysis	983	1163	93688	4370
Methanol Synthesis	16835 kg/h		143	8496
Methanisation	8906 kg/h		61455	6900
Electrical storage	17235 MWh	4014		
Thermal storage	0 MWh			

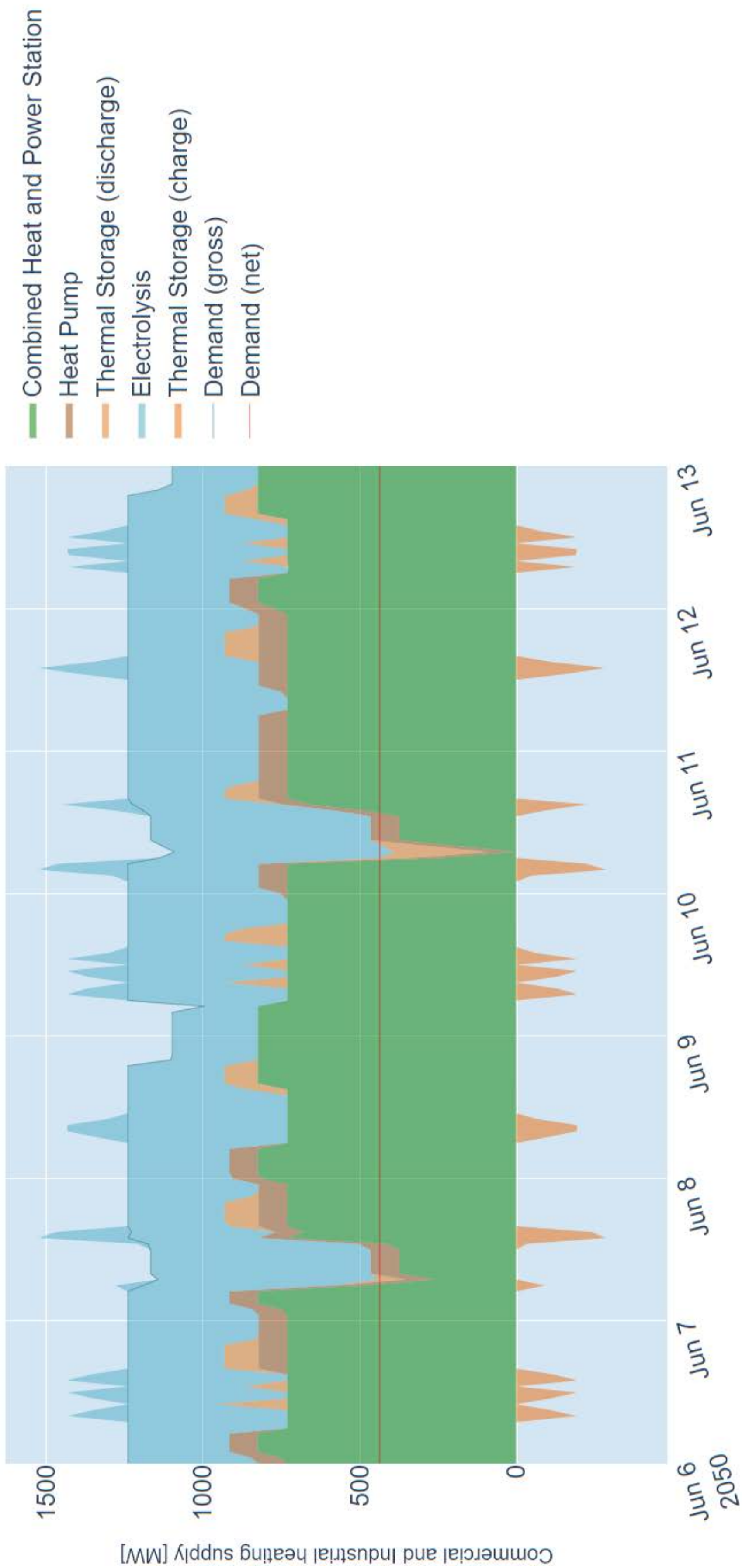
Business as usual scenario, coupled system, mean demand, low fuel price

	Capacity [MW]	Generation [GWh]	Generation [kt]	Full load hours [h]
PV rooftop	663	861649		1300
PV free field	4085	5919210		1449
Wind power	600	1431359		2385
Hydro power	14	54920		4000
Geothermal power	145	1015000		7000
CHP Biogas crops el	0			
CHP Biogas crops th	0			
CHP waste el	0			

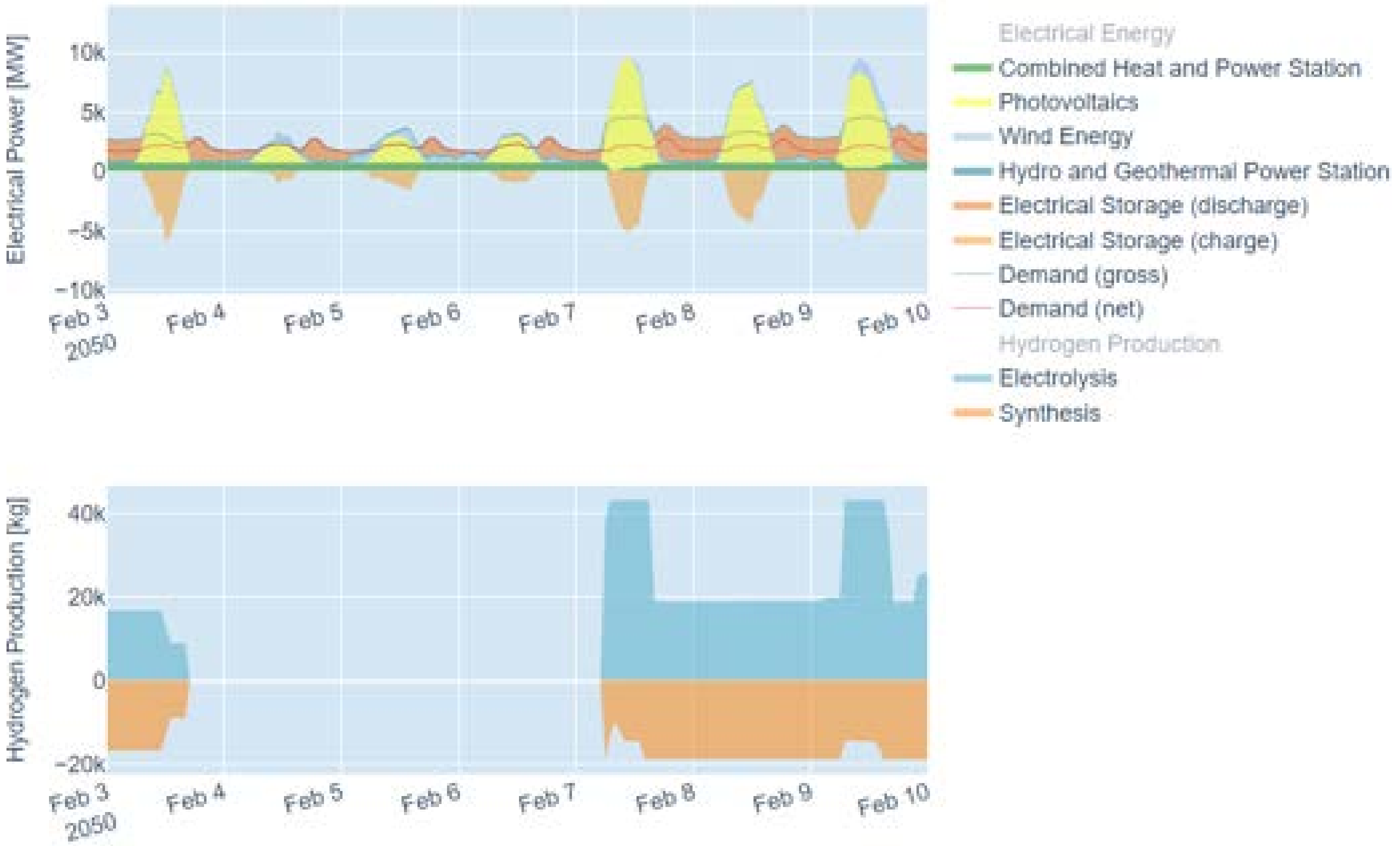
CHP waste th	0			
Coal power plant el	580	4640247		7981
Coal power plant th	276	2199376		
Gas power plant el	744	4640247		3917
Coal power plant th	236	377761		
Heat pumps	0			
Stove biogas crops	239	610400		2555
Stove biogas manure	0			
Electric cooking	0			
LPG cooking	2548	4476		1757
Electrolysis	862	132571	1009	5872
Methanol Synthesis	81269 kg/h		650	8000
Methanisation	0 kg/h			
Electrical storage	8261 MWh	1976		
Thermal storage	0 MWh			

D. Time series of leading scenario




Combined Heat and Power Station
Heat Pump
Thermal Storage (discharge)
Electrolysis
Thermal Storage (charge)
Demand (gross)
Demand (net)
1500
1000
500
0
Jun 6
2050
Jun 7
Jun 8
Jun 9
Jun 10
Jun 11
Jun 12
Jun 13
Commercial and Industrial heating supply [MW]

E. Time series for one week with low solar irradiation (in leading scenario)



References

Adi, Agus Cahyono; Lasnawatin, Farida; Prananto, Anton Budi; Suzanti, Vony Mela; Anutomo, Imam Gagas; et al. (2019): Handbook of energy & economic statistics of Indonesia 2019. Edited by Ministry of energy and mineral resources republic of Indonesia. Available online at https://www.esdm.go.id/assets/media/content/content-handbook-of-energy-and-economic-statistics-of-indonesia-2019.pdf.

Adi, Agus Cahyono; Nunung, Eko Ajlwihanto; Lasnawatin, Farida; Indarwati, Fifi; Anutomo, Imam Gagas; et al. (2018): Handbook of energy &economic statistics of Indonesia. Edited by Ministry of energy and mineral resources republic of Indonesia. Available online at https://www.esdm.go.id/assets/media/content/content-handbook-of-energy-and-economic-statistics-of-indonesia-2018-final-edition.pdf.

Alliance for rural electrification (Ed.) (2019): Close to 600 million people are still without access to electricity in sub-Saharan Africa. Available online at https://www.ruralelec.org/rural-electrification, checked on 8/30/2021.

Anciaux, Amaury; Cornet, Michel; Counsell, Tom; Jossen, Quentin; Matton, Vincent; Meessen, Jérôme et al. (2018): 2050 scenario analysis using the EU CTI 2050 Roadmap Tool. Documentation on costs assumptions. Edited by European Climate Foundation. Available online at https://europeanclimate.org/wp-content/uploads/2019/11/10-18-2050-scenario-analysis-using-the-eu-cti-2050-roadmap-tool-power-sector.pdf.

Böke, Ulrich (2007): Energieeffizienz & Spaß mit 100 % Erneuerbaren Energien. Edited by Solarenergie Förderverein Deutschland e.V. Available online at https://www.sfv.de/artikel/energieeffizienz__spass_mit_100__erneuerbaren_energien#:~:text=Da%20der%20spezifische%20Energieinhalt%20von,%2C8%20l%2F100km%20Ethanol., checked on 5/21/2021.

BPS statistics of Nusa Tenggara Barat Province (Ed.) (2020): Provinsi Nusa Tenggara Barat Dalam Angka Nusa Tenggara Barat Province in Figures 2020.

Bravo, Natalie; Gillispie, Clara; Herberg, Mikkal E.; Nugroho, Hanan; Stuart, Alexandra; Tsafos, Nikos (2015): Indonesia: a regional energy leader in transition. NBR special report #53. Edited by The National Bureau of Asian Research.

Bundesministerium für Wirtschaft und Energie (Ed.) (2021): Zahlen und Fakten: Energiedaten.

Bünnagel, Claus (2020): Studie: Energieverbrauch von Elektrobussen. Edited by Busplaner. Available online at https://www.busplaner.de/de/news/elektromobilitaet-e-mobilitaet_studie-energieverbrauch-von-elektrobussen-35732.html, checked on 5/21/2021.

CleanTech (Ed.) (2017): Understanding coconut as a biomass fuel.

Coady, David; Parry, Ian; Sears, Louis; Shang, Baoping (2015): IMF working paper How large are global energy subsidies? Edited by international monetary fund (IMF) (WP/15/105). Available online at https://www.imf.org/en/Publications/WP/Issues/2016/12/31/How-Large-Are-Global-Energy-Subsidies-42940, checked on 9/1/2021.

Dahlanuddin; Sutaryono, Yusuf Akhyar; Hasan, Sofyan D.; Mastur (2011): Climate Futures and Rural Livelihood Adaptation Strategies in Nusa Tenggara Barat Province, Indonesia. Survey report livestock production systems in Lombok and Sumbawa. Edited by University of Mataram. Available online at https://ei-ado.aciar.gov.au/sites/default/files/DahlanuddinEtAl(2011)ClimateFuturesRuralLivelihoodAdaptationStrategiesNTB_UniMataram.pdf.

Danish Energy Agency (Ed.) (2019): Lombok: Prefeasibility studies on RE Solutions. Available online at https://ens.dk/sites/ens.dk/files/Globalcooperation/prefeasibility_studies_on_re_solutions_in_lombok_-_jan_2019.pdf.

Danish Energy Agency (Ed.) (2021): Technology data for the Indonesian power sector. Catalogue for Generation and Storage of Electricity.

Directorate General of Electricity (Ed.) (2016-2020): Electrification Statistics 2015-2019.

Doman, Linda E.; Arora, Vipin; Singer, Laura E.; Zaretskaya, Victoria; Jones, Ayaka; Huetteman, Thaddeus; et al. (2016): International Energy Outlook 2016. Edited by U.S. energy information administration (eia).

Durix, Laurent (2015): Towards universal access to clean cooking solutions -. Indonesia Clean Stove Initiative - From Concept to the Field to the Lab. Available online at https://openknowledge.worldbank.org/bitstream/handle/10986/16068/792790ESW0P1290ox0377371B00PUBLIC00.pdf?sequence=1&isAllowed=y.

Enercon (2021): E-160 EP5. Available online at https://www.enercon.de/produkte/ep-5/e-160-ep5/, checked on 5/21/2021.

Environmental Agency of West Nusa Tenggara (Ed.) (2019): Dokumen Kebijakan Strategi Daerah (JAKSTRADA).

Fachagentur nachwachsende Rohstoffe e.V. (Ed.) (2021): Faustzahlen. Available online at https://biogas.fnr.de/daten-und-fakten/faustzahlen, checked on 4/30/2021.

Fasihi, Mahdi; Efimova, Olga; Breyer, Christian (2019): Techno-economic assessment of CO2 direct air capture plants. In *Journal of Cleaner Production* 224, pp. 957–980. DOI: 10.1016/j.jclepro.2019.03.086.

Graham, Paul W.; Hayward, Jenny; Foster, James; Story, Oliver; Havas, Lisa (2018): GenCost 2018. Edited by CSIRO. Australia.

Gravalos, Ioannis; Xyradakis, Panagiotis; Kateris, Dimitrios; Gialamas, Theodoros; Bartzialis, Dimitrios; Giannoulis, Kyriakos (2016): An Experimental Determination of Gross Calorific Value of Different Agroforestry Species and Bio-Based Industry Residues. In *NR* 07 (01), pp. 57–68. DOI: 10.4236/nr.2016.71006.

Gubernur Nusa Tenggara Barat (Ed.) (2019): Rencana Umum Energi Daerah (RUED) Provinsi Nusa Tenggara Barat.

Gummert, Martin; van Hung, Nguyen; Chivenge, Pauline; Douthwaite, Boru (2020): Sustainable Rice Straw Management. Cham: Springer International Publishing.

Hank, Christoph; Sternberg, André; Köppel, Nikolas; Holst, Marius; Smolinka, Tom; Schaadt, Achim et al. (2020): Energy efficiency and economic assessment of imported energy carriers based on renewable electricity. In *Sustainable Energy Fuels* 4 (5), pp. 2256–2273. DOI: 10.1039/d0se00067a.

International Energy Agency: World Energy Outlook 2019: OECD Publishing.

International Energy Agency (Ed.) (2018): Thailand, key energy statistics, 2018. Available online at https://www.iea.org/countries/thailand, checked on 5/7/2021.

International Energy Agency (Ed.) (2019): The Future of Cooling in Southeast Asia.

International Energy Agency (Ed.) (2021): IEA country profiles (Argentina, Kenya, Indonesia). Available online at https://www.iea.org/countries, updated on 8/30/2021.

International Renewable Energy Agency (Ed.) (2017a): Biogas Cost Reductions to Boost Sustainable Transport. Available online at https://irena.org/newsroom/articles/2017/Mar/Biogas-Cost-Reductions-to-Boost-Sustainable-Transport, checked on 5/3/2021.

International Renewable Energy Agency (Ed.) (2017b): Biogas for domestic cooking. Technology brief.

International Renewable Energy Agency (Ed.) (2017c): renewable energy outlook Thailand. Available online at https://www.irena.org/-/media/Files/IRENA/Agency/Publication/2017/Nov/IRENA_Outlook_Thailand_2017.pdf.

Islami, Muhamad Saladin; Aditya, Emy (2020): Initial Status Report of Deep-Dive Region: West Nusa Tenggara Province. Edited by ICLEI.

Jeuland, Marc A.; Pattanayak, Subhrendu K. (2012): Benefits and costs of improved cookstoves: assessing the implications of variability in health, forest and climate impacts. In *PloS one* 7 (2), e30338. DOI: 10.1371/journal.pone.0030338.

JIQ magazine on climate and sustainability (Ed.) (2016): Biogas development in Indonesia: household scale. Evaluation of Indonesian transition pathways in biogas utilisation.

KenGen (Ed.) (2021): KenGen- About us. Available online at https://www.kengen.co.ke/index.php/our-company/who-we-are.html, checked on 8/30/2021.

Kenya Power (Ed.) (2015): Annual report and financial statements. financial year ended 30 June 2015. Available online at https://kplc.co.ke/img/full/jSsYVq47rObE_KENYA%20POWER%20ANNUAL%20REPORT%202015%20-%20FOR%20WEB.pdf, checked on 9/1/2021.

Kharina, Anastasia; Malins, Chris; Searle, Stephane (2016): Biofuels policy in Indonesia: Overview and status report. Edited by The international council on clean transportation.

Kupferschmid, Stefan; Faltenbacher, Michael (2019): Einführung von Wasserstoffbussen im ÖPNV. Fahrzeuge, Infrastruktur und betriebliche Aspekte. Edited by now GmbH.

Lizotte, Pierre-Luc; Savoie, Philippe; Champlain, Alain de (2015): Ash Content and Calorific Energy of Corn Stover Components in Eastern Canada. In *Energies* 8 (6), pp. 4827–4838. DOI: 10.3390/en8064827.

Mauch, Wolfgang (2009): Ganzheitliche energetische Bewertung der Elektromobilität. Edited by München Forschungsstelle für Energiewirtschaft.

Meteonorm. Version 7: Meteotest.

Morelli, Ben; Cashman, Sarah; Rodgers, Molly (2017): Life Cycle Assessment of Cooking fuel systems in India, China, Kenya, and Ghana. Edited by U.S. Environmental Protection Agency.

Munyaka, Penninah; Becker, Anna-Lena (2016): Solar power, the next frontier for Kenya's renewable energy sector. Edited by Rödl & Partner. Available online at https://www.roedl.com/insights/renewable-energy/2016-07/solar-power-frontier-kenya-renewable-energy-sector, checked on 8/30/2021.

Perner, Jens; Unteutsch, Michaela; Lövenich, Andrea (2018): The Future Cost of Electricity-Based Synthetic Fuels. Edited by Agora Energiewende Agora Verkehrswende.

Perusahaan Listrik Negara (Ed.) (2019): Statistik PLN 2019.

PLN Regional of West Nusa Tenggara (2020): Lombok and Tambora Demand Series, 2020.

Pollitt, Michael (2008): Electricity reform in Argentina: Lessons for developing countries. In *Energy Economics* 30 (4), pp. 1536–1567. DOI: 10.1016/j.eneco.2007.12.012.

Prabhudessai, Vidhya; Ganguly, Anasuya; Mutnuri, Srikanth (2013): Biochemical Methane Potential of Agro Wastes. In *Journal of Energy* 2013, pp. 1–7. DOI: 10.1155/2013/350731.

Prasodjo, Edi; Nurzaman, Heri; Walujanto; Rosdiana, Dian; Ismutadi, Pandu; Malik, Ceciliya; et al. (2016): Indonesia Energy Outlook 2016. Edited by Secretariate General of National Energy Council.

Ram, Manish; Bogdanov, Dmitrii; Aghahosseini, Arman; Gulagi, Ashish; Oyewo, Solomon A.; Child, Michael et al. (2019): GLOBAL ENERGY SYSTEM BASED ON 100% RENEWABLE ENERGY Power, Heat, Transport and Desalination Sectors. Edited by LUT University, Energy watch group, checked on 4/21/2021.

Regional Planning Agency of West Nusa Tenggara (2020): West Nusa Tenggara GIS Data, 2020.

REN21 (Ed.) (2014): REN21. 2014. Renewables 2014 Global Status Report. Paris.

Rosmaliati (2020): KomMod Data collection spreadsheet, 2020.

Scarlat, Nicolae; Fahl, Fernando; Dallemand, Jean-François; Monforti, Fabio; Motola, Vicenzo (2018): A spatial analysis of biogas potential from manure in Europe. In *Renewable and Sustainable Energy Reviews* 94, pp. 915–930. DOI: 10.1016/j.rser.2018.06.035.

Schmidt, Patrick R.; Zittel, Werner; Weindorf, Werner; Raksha, Tetyana (2016): Renewables in transport 2050 empowering a sustainable mobility future with zwei emission fuels from renewable electricity - Europe and Germany. An expertise for the FVV - Firschungsvereinigung Verbrennungskraftmaschinen e.V. (Research Association for Combustion Engines). Edited by Ludwig Bölkow Systemtechnik.

Schmied, Martin; Mottschall, Moritz (2014): Berechnung des Energieverbrauchs und der Treibhausgasemissionen des ÖPNV. Leitfaden zur Anwendung der europäischen Norm EN 16258. Edited by Bundesministerium für Verkehr und digitale Infrastruktur.

Sterchele, Philip; Brandes, Julian; Heilig, Judith; Wrede, Daniel; Kost, Christoph; Schlegl, Thomas et al. (2020): WEGE ZU EINEM KLIMANEUTRALEN ENERGIESYSTEM. Die deutsche Energiewende im Kontext gesellschaftlicher Verhaltensweisen. Edited by Fraunhofer-Institut für Solare Energiesysteme ISE, Freiburg. Available online at https://www.ise.fraunhofer.de/content/dam/ise/de/documents/publications/studies/Fraunhofer-ISE-Studie-Wege-zu-einem-klimaneutralen-Energiesystem.pdf.

Suharyati; Pambudi, Sadmoko Hesti; Wibowo, Jamaludin Lastiko; Pratiwi, Nurina Indah (2019): Indonesia energy outlook 2019. Edited by National Energy Council.

Thailand Ministry of energy (Ed.) (2015): Thailand Power Development Plan 2015-2036 (PDP2015).

Wikipedia (Ed.) (2021): Elektroautos mit Angaben gemäß WLTP. Available online at https://de.wikipedia.org/wiki/Elektroautos_mit_Angaben_gem%C3%A4%C3%9F_WLTP, checked on 5/21/2021.

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