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ENERGY SYSTEM MODELING RESULTS FOR KISUMU COUNTY, KENYA

100 % RENEWABLES

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List of abbreviations

CHP	Combined heat and power plant
PV	Photovoltaic
RE	Renewable energies
GIS	Geoinformation system
BAU	Business-as-usual
GDP	Gross domestic product
LPG	Liquified Petroleum Gas
NDC	Nationally determined contribution
SDG	Sustainable development goal
DAC	Direct air capture

1 Summary

Achieving the goals laid out in the Paris Agreement will require a shift to 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 100 % Renewables Cities and Regions Roadmap project (100%RE), cities and regions from three countries around the world were selected to develop a plan on how to achieve an energy system based on 100 percent renewables by 2050. These ambitious energy scenarios can serve as beacons 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 Kisumu County in Kenya. Kisumu is a county in western Kenya lying at the shores of Lake Victoria, its capital, Kisumu, is the third largest city of Kenya. The results of the scenario calculations will be used to further develop 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 variable renewables and thus of storage technologies, the increased prominence of sector coupling and limited RE potentials, to name just a few, require the use of computer-aided modeling in order to obtain robust results. The modeling is performed in hourly timesteps to ensure supply security and includes all relevant demand sectors. In the specific case of Kisumu these include cooling demand, electricity demand, cooking demand in households and the commercial sector as well as energy demand for transport on land. 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 Kisumu as well as the whole of Kenya when no specific data for Kisumu is available.

Solar photovoltaics (PV) has the highest possible potentials in Kisumu, followed by bagasse and municipal waste as well as hydropower and biogas from manure and crops. Other renewable energy sources have only minor potentials. Wind power has no potential as wind speeds are rated as too low in Kisumu. While geothermal energy has high potentials in some parts of Kenya and is a focus technology of the national government, there are no potentials in Kisumu.

Seven (7) different 100 % RE scenarios are calculated by varying three different features: biogas fuel price, energy demand, and the fixed usage of hydropower and biomass and waste potentials. In addition, a business-as-usual (BAU) scenario is modelled to allow the comparison of costs and carbon dioxide (CO_2) emissions. A leading scenario has been chosen in workshops between ICLEI, Fraunhofer ISE, and local stakeholders from Kisumu county. This scenario uses low fuel price, mean demand and technologies are chosen according to the target function of the least cost system. A scenario where the usage of hydropower is fixed is only 0.2 % more expensive and can be rated as economically equal. This is why both scenarios are presented in detail in the results sections. Solar photovoltaic is the main electricity source in both scenarios with a share of 90-98 %, biogas supplies 2 % in both scenarios, while hydropower supplies 8 % in the hydropower fixed scenario and is not installed at all in the least-cost scenario. Energy demand for cooking is mainly covered with electric stoves (79-84 %), although it is the most expensive cooking technology. But biomass and biogas potentials are low and are not sufficient to cover energy demand for cooking.

As photovoltaic is the main electric supply technology in all scenarios it is recommended to push forward its deployment. Prices are already competitive with other power plants types today and photovoltaics can contribute to the electrification of remote areas due to its decentralized applicability.

2 The 100% RE project and its case studies

Achieving the goal laid out in the Paris Agreement i.e. to reduce the rise in global temperatures to 2°C above pre-industrial levels, will require a shift to net-zero emissions by mid-century and therefore an unprecedented transformation of energy supply toward renewable energy in all sectors globally.
Global electricity demand is projected to increase by 69 % until 2040 (Doman et al. 2016). This will exacerbate the challenge of meeting electricity 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 their use.
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 this reason, the 100% Renewables Cities and Regions Roadmap project supports cities and regions in Argentina, Indonesia, and Kenya to develop strategies for 100 percent RE supply across all end uses (transport, heating/cooling and electricity), and strengthen awareness-raising and stakeholder engagement. At the same time, it supports the assessment of local RE potential and project designs, as well as the development of bankable projects. To this end, the project will provide 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 and SDGs.
In each country, one project city/region is designated as a lighthouse city/region (deep-dive cities/regions). This city/region receives 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 in each country 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 (in bold) 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 percent 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 percent RE shall be achieved at the latest is 2050. These scenarios present possible energy systems with 100 percent renewables that cover all relevant local energy demands and show therefore what should happen to reach the goal of an energy supply fully based on renewable energies. Questions that are answered in this report are:

- What are possible developments of all relevant energy demand sectors until 2050 and how high is the electricity demand in 2050 compared to other countries? (Section 4.1)
- How high are the usable potentials for different kinds of renewable energy technologies? (Section 0)
- What is the technology mix required to reach the least total system costs and at the same time supply all energy demands with 100 percent renewable energies? (Section 6.1)
- How are these technologies operated throughout the year? (Section 6.1.2)
- How much storage capacity is needed to use variable renewables in the most optimal way? (Sub-Section 6.1.1)
- How high are the total system costs in different system configurations? (Including a business-as-usual scenario) (Section 6.2)
- What are the levelized costs of energy for the different technologies? (Section 6.2)
- What is one possible transition path to reach 100 percent RE in 2050? (Section 6.3)
- What are potential risks and which recommendations can be given to overcome these risks in reaching 100 % RE? (Section 6.4)

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

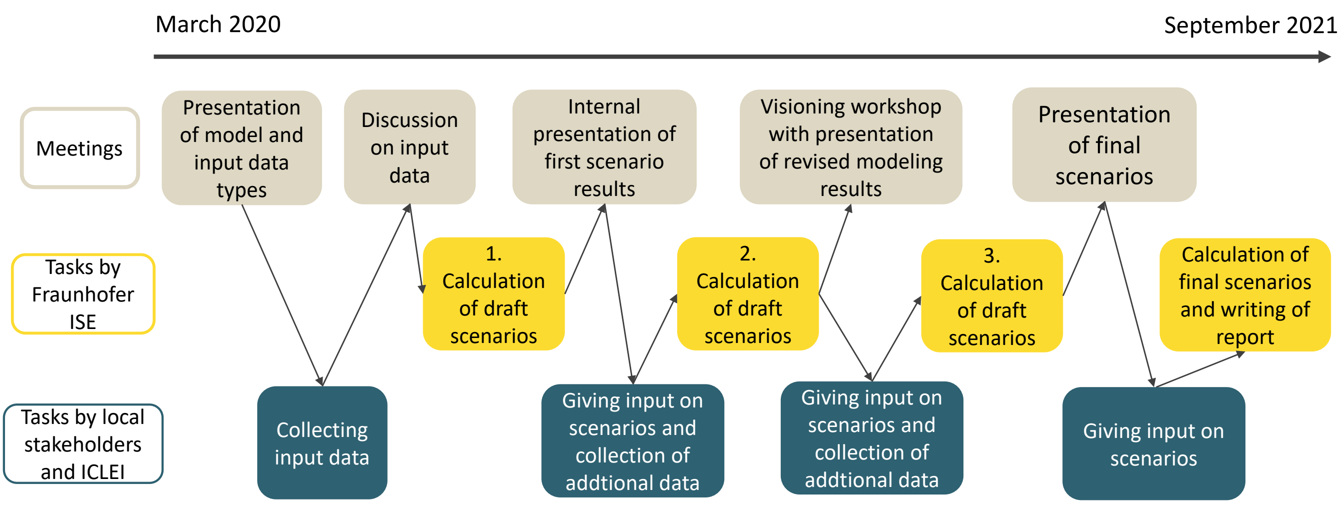


Figure 1: Structure of the process of energy system modeling between the different stakeholders

The outline of this report is as follows. Chapter 2 is giving a short overview about the project and the deep dive region of Kisumu, Kenya, 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 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 went down between 1990 and 2019 because of rising electricity demand but rather constant renewable energy supply from 36 % to 25 %. 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 to about 91.7 % and RE to 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 (PLN) 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 continue to have potential. 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 and Lighting Company (KPLC, or 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 and PV about 16.2 % (all in 2018).
Renewable energy sources have a high share in electricity generation in Kenya. In 2018, this was 82 %, with about 34 % from hydropower, 47 % from geothermal and 3.2 % from solar and and wind. (International Energy Agency 2021).
In 2018 75 % of the population had access to electricity, in 2030 according to governments goals it should be 100 %. 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 has reinstated the VAT exemption on renewable energy products (wind, solar and clean cooking) to make them more attractive, and promote access to clean energy and cooking (GOGLA 2021) especially for rural, sparsely populated, arid, and semi-arid areas

2.2 Case study of Kisumu County, Kenya

Kisumu County was chosen as the deep dive region for Kenya. Kisumu is one of the 47 counties of Kenya. The capital is Kisumu which is the third largest city of Kenya. Some key facts about Kisumu County (in report abbreviated with Kisumu) are summarized in Table 2.
According to Buma (2021) the main energy sources in Kisumu are biomass and hydropower. Biomass is used in the cooking sector and in sugar cane factories to cover their own electricity demand. There are two hydropower plants installed with a total capacity of 80 MW as well as three combined heat and power (CHP) plants that use bagasse in the sugar cane factories with a total installed capacity of 21 MW. In addition, there is one gas turbine with a capacity of 28 MW installed. In total the most recent data from 2017/2018 state an electricity production of around 665 GWh with values for electricity production of CHPs in sugarcane factories being from 2015 and added to other electricity production data for the years 2017/2018. This is more than the anticipated demand which was around 283 GWh in 2018 which means that Kisumu cold export electricity to the national grid.

Table 2: General information about Kisumu County, information according to (Buma 2021)

Location	Kisumu County lies to the west of Kenya, between longitudes 33°20’ East and 35° 20’ East and latitude 0°20’ South and 0°50’ South
Size	2,085.9 km2
Capital	Kisumu
Currency	Kenyan Shilling (KSH)
Population	1,155,574 (2019)
Climate	Tropical climate; mean annual temperature of 23°C with maximum temperature ranges between 25°C and 35°C and annual minimum temperature ranges between 16°C and 18°C. Average annual rainfall varies from 1,000 to 1,800 mm during the long rains (March to May) and 450 to 600 mm during the short rains (September to November)
Main economic activities	Farming, livestock keeping, fishing, rice farming, sugar cane farming, small-scale trading, sugar production, ballast manufacturers, paint-producing plants, and steel and cement factories
Household grid connectivity (Households using electricity for lighting)	52.6%

3 Energy system modeling with KomMod

The energy system optimization model 'KomMod' identifies the cost minimal combination of supply technologies for an energy system for 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 needed too. For consistency, all data has to be projected for the target year, in which the goal shall be achieved – in this study the year 2050.
Concurrently, 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 imports or exports. Total costs include investments, operation and maintenance (O&M) 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 to cover the energy demand at all times or are generating surpluses.
Mathematically the optimization is done by setting up a linear equation system which is then 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. Used energy sources 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 hydropower resources and conversion to electricity 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. Besides, combined heat and power (CHP) plants that produce heat and electricity by converting different 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. It can also be used to produce other synthetic fuels like methane or methanol. To produce these synthetic fuels carbon dioxide is needed in addition hydrogen. This carbon dioxide can be either extracted from the air via direct air capture (DAC) or extracted from exhaust gases from CHP plants. All these extraction processes and synthesis processes need heat and incur certain losses. Although producing methane and methanol is much more energy-intensive than producing hydrogen, it has some advantages. Methane can be used in the same way as natural gas and therefore can be fed into a gas grid or used in a gas power plant. Methanol is a liquid fuel which makes it easier to store and

transport and can be used in the transport sector for example. Overall, hydrogen is quite hard to handle as it is very volatile and easily flammable. As it has a low density it must be compressed to at least 200 bars to be transported.
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 and other fuels that can be stored and used later, are also depicted. 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 has to be noted, that for electricity all demands are summed up in the model to one demand time series. This has to be covered at every hour of the year as in the model the grid is seen as ideal and no transmission restrictions for any energy type is taken into account. For heat different types of heating demands can be implemented in the model and they can be assigned to different technologies.

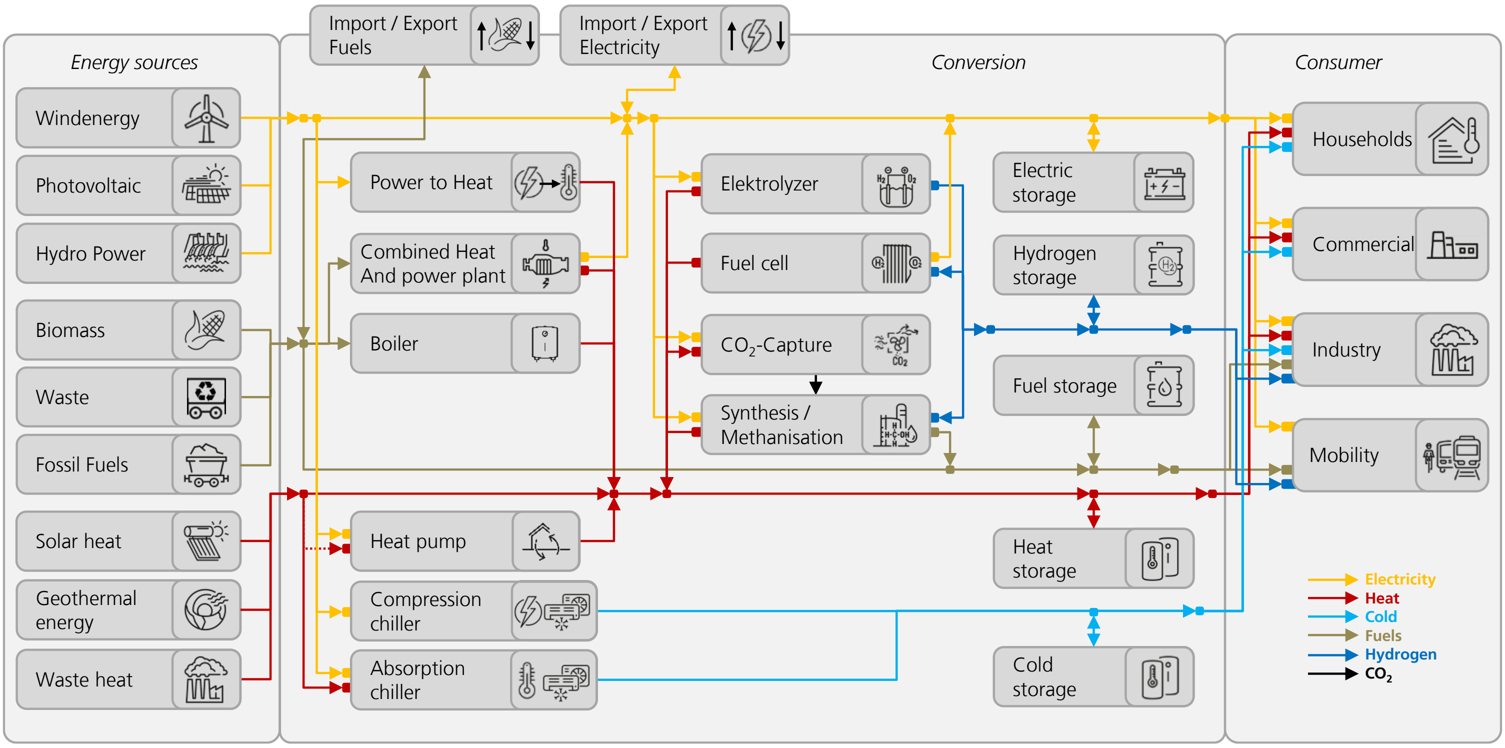


Figure 2: Graphical representation of the model KomMod with all technologies included

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. However, 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 that are not included in the model are for example network charges as well as grid expansion costs or profits for energy providers.

4 Input data

This chapter describes in detail the input data used for the model. In section 4.1 all energy demand projections are described in detail, including the applied time series. The potentials for all applicable kinds of renewable energy technologies are described in 0 while all costs data used is stated in section 4.3. In the last section 4.4 the used weather data is presented.

4.1 Energy demands today and projections

All relevant demand sectors are included in the scenarios. In the transport sector only road traffic is taken into account (see sub-section 4.1.4). Cooling demand is assumed to be implicitly included in the electricity demand (see sub-section 4.1.2). In the following sub-sections, the demand projections for every demand sector are summarized with all used sources and calculation steps. In the last sub-section (4.1.5) a summary of the total energy demand today and in 2050 is given.

4.1.1 Population development

Energy demand in the different sectors is often correlated to the development of gross domestic product (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 future development of the indicators is known. Because of this, projections for population are discussed shortly, no data on future GDP development either county nor nationwide was available. Population development until 2030 is included in the Draft sustainable energy policy report for Kisumu County from 2016 (Kisumu County Government 2016) and shown in Figure 3 in blue and taken as the baseline projection for population. As the scenarios in this study are calculated for the year 2050, the projection is extrapolated until the year 2050 with the equation shown in Figure 3. For comparison, population projections for whole Kenya from the United Nations are taken (United Nations 2019) and the share of the population of Kisumu is calculated. This share was 2.287 % in 2016 and is 2.286 % according to projections in 2050. Data from United Nations (2019) and Kisumu County Government (2016) matches well and this population development is therefore taken for calculations of energy demands (see following chapters). In addition, there is actual population data available for the year 2019 (KNBS 2019a) which shows lower values than what Kisumu County Government (2016) projected in 2016. With the actual values for 2015 and 2019 a second projection is calculated which yields in a 21.5 % lower population than in the baseline scenario for 2050. Therefore, taking the higher population development is a safer estimate, as it results in higher energy demands.

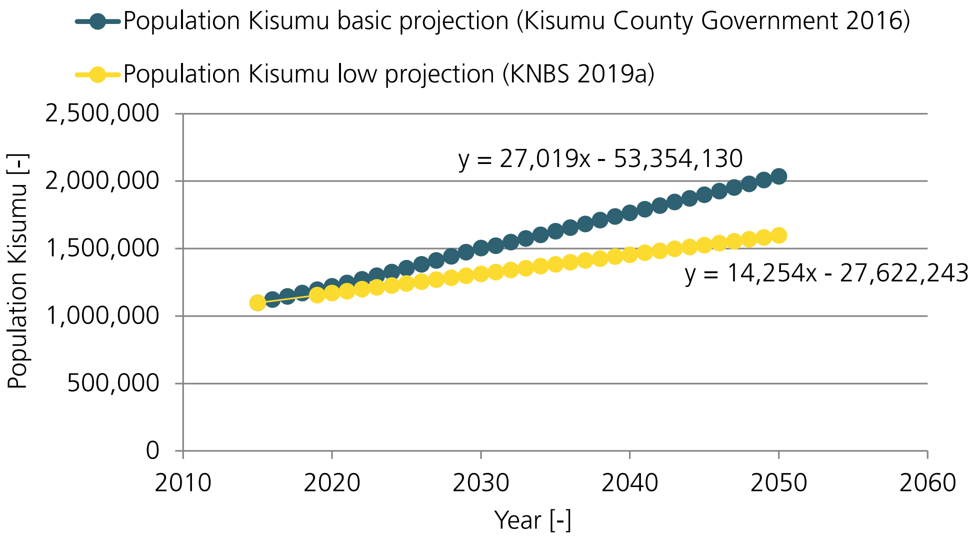


Figure 3: Population development in Kisumu historic and projections (Kisumu County Government 2016; KNBS 2019a)

4.1.2 Electricity demand (including cooling)

The electricity demand from Kisumu is known for the year 2015 for different demand sectors (Kisumu County Government 2016). For 2019 total electricity demand is known but no subdivision on different sectors (County Government of Kisumu 2021). Values are shown in Table 3.

Table 3: Electricity demand in different sectors

	Electricity demand in 2015 from (Kisumu County Government 2016) [GWh]	Share of total demand (Kisumu County Government 2016) [%]	Electricity demand in 2019 (County Government of Kisumu 2021) [GWh]
Households	9.5	3.80%	
SMEs (Domestic consumer Businesses)	48.4	19.34%	
Private sector within top 100 consumers	55.3	22.09%	
Public sector within top 100 consumers	8.3	3.32%	
Company installations	0	0.00%	
SL (street lighting)	0.1	0.04%	
Other public and private sector consumers	42.5	16.98%	
Sugar industry own generation	86.2	34.44%	
Total	250.3		237 (without sugar industry generation)

Total demand including the own generation and usage of the sugar industry was 250.3 GWh in 2015. For 2019 only the total demand without the sugar industry is available and was 237 GWh. Table 4 lists the number of consumers in different consumer categories from different sources. Consumer numbers show huge differences between the different data sources. As these differences could not be explained and number of consumers in the different categories remains unsure it is decided to not use this data for projection of electricity demand.

Table 4: Number of consumers in different consumer categories

	Number of consumers (Kisumu County Government 2016)	**Number of consumers from Kisumu census 2015 (KNBS 2015)**	**Number of consumers according to KPLC (KPLC 2020)**	**Number of consumers (County Government of Kisumu 2021)**
Households	116,332	88,138	224,087	242,516
SMEs (DC Businesses)	564,904	9,046	10,634	14,768
Private sector within top 100 consumers	55	113 (industrial)	108 (commercial and industrial)	279 (large power consumers)
Public sector within top 100 consumers	15			
F9 company installations	461			
SL (street lighting)	86	10	458	458
Other public and private sector consumers	111,857			
Sugar industry own generation	3			
Total	793,713	97,307	235,287	258,021

A projection of electricity demand of Kenya is available in the Updated least cost power development plan, study period 2017-2037 (abbreviated Kenya's LCPDP 2017-2037) (Republic of Kenya 2018). An update of this report was published in 2020 (abbreviated Kenya's LCPDP 2020-2040) (Republic of Kenya 2020). In Kenya's LCPDP 2017-2037 electricity demand is projected for different regions of Kenya: Nairobi, Coast, Mt Kenya and Western and the projection is made for the years 2017-2037[1]. In the updated study a projection is only given for the whole of Kenya for the years 2020-2040. According to the study several factors have been included to calculate the projections. These include the projection of GDP, population, electrification rate, urbanization rate and several flagship projects with high electricity needs such as the expansion of public transport in the capital. Other factors are not included such as cooling and electricity needs for the cooking and transport sector. These have to be added manually. The projection of demand for the transport sector is described in sub-section 4.1.4 and electricity demand for cooking is calculated in the model endogenously. No information on cooling demand could be obtained during the data collection process, so cooling data was generated through assumptions. In addition data from International Energy Agency (IEA 2019) is available on the growth of electricity demand for all of Kenya until 2040 under two different scenarios. For the Africa Case scenario it is explicitly said that higher cooling demands lead to high electricity demands. Demands in 2037 and 2040 respectively from all three data sources are shown in Table 5. Data from IEA (2019) shows much higher electricity

[1] The regions referred to in this report refer to the regions served by Kenya Power. Kisumu County belongs to the Western Region. They do not refer to the political regions/subdivisions of Kenya, which were replaced by a system of counties in 2010.

demands than data from Republic of Kenya (2018; Republic of Kenya) for the high demand scenario. For the mean demand scenario data from IEA (2019) and Kenya's LCPDP 2017-2037 show similar values, while Kenya's LCPDP 2020-2040 projects lower demands than the former version from 2018. However, Kenya's LCPDP 2017-2037 is the only source stating values explicitly for a subregion of i.e. the erstwhile Western Region where Kisumu is located, and they lie in between the other two sources. Therefore, data from this study was taken as the demand projection for the electricity demand of Kisumu County. By not taking the even lower values of Kenya's LCPDP 2020-2040 an implicit inclusion of electricity demand for cooling is assumed.

Table 5: Electricity demand projections for Kenya in three different data sources

	Low demand scenario [TWh]	**Reference scenario [TWh]**	**High demand scenario [TWh]**
Kenya's LCPDP 2017-2037 in 2037 (Republic of Kenya 2018)	27,945	39,187	57,990
Kenya's LCPDP 2020-2040 in 2040 (Republic of Kenya 2020)	29,906 (25,443 in 2037)	32,914 (27,976 in 2037)	56,845 (44,795 in 2037)
International Energy Agency in 2040 (IEA 2019)		43,900 (Stated policy scenario)	81,700 (Africa case scenario)

As the projection in Kenya's LCPDP 2017-2037 does not continue to 2050 and only starts in 2017, it is extrapolated for 2015-2016 and 2038-2050 with a quadratic function (see Figure 4). There are three different scenarios: a reference, one vision (high) and one low demand scenario.

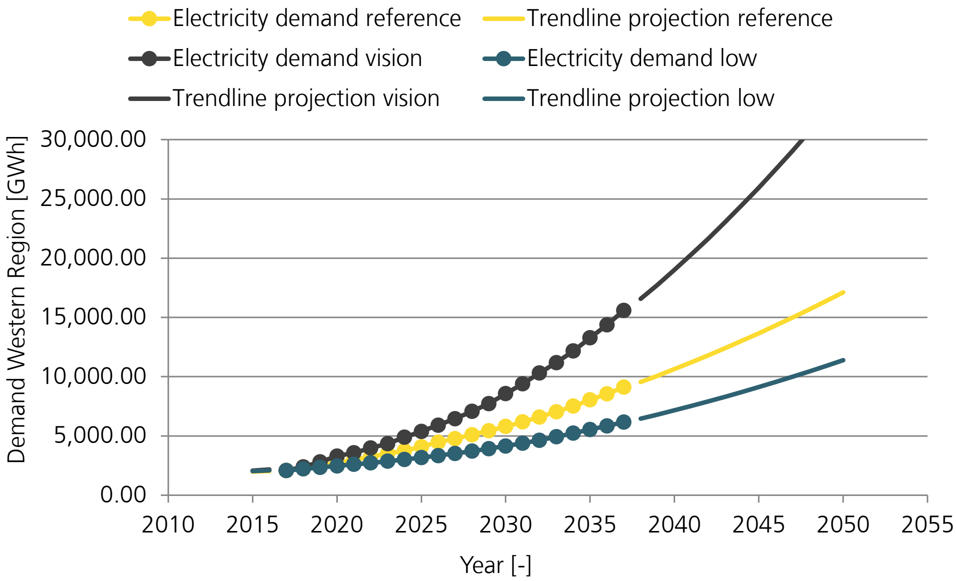


Figure 4: Electricity demand projections for the Western Region (Republic of Kenya 2018, 2020)

In 2018, Kisumu was situated in Kenya's erstwhile Western Region. As this region contained other counties besides Kisumu, the total given electricity demand cannot be directly taken. For the year 2015 the share of Kisumu's electricity demand in relation to the total demand of the Western Region is calculated and this share is set constant until 2050 (14 %). This procedure is subject to many uncertainties:

1. For Kisumu, the total electricity demand is only given for one year (2015). The available 2019 data excludes sugarcane industry data. However, if electricity supply of sugarcane industry is set constant, projection fits quite well to the demand in 2019.
2. For the year 2015, the electricity demand of the Western Region is not known. Data is provided starting in 2017, so the value for 2015 for the Western Region has to be extrapolated
3. With the proposed procedure, it is assumed that Kisumu's share of demand will stay constant until 2050, which neglects different developments in the populations and economies of different counties. At least Kisumu's population development is projected accordingly to the one for Kenya.

The resulting electricity demand for 2050 in the reference case is 2,137 GWh, which is 8.5 times higher than 2015. In the low demand scenario electricity demand in 2050 is 1402 GWh and in the vision (high) demand scenario it is 4104 GWh. All three projections are used in the scenarios, for details it is referred to section 5.2.
A comparison of specific electricity demands shall help to judge if the calculated projection is of a realistic order of magnitude. Therefore, the specific electricity demands of Kisumu are compared with the specific electricity demands of the other two case studies in the project, Indonesia and Argentina as well as from two other countries, Germany and South Africa (see Table 6).

Table 6: Specific electricity demands in Kisumu County today and in 2050 in comparison with specific electricity demands in other countries

	Specific electricity demand calculated with total demand	**Specific electricity demand calculated with residential demand**
	[kWh/cap]	[kWh/cap]
Kisumu in 2015	227	3.2 (81.7 for connected households)
Kisumu in 2050 reference scenario	1,173.5	352 (assumption: 30 % of electricity demand for households)
Kisumu in 2050 high-demand scenario	2,017.6	605.3 (assumption: 30 % of electricity demand for households)
Kisumu in 2050 low-demand scenario	689.2	206.8 (assumption: 30 % of electricity demand for households)
West Nusa Tenggara according to projections in 2050	1,824-4,183	673-1,633
Avellaneda according to projections in 2050	3,387-4,403	807-1,049
Germany in 2019 (Bundesministerium für Wirtschaft und Energie 2021)	6,237	1,558
South Africa (Enerdata 2021; Department: Statistics South Africa Republic of South Africa 2021)	3,991	958

Electricity demand in Kisumu today is low: the household grid connectivity in 2019 was 52.6 %. In 2050 the projected electricity demand is between 689.2 and 2,017.6 kWh per capita depending on the demand scenario. This demand is still the lowest compared

to all other countries compared to. In the high-demand scenario, the specific electricity demand lies in the same order of magnitude as in the low-demand scenario for West Nusa Tenggara, Indonesia, which can currently be considered as being somewhere between a developing country and a newly industrialized country Therefore, it makes sense that electricity demand in West Nusa Tenggara will be higher in 2050 than it will be in Kisumu. The city of Avellaneda in Argentina has a high industrial energy demand, so the specific electricity demand calculated with the total electricity demand is very high. Household specific electricity demand in Avellaneda is projected to be slightly higher than in the Kisumu high demand scenario, which seems reasonable, as Argentina is a much more developed country than Kenya. Overall, it can be concluded that projected electricity demands in Kisumu seem to be of a realistic order of magnitude. A further increase in demand after 2050 is to be expected, causing Kenya to reach the level of other comparable countries, for instance South Africa.
A time series of electricity demand is given for the time span July 2016 until June 2019 for the Western Region (Kenya Power and Lighting Company Limited 2020). As this data is taken for Kisumu for the year 2050 the underlying assumptions are that Kisumu's demand pattern is the same as the Western Region's and that this demand pattern does not change within the next 29 years. In Figure 5 the distribution of electricity demand for Kisumu in deciles is shown. In this diagram, electricity demand is taken for all 52 weeks of one year, and the percentage of values in a certain range are calculated for each hour of the week. 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 8 pm in the evening, which is a rather typical pattern. This is the time when everyone comes home, switches on lights, and starts using different devices like televisions or computers. Afterwards, electricity demand goes down and reaches its lowest value at 4 am, when nearly everybody is asleep. In the morning hours it starts rising again and stays on a constant level until the evening. There is little variation in demand between days of the week, except for slightly lower demand on Sundays.

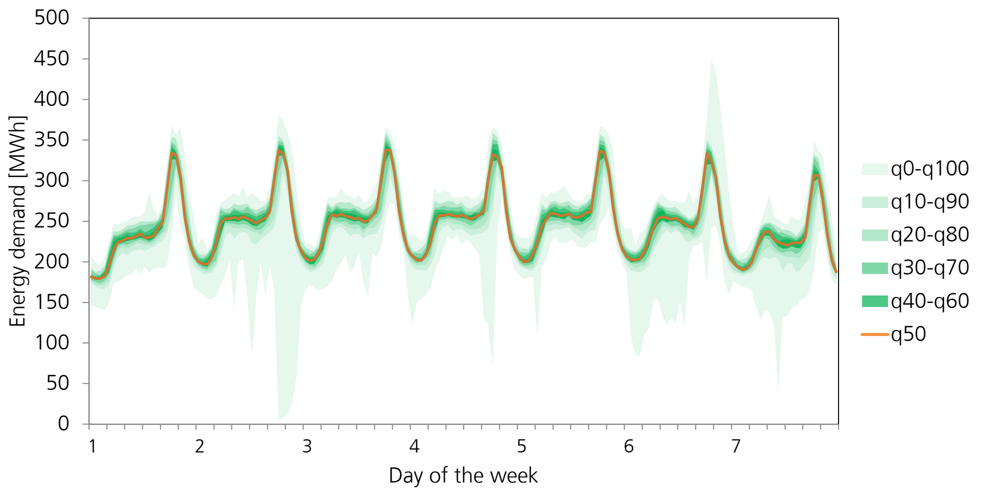


Figure 5: Distribution of the electricity demand in Kisumu shown in deciles (Monday until Sunday)

4.1.3 Energy for cooking demand

In Kenya's household sector there is no heating demand but only cooking demand. Outside temperatures are high all year around and there is no need for space heating. For cooking different kinds of fuel are used. Table 7 lists all data on shares of different fuels that have been available. Two sources state shares explicitly for households (County Government of Kisumu 2021; Kisumu County Government 2016). As one dataset is from 2016 and one from 2021 the differences between the two datasets look reasonable. According to the more recent dataset from County Government of Kisumu (2021) charcoal and wood are the most used cooking fuels in households each with a share of 36 %. The same two sources state also shares for different cooking fuels for the commercial sector. These two datasets differ significantly from each other. In particular, the share of institutions and enterprises that don't cook differs tremendously from 12 % in Kisumu County Government (2016) to 74 % in County Government of Kisumu (2021). It could not be determined if both reports refer to the same group of institutions and enterprises; furthermore in County Government of Kisumu (2021) the number of enterprises is not known. Data from the Kenyan census from 2019 (KNBS 2019b) states shares for the main cooking fuel, which are not further divided into different sectors. According to this data, wood is the main used cooking fuel with a share of 49.6 %. As household cooking demand is definitely higher than institutional energy demand for cooking (see below) these numbers are again difficult to reconcile with the numbers from the other two datasets, in which charcoal has the same share as wood in households. To summarize, accurate assessment of shares of different cooking fuels is difficult, given the available data sources.

Table 7: Share of different fuels for cooking according to different studies in Kisumu

	Share in households [%] (Kisumu County Government 2016)	**Share in commercial and public sector [%] (Kisumu County Government 2016)**	**Overall share [%] (KNBS 2019b)**	**Share in households [%] (County Government of Kisumu 2021)**	**Share in SME's [%] (County Government of Kisumu 2021)**
Wood	27	54.5	49.6	36	22.2
Gas (LPG)	22	8	18.7	21	27.8
Electricity	1	1	0.9	1.5	11.6
Charcoal	41	19.3	22.2	36	35.8
Kerosene	9		7.8	3.2	0.8
Crop residues (biogas)			0.6	0.05	
Combinations of several fuels		18			
No cooking		12 %			74 %

Table 8 summarizes all given information about the fuel demand for cooking. To facilitate comparison between the different stove types, the fuel demand has been recalculated as useable energy demand for cooking, by using the mean efficiencies of different stove types. Four different sources are available stating fuel demands for cooking, two of them are explicitly for Kisumu, while the remaining two sources show data for Kenya (Republic of Kenya Ministry of Energy 2019) and another county (Fuso Nerini et al. 2017). Like the data on the shares of different cooking fuels, the differences between the different sources are significant. The highest values are to be found in Kisumu County Government (2016) with useable energy demand of 1,268-1,518 kWh. The lowest values are reported in Republic of Kenya Ministry of Energy (2019), which is most probably because the values take into account the use of several fuels. Compared to end energy demand for cooking in other countries, for example Germany, all values are high. In Germany, yearly electricity demand for cooking for one household is around 450 kWh with an efficiency of the stove of 50-60 % which leads to a useable energy demand of around 200 kWh per household. For the Indonesian case study, a useable energy demand for cooking of 162 kWh is calculated per household. For the base scenario for Kisumu, a mean of the values from County Government of Kisumu (2021) is taken as this is the most recent data. No weighted average, taking the shares of the different fuels into account, is calculated. Such a calculation is neglected for two reasons: first, the exact shares are not known (see above), and second, the useable energy demand for cooking should not be dependent on the used fuel as this would mean that there is a correlation between the used fuel and cooking length and frequency which is seen as rather unlikely. As this cooking demand is already high compared to Germany and Indonesia, no additional high demand scenario is calculated but useable energy demand for cooking is constant in all scenarios.

Table 8: Yearly useable energy demand for cooking for one household according to different studies

	Efficiency	Calorific values [kWh/kg]	(Kisumu County Government 2016) [kWh/a]	(Republic of Kenya Ministry of Energy 2019) [kWh/a]	(Fuso Nerini et al. 2017) [kWh/a]	(County Government of Kisumu 2021) [kWh/a]
Wood	10%	4.2	1,268	567	721	756
Gas (LPG)	60%	13.6	1,519	465	735	588
Electricity	59%	-	-	0	777	
Charcoal	25%	7.8	1,495	770	1,285	869
Kerosene	40 %	11.9	1,518	624	1,140	460
Crop residues (biogas)	10 %	4		176		

According to (Kisumu County Government 2016), in the commercial sector, cooking is done in 88 % of all institutions and the total number of institutions is 1,410. (County Government of Kisumu 2021) state that 26 % of all small enterprises cook, but no total number is known. Therefor data from (Kisumu County Government 2016) is taken to make a rough projection of cooking demand in institutions and enterprises. It is assumed that the number of institutions rises with the population, so in 2050 Kisumu would have 2296 institutions. For schools it is known that most use firewood; according to Wanjiru (2016), the amount of firewood used per pupil per day is 0.5 kg. For Kisumu, it is known that there are 900 schools and 32 % of the population are pupils, which leads to a mean of 400 pupils per school and a fuel demand for cooking of 172.8 MWh, when school is 270 days per year. For other types of institutions no information about cooking demand are available, therefore the same fuel demand is assumed for all types of institutions. Using the current efficiency of wood stoves, the useable energy demand for cooking for one institution can be calculated as 22.5 MWh per year. With the projected population increase this leads to a commercial and institutional useable energy demand for cooking of 51.58 GWh. This demand is set constant in all scenarios and further varied.

Meal-times are analyzed to implement a meaningful energy demand timeline for cooking. From Wanjiru (2016), meal times for institutions are known and from internal discussions with Kisumu officials mealtimes for households can be deduced (see Table 9). It is assumed that cooking is done the hour before the meal. The timeline has no implications on the total energy demand, only on its distribution throughout the day.

Table 9: Meal-times in institutions and households (based on internal discussions and Wanjiru (2016))

	Boarding school	Day school	Households
Breakfast (7 am)	x		x
Tea break (10 am)	x	x	x

Lunch (1 pm)	x	x	
Dinner (6 pm)	x		x

4.1.4 Energy demand for transport sector

There was no county-specific data for transport energy demand; instead, Kenya-wide data was used. To scale down the number of vehicles known for Kenya to Kisumu, the share of population and GDP is taken which is for both 2.27 % according to Kisumu County Government (2016). The historic development as well as a projection for the total number of vehicles in Kenya is given in University of Nairobi and Services Ltd (2014). Historic numbers for the total amount of vehicles are also included in Kenya National Bureau of Statistics (2013). The values of both resources are shown in Figure 6. The historic values of the two documents match well.

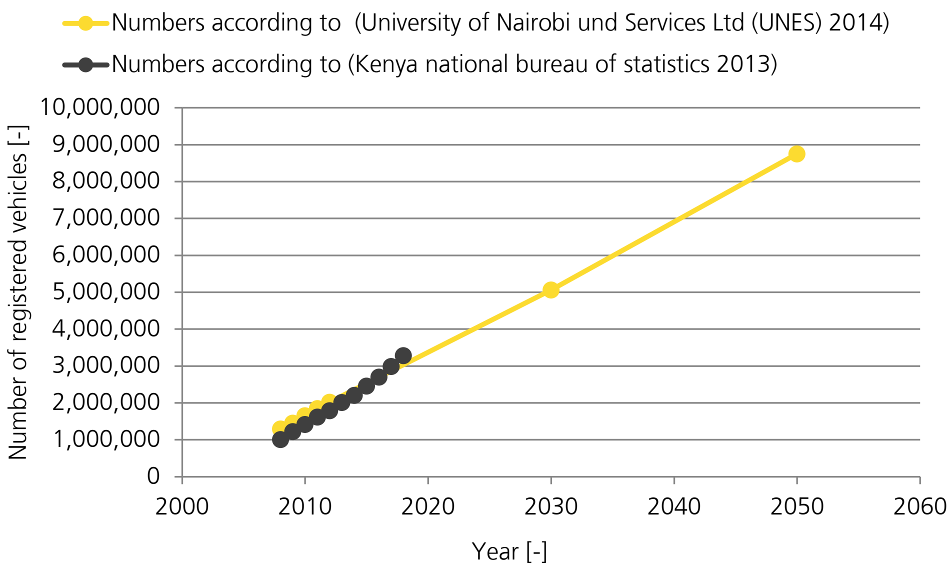


Figure 6: Number of registered vehicles (Kenya National Bureau of Statistics 2013) and (University of Nairobi and Services Ltd 2014)

In the Kenya National Bureau of Statistics (2013), information about the number of registered vehicles across seven different vehicle types is included. This data is aggregated to three different types for further data assessment: cars, motorcycles, and trucks and buses. The most recent information for the number of vehicles by vehicle type is from 2012; these shares are assumed to be the same in 2050. Specific mileages for these three vehicle categories are taken from Notter et al. (2019). This study also states a projection for the amount of passenger cars in Kenya through 2050. The number of passenger cars is projected to be 3,142,422 for the whole of Kenya for 2050. With a share of 2.27 % for Kisumu this would make 71332 passenger cars registered in Kisumu in 2050. Meanwhile with the above described method based on University of Nairobi and Services Ltd (2014), the number of passenger cars was calculated as 77,760 vehicles in Kisumu County in 2050. As many different data sources have to be combined for the projection, these two numbers are evaluated as sufficiently close to each other. For the number of passenger cars as well as all other vehicle types the data based on University of Nairobi and Services Ltd (2014), is taken as Notter et al. (2019) gives no information about the amount of vehicles in other vehicle categories.
The total number of vehicles in Kisumu in the three vehicle categories, the specific mileages and resulting final energy demands with assumed shares of electric and hydrogen

vehicles are shown in Table 10. The final energy demands of the transport sector are set constant in all scenarios.
It is assumed that cars and motorcycles are 100 % electric in 2050. Electric driven mobility is preferred over hydrogen mobility in this study because of a better overall efficiency of electric vehicles compared to hydrogen vehicles. Energy efficiency is seen as very important when 100 percent renewables shall be reached with limited renewable energy resource potentials. In addition, electric cars and motorcycles are more widely available in the market nowadays.
For motorcycles, electric vehicles are currently available at reasonable prices, and range is usually not a problem as driven distances with motorcycles are rather short. Therefore, charging can take place at home. For cars, charging infrastructure will be needed in the future; the implications of this are discussed in detail in section 6.4. Trucks and busses are assumed to be half electric vehicles and half hydrogen vehicles. The range of trucks and buses that is required to ensure economic feasibility is still being discussed among experts. Electric buses and trucks generally have a lower range but have the advantage that their energy demand is lower as they can use electricity directly. Whereas hydrogen trucks and buses have a higher range as well as a higher energy demand. The higher energy demand of hydrogen vehicles is resulting mainly from conversion losses from electricity to hydrogen. With the assumption of 50 % hydrogen buses and trucks in Kisumu in 2050, the estimation of energy demand is relatively high compared to other possible scenarios. This is discussed further in section 6.4 in the risk analysis of the transition of the transport sector.

Table 10: Share of different vehicle types and resulting energy demands for electric and hydrogen vehicles in 2050

	Share of total cars in 2050 [%]	**Number of vehicles in 2050**	**Share of electric vehicles in 2050 (base scenario) [%]**	**Share of hydrogen vehicles in 2050 (base scenario) [%]**	**Mileage of one vehicle [km/year]**	**Energy demand of electric vehicles [GWh]**	**Energy demand of hydrogen vehicles [GWh]**
Cars	0.39	77,760.12	100	0	22,223	345.61	
Motorcycles and scooter	0.34	67,744.03	100	0	17,807	48.25	
Busses, trucks and lorries	0.27	53,244.03	50	50	43,815	1,341.41	3,499.33
Total		198,748.17				1,735.28	3,499.33

No demand time series is generated for hydrogen, as it can be produced at any time in the year. For electric vehicles, a simple charging time series is taken, as shown in Figure 7. For this time series, it is assumed that most vehicles are charged in the evening hours when people come home and the vehicles are not in use. In Figure 7 the charging time series is shown normalized with the lowest charging demand at 1 (mainly in the night hours) and the highest charging demand being 3 times higher in the evening. This normalized demand curve is adapted with the daily demand for electricity in transport sector for the usage in the model.

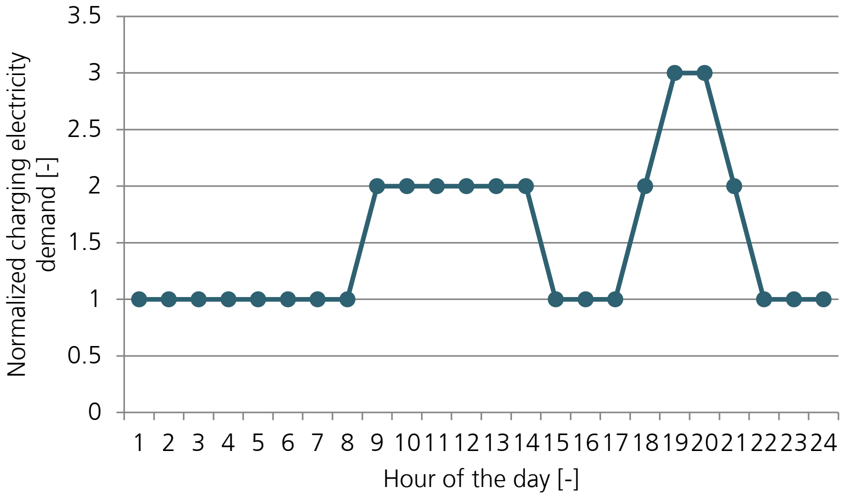


Figure 7: Normalized charging electricity demand for electric vehicles for Kisumu in 2050

4.1.5 Demand in 2021 and in 2050

In Figure 8 the energy demand today and in the three demand scenarios for 2050 for Kisumu is depicted. As described in the previous sections electricity demand is varied in three different demand scenarios, while final energy demand in the other demand sectors is set constant for all scenarios.

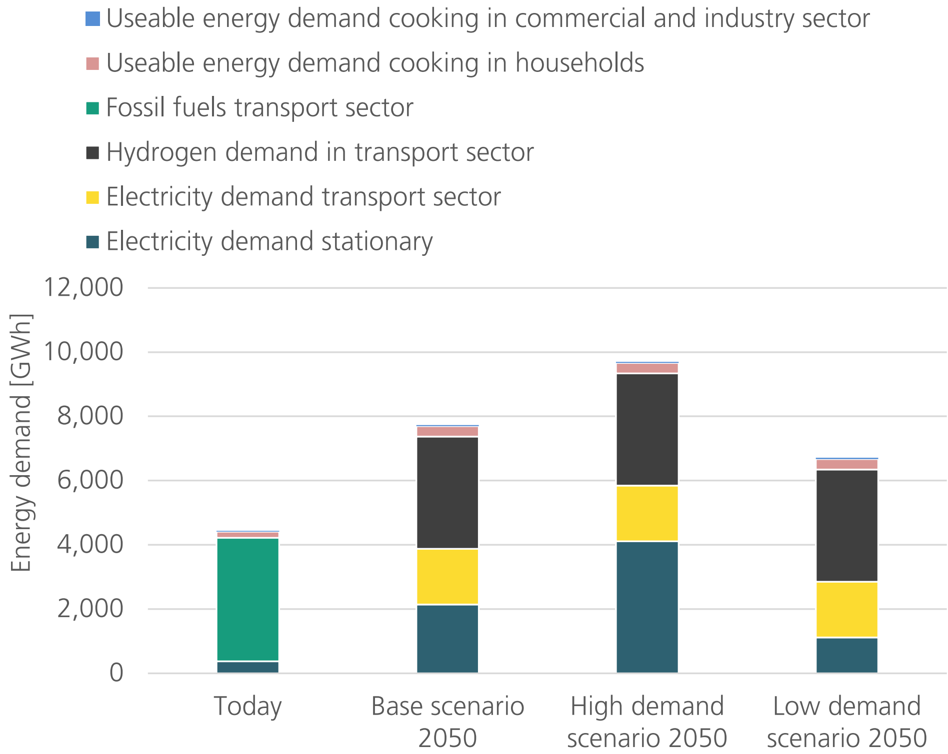


Figure 8: Energy demand today and in 2050 in the two scenarios

Today's data is for the year 2021 which means that some data had to be projected for that year, but no consistent dataset for one year is available. Today's energy demand is dominated by demand for fossil fuels in the transport sector. Electricity demand is low, with 373 GWh in 2021. In 2050 electricity demand is 5.7 times higher in the base

scenario and 9.5 times higher in the high-demand scenario compared to 2021. The transport sector still has the highest demand, but is now powered by electricity and hydrogen. The number of vehicles rises by 2.47 times, but energy demand only by 1.36 times, as electric and hydrogen vehicles consume less specific energy per 100 km than fossil fuel powered cars.
Overall, the energy demand in 2021 and the projected increase until 2050 is depicted in Table 11. In the base scenario for 2050, final energy demand increases by 1.8 times. In the high demand scenario, it increases by 2.4 times and in the low demand scenario, it increases by 1.6 times.

Table 11: Total end energy demand today (2021) and in the scenarios and increase from today to 2050

	Total energy demand [GWh]	Increase from today to 2050
Today (2021)	4,433	
Base scenario 2050	8,092	1.8
High demand scenario 2050	10,464	2.4
Low demand scenario 2050	7,067	1.6

4.2 Renewable energy potentials

In the following section, data processing for the evaluation of all different renewable energy potentials is described in detail.

4.2.1 GIS data assessment

To assess renewable energy potential, a GIS data assessment was conducted by GIS Limited (2021). The results are shown in Table 12. In total, eight different land cover types are distinguished, which sum up to the total area of Kisumu at 2,675.2 km². The building footprint is contained within the urban/built up category, but it is shown separately as building area is used to calculate rooftop area (see 4.2.4).

Table 12: Results from GIS data assessment (GIS Limited 2021)

	Area [km²]	Description
Forest cover	20.7	Covered chiefly with scattered trees and undergrowth in natural and modified landscapes
Shrubs	428.9	Woody perennial plants with persistent and woody stems and without any defined main stem being less than 5 m tall. The shrub foliage can be either evergreen or deciduous.
Herbaceous vegetation	548.1	Plants without persistent stems or shoots above ground and lacking definite firm structure (tree and shrub cover would be expected to be less than 10%).
Herbaceous wetland	38.3	Lands with a permanent mixture of water and herbaceous or woody vegetation. The vegetation can be present in either salt, brackish, or fresh water.

Bare/sparse vegetation	237.7	Lands with exposed soil, sand, or rocks and never has more than 10% vegetated cover during any time of the year.
Cropland	763.1	Lands covered with temporary crops followed by harvest and a bare soil period (e.g. Single and multiple cropping systems). Perennial woody crops was classified as the appropriate forest or shrub land cover type
Permanent water body	589	Can be either fresh or salt-water bodies.
Urban built up	49.4	Land covered by buildings and other manmade structures
Of which: Building footprint (within urban built up)	20.7	Land covered by buildings
Total area	2675.2	

4.2.2 Free field photovoltaic potential

Certain land cover types are rated as suitable for the installation of free field photovoltaic power plants, which are herbaceous vegetation and bare/spare vegetation. As these areas are also used for other purposes, it is assumed that 20 % of the area is usable for the installation of PV. The assumption is later checked, when the results show how much potential has actually been used in the different scenarios (see section 6.2). On a flat surface, the modules have to be erected to achieve the optimal yield. For Kisumu, the best yield was calculated with a tilt of 30° with modules being erected in the eastern direction which results in 1,500 full load hours. Because of this the ratio between module size and used ground area is around 50 %. The assumed surface efficiency is 200 W/m². This leads to a total installable capacity of 15,716.26 MW.

4.2.3 Wind power potential

An assessment of wind speed data for Kisumu county shows that commercial wind power plants cannot be operated feasibly. It could be that there are certain sites where small wind power plants can be operated, but the feasibility is highly dependent on the specific condition at the sites and cannot be included in a model depicting the whole of Kisumu.

4.2.4 Photovoltaic rooftop potential

For the assessment of rooftop potential of all buildings in Kisumu County, GIS data is used as it provides information about the building footprint in Kisumu which is correlated to the rooftop area (see Table 12). It is assumed that the usable rooftop area is 20 % of the total rooftop area. This is considering a possible elevation of the modules on flat roofs as well as unusable areas on all roofs. However, this is a rather conservative assumption and the true potential could be higher. 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]
20.65	1.0325	206.5

4.2.5 Biomass potentials

There are several kinds of biomass feedstocks available in Kisumu that have been evaluated. A portion of the crop residues from different types of crops that are cultivated in Kisumu can be used. In addition, manure from livestock and wood from forests is available. Furthermore, sugarcane is cultivated and processed to sugar in Kisumu. Bagasse and ethanol are produced as byproducts, and they can also be used as fuels.

4.2.5.1 Crop residues

The harvested amounts of different kinds of crops are known for the year 2016 (https://www.opendata.go.ke/ 2020). With the residue to crop ratios for these crop types, the amount of crop residues and their potential to produce biogas can be calculated (see Table 14).

Table 14: Amount of crop residues and amounts of biogas that can be produced from crop residues

	Bags of 90 kg per year (https://www.opendata.go.ke/ 2020)	Residue to full crop weight ratio	Dry residues amount [t]	Biogas from crop residues with mean methane yield [m³]	Primary energy amount (when 40 % of crop residues can be used) [MWh]
Maize	205,340				
Maize cobs		0.093	1,587	519,816	2,073
Maize stalks		0.57	9,867	3,231,544	1,2887
Rice	82,754				
Rice husks		0.091	623	19,634	78
Rice straw		0.56	3,862	1,008,022	4,020
Sorghum	82,754	0.67	4,461	1,338,373	5,337
Soybean	1,840	0.78	116		
Cowpea	16,666	0.64	859	30,067	120
Total				**6,147,456**	**24,516**

Crop residues are normally left on the field as they play an important role in agricultural practice. Therefore, crop residues cannot be used completely for energy production. In Iqbal et al. (2016) a sustainable usage rate of 40-50 % for different crop types is given and will be also used in this assessment of the potential. Reference is made to this study for more information on the usage of crop residues. The data source provides data only on the harvested amounts of crops, so crop residue amounts must be derived through calculation. Three different references have been used to find typical residue to product ratios; these ratios have been recalculated as residue to full weight ratios (Wekesa 2013; Kemausuor et al. 2014; Alhassan et al. 2019). The calculated total primary energy of the biogas produced from crop residues is 24,516 MWh.

4.2.5.2 Manure

Livestock data is given for the years 2012-2015 and 2019 (Table 15). The number of livestock, and therefore the possible amounts of biogas that can be produced from manure, has decreased in this time. Data for 2019 is taken for the projection of biogas to make a rather conservative estimation.
Furthermore, livestock data is given for many different types of livestock, but data on biogas yields are available for only four of them. These are cattle dairy, cattle beef, pigs and poultry layer. For indigenous poultry it is assumed that collection of chicken manure is too complicated and it can therefore not be used for biogas production as they are not kept in cages. The resulting amount of biogas potential from manure is 464,575 MWh for 2019 which is used as the usable amount in the year 2050. Biogas from livestock and crop residues can be used in thermal power plants to produce electricity and heat if needed in the scenarios.

Table 15: Livestock amounts in Kisumu in the years 2012-2015 and 2019

		2012	2013	2014	2015	2019
Cattle	Dairy	16,346	17,530	19,716	14,688	13,799
Cattle	Beef	295,216	268,356	278,041	278,041	229,197
Sheep	Wool	0	0	0	0	
Sheep	Hair	219,849	237,788	240,174	240,174	163,537
Goats	Dairy	1,702	1,798	2,174	2,174	
Goats	Meat	220,436	235,665	241,981	241,981	137,696
Pigs	_	5,789	6,101	5,124	5,124	4,755
Rabbits	_	11,172	10,336	11,066	6,631	5,836
Poultry	Broilers	381,484	302,608	362,500	362,500	74,235
Poultry	layers	72,112	73,712	88,150	88,150	71,699
Poultry	indigenous	802,035	849,535	862,278	862,278	733,465
Poultry	Others (quail,turkeys,guinea fowl, pigeons,geese, ducks)	42,803	42,803	7,115	7,115	
Donkeys	_	7,849	7,849	7,927	3,064	3,542
Camels	_	0	0	0	0	
Hives	Log	162	140	120	120	
Hives	KTBH	1,710	2,310	2,330	2,330	
Hives	Lang	2,638	2,648	3,328	3,328	2,503
Hives	Box	0	0	0	0	
Ostrich	_	2	2	2	2	

4.2.5.3 Sustainable wood potential

Wood is an important fuel today in Kisumu, as well as in all of Kenya, and is one of the main fuels used for cooking (see also sub-section 4.1.3). Forest areas are decreasing in Kenya in recent years, as the amount of wood used is not sustainable. This process must be stopped as soon as possible, and afforestation measures must be taken. Because of this the usable wood potential for 2050 is calculated conservatively based on today's forest area of Kisumu (PIT 2020) and the sustainable amounts of wood which can be used every year. This leads to 2,469 m^3 of sustainable wood usable per year in 2050. It is assumed that wood is solely used in cookstoves.

4.2.5.4 Bagasse and molasses potential

As byproducts of sugar production, bagasse and molasses are produced in the sugarcane factories, and the latter can be further processed to Ethanol. Table 16 lists the amount of bagasse and molasses. For bagasse data for the years 2005-2008 as well as a projection for 2015 is available (Kisumu County Government 2016). For molasses values for the years 2007 and 2008 are available (Kisumu County Government 2016). For both products the most recent data is taken and left constant for the projection of usable amounts in 2050, which means that it is assumed that sugar production will stay constant. For molasses this results in a usable amount of 53,682 tons which can be further processed to 12,090,541 liters of Ethanol. It is assumed that ethanol can be used in cooking stoves. For bagasse an amount of 714,766 t is taken for the scenario calculations. Bagasse has a heating value of 4.2 kWh/kg and a direct combustion in power plants together with municipal waste is assumed.

Table 16: Amounts of bagasse and molasse from sugar production

	2005	2006	2007	2008	2015 (projections)
Bagasse as waste from sugarmills [t]	337,563	432,351	456,342	581,170	714,766
Molasses as waste from sugarmills [t]			38,721	53,682	
Ethanol that could be produced [l] from molasses			8,720,946	12,090,541	

4.2.6 Municipal waste potential

The collected amounts of municipal solid waste are given for the years 2015 until 2030 (Kisumu County Government 2016). This data includes all types of municipal solid waste that are collected. As data for 2050 is needed, specific amounts of waste per capita are calculated and the total amount of waste is then projected for the year 2050. This leads to 371312 tons of waste per year. As the exact composition is not known a mean heating value of 2.8 kWh/ kg is set. Direct combustion of waste in waste power plants is assumed.

4.2.7 Hydro energy potential

In Kisumu County Government (2016) a total hydropower potential of 160 MW is given for Kisumu. Two hydropower plants with a combined capacity of 80 MW are already installed, which results in 80 MW of additional potential. From the existing hydropower plants the load profile is known for the timespan July 2016 until June 2019 and can be used in the model to depict hydropower in a realistic way. In Table 17, the full load hours of the hydropower plants Sangoro and Sondu Miriu for the years 2017 and 2018 are depicted (information about the full year is available). They have been calculated using the information about installed capacity which is 60 MW for Sondu Miriu and 20 MW for Sangoro.

Table 17: Full load hours of the two hydropower plants Sangoro and Sondu Miriu in the years 2017 and 2018

	Full load hours in 2017	Full load hours in 2018
Sangoro	4,975	5,649
Sondu Miriu	5,117	5,799

In 2018, the conditions for the usage of hydropower were better than in 2017 which results in higher full load hours. This could be because the amount of rainfall in that year was more suitable for the design of the hydropower plants which cannot run with too little or too much water running in the rivers. For depicting hydropower in the model the mean of the two generation profiles from 2017 and 2018 of Sondu Miriu is taken, which is depicted in Figure 9 for the year 2017. As hydropower potential is higher than the installed capacity of Sondu Miriu power plant the load profile is normalized for using it in the model and scaled up with the installed capacity to calculate hourly resolved output from hydropower.

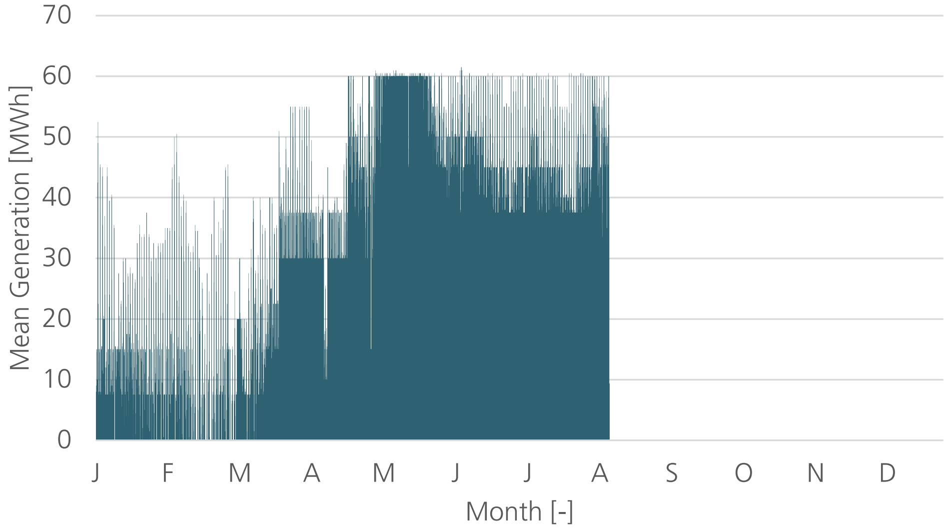


Figure 9: Generation profile of Sondu Miriu hydropower plant for the year 2017

4.2.8 Geothermal energy potential

In Kenya geothermal power is an important energy source but potential is only locally available in some regions. According to Buma (2021) there is no geothermal potential in Kisumu county.

4.2.9 Waste water potential

According to Kisumu County Government (2016) there is a potential of 70 kWh of electrical power (sic!) that can be produced from waste water in a CHP. As potential is small and usability unclear, this potential is not included in the model.

4.2.10 Summary of renewable energy potentials

A summary of the primary energy supply calculated with expected full load hours is presented in Figure 10. The largest potential is for solar electricity from PV (rooftop and free field) which accounts for 89.4 % of the total potential.

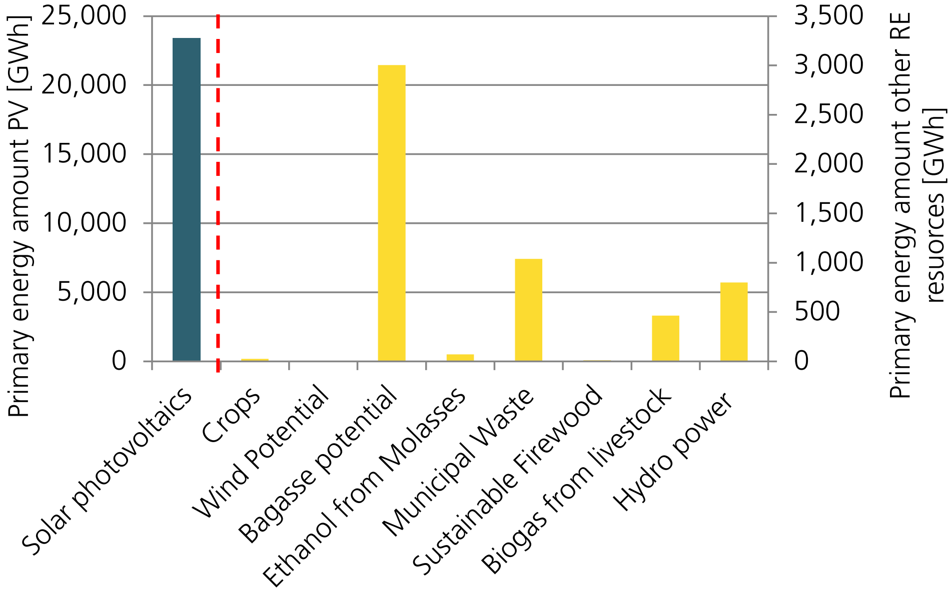


Figure 10: Primary energy supply potential of all renewable energy resources

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 18. Technology-specific data is taken from several sources. Most data has been taken from the same sources: Sterchele et al. (2020) and Ram et al. (2019). Data was then cross-checked with other sources. As data for all technologies was not available in Sterchele et al. (2020) and Ram et al. (2019), other sources have been used as well, again in accordance with the other two case studies from the 100 % RE project.

Table 18: Technology specific data for the scenarios

	Full load hours	Efficiency	Investment costs [€2021/kW] ([1,000KSH2021/ kWh])	O&M costs [% Investment]	Lifetime [Years]	References
Photovoltaics	1,287-1,417	200 W/m², inverter: 98 %	508 (65.5)	2	30	(Sterchele et al. 2020; Ram et al. 2019)
Biogas power plants	0-8,000	El: 40 % Th: 45 %	1,818 (234.4)	3.8	30	(Ram et al. 2019; International Energy Agency)
Waste power plants	0-8,000	El: 40 % Th: 45 %	4,663 (601.2)	3.5	20	(Danish Energy Agency 2021)
Hydropower Plants	0-4,000	92 %	3,350 (431.9)	2	50	(Ram et al. 2019; Anciaux et al. 2018)
Coal power Plants	0-7,000	El: 42 % Th: 20 %	1,571 (202.6)	1.3	50	(Ram et al. 2019)
Gas power Plants	0-7,000	El: 63 % Th: 20 %	811 (104.6)	2.5	35	(Ram et al. 2019)
Heat pumps	0-8,000	COP: 4	1,218 (157)	1	20	(Sterchele et al. 2020)
Biomass boilers	0-8,000	85 %	209 (26.9)	3	20	(Sterchele et al. 2020)
Biogas stoves	0-8,000	45 %	354 (45.6)	3.8	20	(JIQ magazine on climate and sustainability 2016)
Electric stoves	0-8,000	80 %	282 (36.4)	2	20	(Jeuland and Pattanayak 2012)
Wood stoves	0-8,000	50 %	39 (5)	2	20	(Lambe 2016; Jeuland and Pattanayak 2012; GVEP international 2012; Morelli et al. 2017)

Ethanol stoves	0-8,000	66 %	78 (10.1)	2	20	(GVEP international 2012; Lambe 2016; Jeuland and Pattanayak 2012; Morelli et al. 2017)
Electrolysis	0-8,000	El: 64 % Th: 20 %	471 (60.7)	3	20	(Perner et al. 2018)
Hydrogen storage	-	Dis/charge: 0.1 % Self-discharge: 0.01 %	165 [€/kg] (21.3 [1000KSH/kg])	2.5	20	(Sterchele et al. 2020)
Batteries	-	Self-discharge: 0.03 %	101 [€/kWh] (13 1000KSH /kWh])	1	15	(Sterchele et al. 2020)
Thermal storages		Self-discharge: 0.09 %	101 [€/kWh] (13 [1000KSH /kWh])	1.3	20	(Sterchele et al. 2020)

4.3.2 Fuel costs

In addition to capital and maintenance costs for different technologies, fuel costs are also an important input parameter that can have a major influence on the results. Fuel costs make up a large part of the overall costs when fuel-consuming power plants supply a large share of energy in the energy system scenario. To reflect this, biogas fuel costs are varied in the scenarios to account for uncertainties in fuel price prediction. For further information on this variation, refer to section 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 section 5.6) different fossil fuels are still in use; their prices are also given in Table 19.

Table 19: Fuel prices today and projections for 2050 used for Kisumu

Fuel	Fuel price today	Fuel price in 2050	References
Biomass	0.025 €/kWh (3.22 KSH/kWh)	0.025 €/kWh (3.22 KSH/kWh)	(Global Alliance for Clean Cookstoves 2012) and (Fuso Nerini et al. 2017)
Waste	-	Same price as for biomass taken	No information available
Biogas from crops and manure	-	Low: 0.0183 €/kWh (2.36 KSH/kWh) High: 0.0325 €/kWh (4.19 KSH/kWh)	Biogas production costs (International Renewable Energy Agency 2017)
Natural Gas	0.00798 €/kWh (1.03 KSH/kWh)	0.00798 €/kWh (1.03 KSH/kWh)	(Republic of Kenya 2020)
Hard coal	0.03 €/kWh (3.87 KSH/kWh)	0.028 €/kWh (3.61 KSH/kWh)	(Republic of Kenya 2020)
Ethanol	0.0897 €/kWh (11.57 KSH/kWh)	0.0897 €/kWh (11.57 KSH/kWh)	(Afrinol)
Bagasse	0.049 – 0.072 €/kWh (6.32 – 9.28 KSH/kWh)	Low: 0.049 €/kWh (6.32 KSH/kWh) High: 0.072 €/kWh (9.28 KSH/kWh)	(UN environment programme 2019)

4.4 Climate data

Climate data is given to the model in the same time resolution as the demand time series, which is hourly. Meteonorm is used as the source for climate data (Meteonorm). Data from the Kisumu weather station is taken which is located as shown in Figure 11. Meteonorm provides synthetic climate data which are representative for a certain weather station in a certain time span. The climate data used is a projection for the year 2050, incorporating anticipated effects of climate change which are for example higher outside temperatures which will lead to higher cooling demands.

Figure 11: Location of weather station in Kisumu (Meteonorm)

Temperatures in Kisumu are high throughout the year with a mean temperature of 23.58 °C. The sum of global solar irradiance on a horizontal plane is 1990 kWh/m². In Kenya there are two rainy seasons - the long rains from March to May, and the short rains from November until the end of December. However, these rainy periods don't seem to affect the solar irradiation as they are not visible in the irradiation data (see Figure 12).

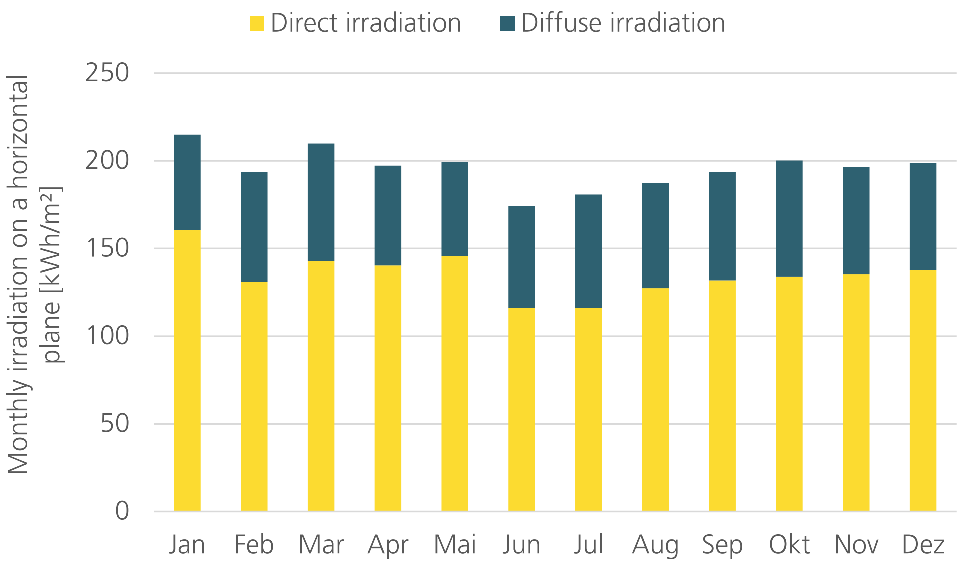


Figure 12: Solar irradiation global on a horizontal plane for Kisumu with data from (Meteonorm)

5 Overview of scenarios

In this chapter, first all technologies considered in the different scenarios are described (section 5.1), following which an explanation of all calculated scenarios is presented (sections 5.2–5.7).

5.1 Technologies considered

Certain technologies that have been used in the model (see Figure 2) can only supply certain demand sectors as shown in Figure 13. The technologies are chosen according to their potential use in Kisumu. Some of the technologies shown shown earlier in this report (Figure 2) are therefore not implemented; these are for example solar heaters, power to heat, chillers and cold storages. Cooling demand is considered to be included in electricity demand (see sub-section 4.1.2). Power to heat and solar heaters could supply to heat demand, but their usage was tested at the beginning of the modeling process and their deployment was determined to be economically infeasible.

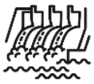
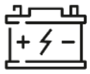
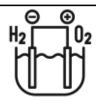
Demand sector	**Supply technologies**				**Storage technologies**
Electricity	Hydro-power 	CHPs using Biogas and municipal waste 	Photovoltaics 		Batteries and hydro storage 
Commercial and industrial heat	CHPs using Biogas and municipal waste 	Heat pumps 	Electrolysis 		Heat storage 
Cooking	Biogas stove 	Electric stove 	Ethanol stove 	Wood stove 	
Hydrogen	Electrolysis 				Hydrogen storage 

Figure 13: Display of supply technologies implemented in the model to meet the different demand types (stove type pictures from: (Various 2020))

Electricity demand can be covered by hydropower plants, photovoltaics and CHPs using biogas, municipal waste and bagasse. 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 by 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. Cooking demand has to be covered directly in the households or commercial sites with biogas stoves, electric stoves, modern wood stoves or ethanol stoves. In the transport sector, it is assumed that vehicles are using either 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

The scenarios incorporate different levels of electricity demand in 2050. There are three variations: one high-demand, one low-demand and one mean demand scenario (Republic of Kenya 2020, 2018). Energy for cooking and for the transport sector is assumed to be constant in all scenarios.

5.3 Variation of fuel price

The scenarios vary based on the assumptions for fuel prices, namely biogas in this case. While costs for technologies change rather slowly and can usually be predicted quite well based on economies of scale, fuel costs are dependent on many boundary conditions such as 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 various options for 100 percent RE (except the business-as-usual scenario) the energy system is independent from fossil fuels such as 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. For biogas, costs are driven by production costs and costs for collection, transport, labour and profit. To account for insecurities in cost prediction, two different costs for biogas are taken in different scenarios. These are 0.0183 €/kWh (2.36 KSH/kWh) for the low fuel price and 0.0325 €/kWh (4.19 KSH/kWh) for the high fuel price.

5.4 Fixed usage of different RE technologies

In some of the scenarios, the usage of some sources of energy, namely hydropower and biomass, is fixed i.e. the full available potential is used. The modeling results show a strong dependence on photovoltaics in the scenarios when a purely cost driven optimization is conducted (see chapter 6). However, in real world energy system planning other aspects are considered as well. For example, one might opt for a diversification of technologies to enhance supply security. In addition, when the costs of different technologies are very similar to each other, a mathematical optimization model will choose to only install the cheapest. As cost predictions are subject to uncertainties, it makes sense to test options which could be almost equal in cost to the least cost scenario. This helps to understand that there are different options for the future energy system and not only one possible to path to reach 100 % renewables.

5.5 Heating demand

In one of the scenarios, additional heating demand is included. No concrete information on heat demand in the industrial sector could be obtained during data collection. Most probably there will be industrial sites which have heating demand; therefore, in the "least cost plus heating scenario" a theoretical heating demand in the industry sector is considered just to test how heating demand could be covered. The heating demand in this scenario is set to the same amount as the useable energy demand for cooking, which is around 360 GWh as a first guess in this scenario.

5.6 Business-as-usual scenario

The business-as-usual (BAU) scenario projects Kisumu's energy system in 2050 if no concerted efforts were made to transition to renewable energy, meaning fossil fuels would still be in use, among various other assumptions. It is included to allow for the comparison with the 100% RE scenarios, in terms of costs and CO_2 emissions. 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. In the model, the transport of energy is ideal and therefore loss-free, which leads to an underestimation of the required installed 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 for comparison with "real" total costs of an energy system. Therefore, a business-as-usual scenario is calculated where electricity supply structure in 2050 is implemented in the model as shown in Republic of Kenya (2020). In this report a possible projection for a future energy system for the whole of Kenya is made which is adapted for this study. This is also the reason why in the business-as-usual scenario potentials are used that are not available in Kisumu like geothermal power. Projections for electrification rates in transport sector were researched but could not be found. Therefor the assumption that 20 % of all vehicles will drive electric while the rest is still using fossil fuels is made based on projection data from (Notter et al. 2019) for the year 2050. The shares of different energy supply technologies in this scenario are given in Table 20.

Table 20: Share of different energy supply technologies in the business-as-usual scenario for 2050

	Cooking	Electricity (adapted from (Republic of Kenya 2020)	Transportation (own assumptions and information from (Notter et al. 2019))
Geothermal		58.8 %	
Hydropower		17.8 %	
Photovoltaics		1.4 %	
Wind Power		7 %	
Gas power plants		8.1 %	
Coal power plants		7 %	
Diesel/Gasoline			80 %
Electric			20 %
Remarks	Optimized in model, same technologies as in 100 % RE scenarios		

5.7 Overview of all scenarios

Table 21 gives an overview of all the scenarios that have been calculated and are presented in this report. Overall, eight scenarios were calculated and compared. All scenarios except the business-as-usual (BAU) scenario only consider renewable energy sources. The differences between these scenarios were described earlier in sections 5.2 until 5.6.

Table 21: Overview over all calculated scenarios

Scenario name	Low/High/ fuel price	Low/Mean/High/ demand	Full usage of potentials fixed	Heating demand	Share of renewables
Hydropower fixed	Low	mean	Hydropower	No	100 %
Least cost	Low	mean	-	No	100 %
Least cost plus heating demand	Low	mean	-	Yes	100 %
High demand	Low	High	-	No	100 %
High fuel price	High	mean	-	No	100 %
Hydro and biomass fixed	Low	mean	Hydropower, biomass, municipal waste	No	100 %
Low demand	Low	Low	-	No	100 %
Business-as-usual	Low	mean	-	No	48.1 %

6 Results

In this chapter the results for all scenarios for the target energy system in 2050 are shown and discussed. There are two leading scenarios that the Kisumu County government can pursue. In the least cost scenario, technologies are installed and operated under the premise of minimizing the total system costs under the given boundary conditions (see Chapter 5). The second option is the hydropower fixed scenario, a scenario where the full usage of all hydropower potentials is fixed (see Table 21). As the latter is 0.2 % more expensive, it can therefore be rated as an equal option. This is why both will be presented in full detail in sub-section 6.1.1. In sub-section 6.1.2 a detailed discussion of the operation of the different power plants during the year is done. In section 6.2 a comparison of all calculated scenarios is conducted. section 6.3 presents a transition plan from today until 2050 to reach the hydropower fixed scenario. It has been chosen for the transition path as it has a higher variation in technologies and thus shows more options for future energy supply. In sub-section 6.4 a risk analysis is performed, linked with recommendations for how to overcome the most common risks when transforming to 100 % RE.

6.1 Leading scenarios: Least cost and hydropower fixed

6.1.1 Energy supply

The total electricity demand in 2050 consists of the electricity demand in the different sectors (households, industry, commercial sector), demand in the transport sector for vehicles using electricity directly and the production of hydrogen, and cooking demand that is covered with electric stoves. The total electricity demand to be covered in this scenario is around 9,700 GWh. Figure 14 shows how electricity demand is covered with the different technologies in the leading scenarios least cost and hydro power fixed.

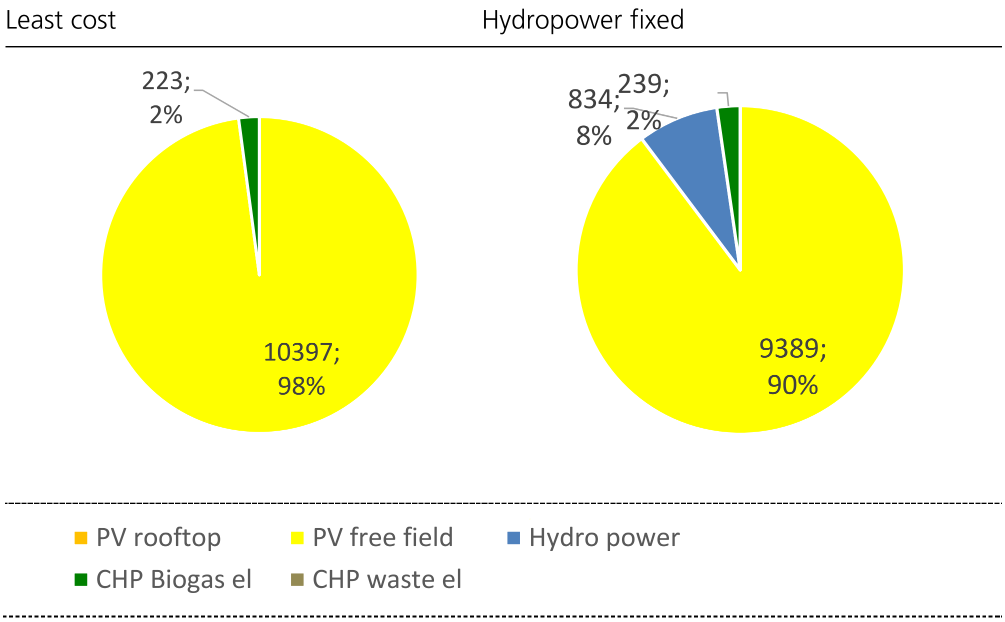


Figure 14: Results for electricity supply for the two leading scenarios in 2050 in GWh

The electricity demand differs slightly between the two scenarios because of different shares of electric stoves for cooking. The largest electricity supply source is photovoltaics with a 98 % share in the least cost scenario and 90 % in the hydropower fixed scenario. All installed PV power plants in both scenarios are free field PV systems because the tilt angle can be chosen to be optimal, while for rooftop PV tilt and angle are dependent on

the rooftop elevation and orientation. It is nevertheless recommended to install rooftop PV on suitable roofs, for several reasons. First, decentralized installations are better for the electricity grid, as feeding to the grid is also decentralized. This means less risks for grid congestions which would lead to curtailment. In addition, households with PV power plants can us their own electricity directly, which relieves the grid even more. Furthermore, rooftop areas are unused areas, while free field areas could be used for other purposes.
In both scenarios 2 % of electricity demand is covered with CHPs using biogas, while in the hydropower fixed scenario 8 % of the electricity demand is covered with hydropower. As installed capacity of hydropower is fixed at the maximum, a larger share of hydropower in Kisumu's energy systems is not possible when using only local resources. Waste CHPs are not installed in this scenario. The levelized costs of energy (average net present cost of energy for a generating plant over its lifetime) for waste CHPs are shown in Figure 26 and, as they are higher than the levelized costs of energy for biogas CHPs and PV, they are only installed when their usage is fixed in the scenario.
In the transport sector electric vehicles need to be charged according to their charging curve (see sub section 4.1.4) which results in a total electricity demand of 1,735.28 GWh. In addition, 5467 GWh of electricity is needed to produce 3,499.33 GWh of hydrogen for transport sector. These electricity demands are included in the total demand that is supplied by the shown technologies in Figure 14.
Energy for cooking demand is met with 100 percent renewable energies in 2050. The main cooking stove type are electric stoves, covering between 79 % and 84 % of energy demand (see Figure 15). The rest is covered with ethanol stoves (13 %), wood stoves (1 %) and biogas stoves (2-7 %). Potentials for ethanol, wood and biogas are fully used as these cooking types are cheaper than electric cooking, but potentials are small. Today wood in its original form or in the form of charcoal is the main energy carrier in the cooking sector, but more wood is taken from the forest every year than can regrow in a year, leading to shrinking forests, a process which even accelerates climate change as plants bind carbon dioxide. In addition, local climates can change when forests shrink; in addition, erosion often becomes a problem. Therefore, it is highly recommended to stop forest exploitation and conduct reforestation.

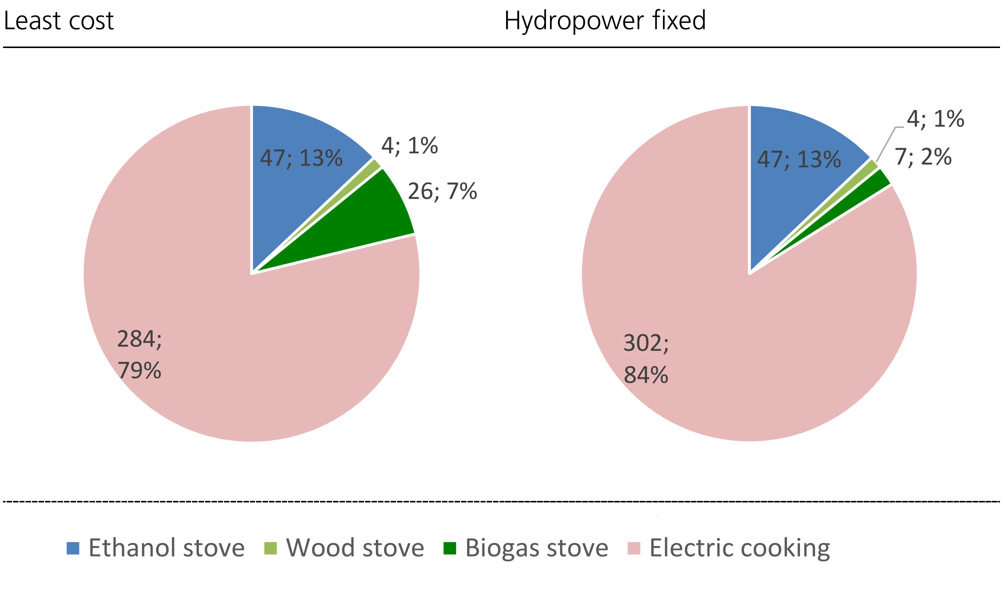


Figure 15: Results for useable energy for cooking supply for the two leading scenarios in 2050 in GWh

Figure 16 shows the energy flow (Sankey) diagram for the hydro power fixed scenario. The left side shows the different power plant types that are used to produce electricity or heat. On the right-hand side, the different energy demand types are presented. In this energy flow diagram, demand sources are differentiated as electricity demand, energy demand in the transport sector, and cooking demand. Electricity supply adds up to 10,462 GWh including electricity demand for appliances in the different sectors (households, commercial and industry sector), in transport sector, for the production of hydrogen, and for cooking. Electrolyzers can be found in the upper middle part of the diagram. They use electricity to produce hydrogen for transport sector, a process which is subject to losses, which are also depicted in the diagram. Electric stoves are another source of demand which use electricity to produce heat for cooking. Not all losses are depicted, only the ones from electrolysis, battery storage and electric cooking are shown. 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.

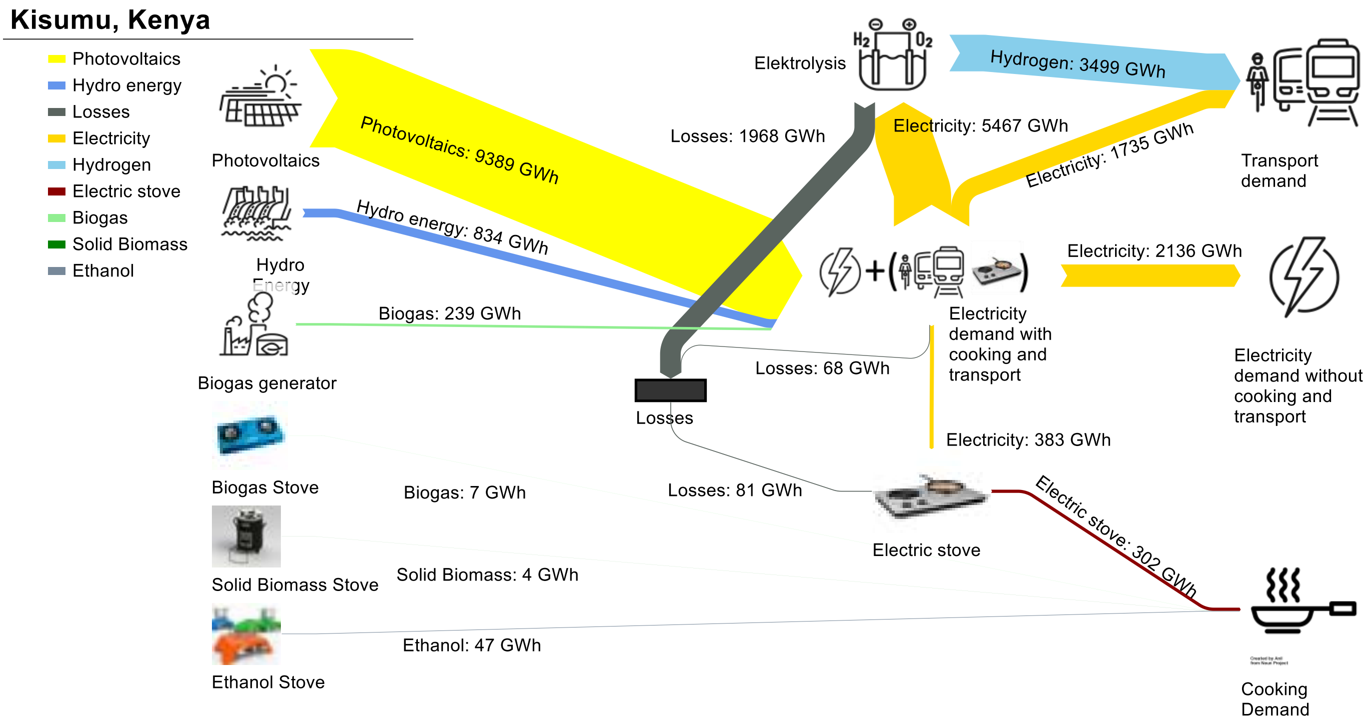


Figure 16: Energy Flow diagram of one of the leading scenarios: hydropower fixed

Figure 17 depicts the installed capacity of all technologies. As the installed capacity from solar PV, electrolyzers and batteries is much larger than for the other supply technologies, these three are shown on a second y-axis. PV is the supply technology with the largest amount of supplied energy, and at the same time the lowest full load hours of around 1,500 hours per year. Batteries are also installed to a high extent as the majority of electricity supply would come from PV. Storage technologies would be needed to balance supply and demand for this variable energy source, especially for the night hours. In the hydropower fixed scenario, as less PV is installed and therefore also supplies less electricity, the installed battery capacity required is also lower.

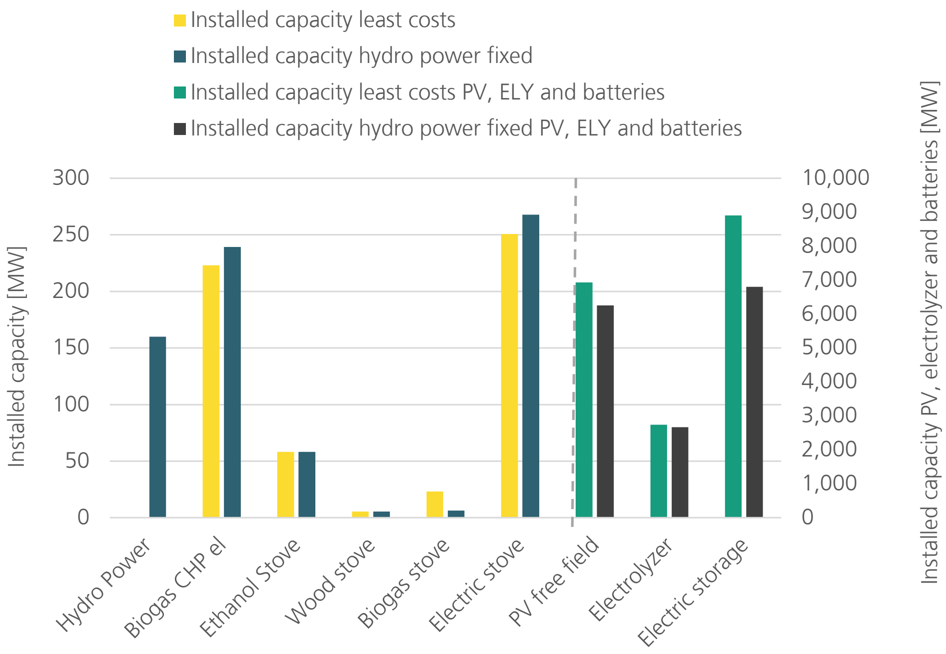


Figure 17: Installed capacities of all installed technologies in the two leading scenarios in comparison

The potential for biogas is used to the full extent. While in the least cost scenario it is used more in stoves, in the hydropower fixed scenario the installed capacity and supplied electricity of CHPs is a little bit higher.

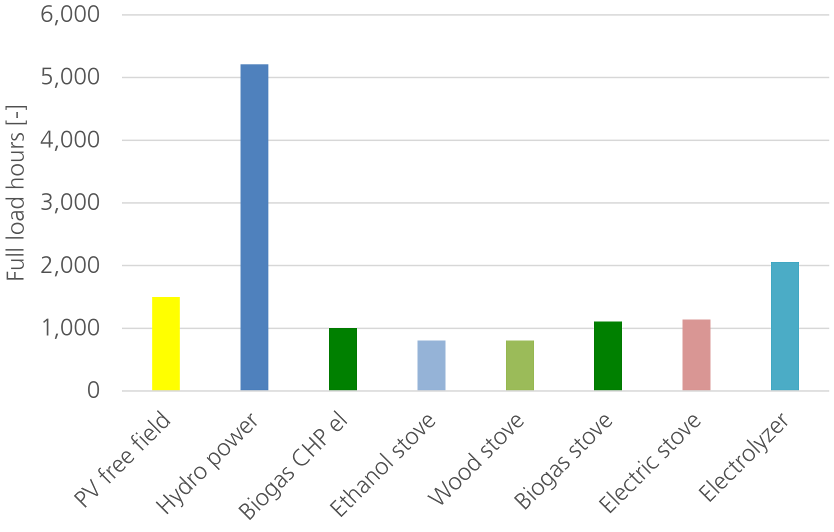


Figure 18: Full load hours of the different technologies in the hydropower fixed scenario

The full load hours are defined as the ratio between produces energy and installed capacity of a power plant and show therefor how much a technology is used during one year. The highest full load hours are reached by hydropower plants with 5,211 h (see Figure 18). These full load hours are determined by the fixed load curve for hydropower (see sub-section 4.2.7. It is assumed that a curtailment is possible and less electricity might be produced with hydropower but not more than anticipated by the load curve. The full load hours of several power plants and stoves are at the fixed minimum which is 1,000 h for CHPs and 800 h for stoves.

6.1.2 Time series evaluation

An assessment of the temporally resolved results of the scenarios helps to understand how the different power plants are operated throughout the year and how storage technologies help to balance power generation from fluctuating renewable technologies. Figure 19 and Figure 20 show power generation and demand for one week in January 2050 and for comparison for one week in April for the two leading scenarios. The figures are to 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 cooking purposes and production of hydrogen).
In the least cost scenario in Figure 19 PV is the main electricity supply source, peaking around noon every day with a maximum output of 6,327 MW. CHPs run on the first day of the week, when output from PV is only 426 MW as solar irradiation is low at that day, and at the end of every night for a short period of time. The output from PV is much higher than demand during the daytime and this excess production can be used in two ways. It can either be stored in batteries (orange area below zero) for later use, or to produce hydrogen for the transport sector (blue line indicating gross demand). Still, some electricity cannot be used and can either be exported or curtailed (grey area below zero).

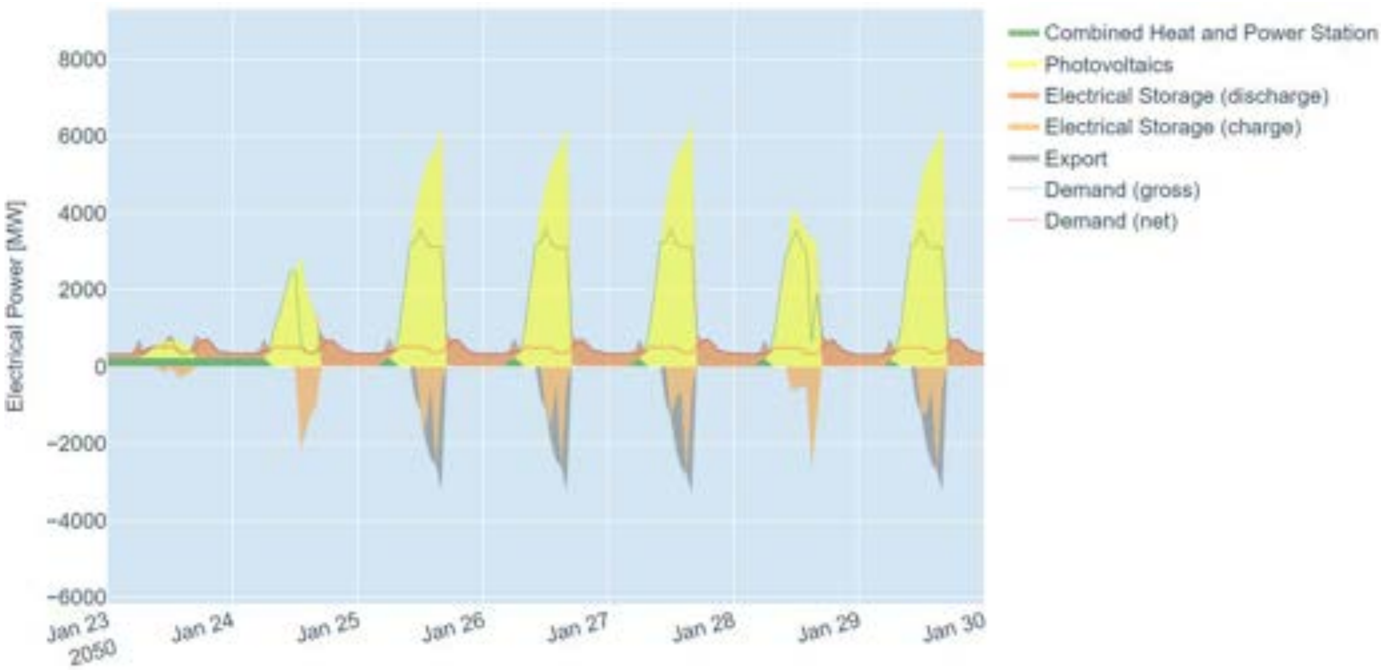


Figure 19: Time series for one week in January 2050 for electricity supply and demand for the leading scenario: least cost

The high amount of excess electricity stored during daytime could cause congestions in the electricity grid if 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 onsite for later use. As KomMod does not model any networks, no quantification of grid load can be given here. Instead, this must be part of a more detailed planning process for grid expansion, taking into account a rising share of PV power plants in the electricity system of Kisumu.

Figure 20 shows the same week in January 2050 for the hydropower fixed scenario. In January electricity output is low, as water levels in rivers are low at that time. Because of that there are only minor differences in electricity generation between the two scenarios in that week. First, the installed capacity of PV is lower in the hydropower fixed scenario, and therefore maximum output of PV is around 5,700 MW instead of 6,327 MW. Therefore, CHPs cover more demand at nighttime, as less electricity is being stored in batteries. In addition, small amounts of electricity supply from hydropower are available during night time.

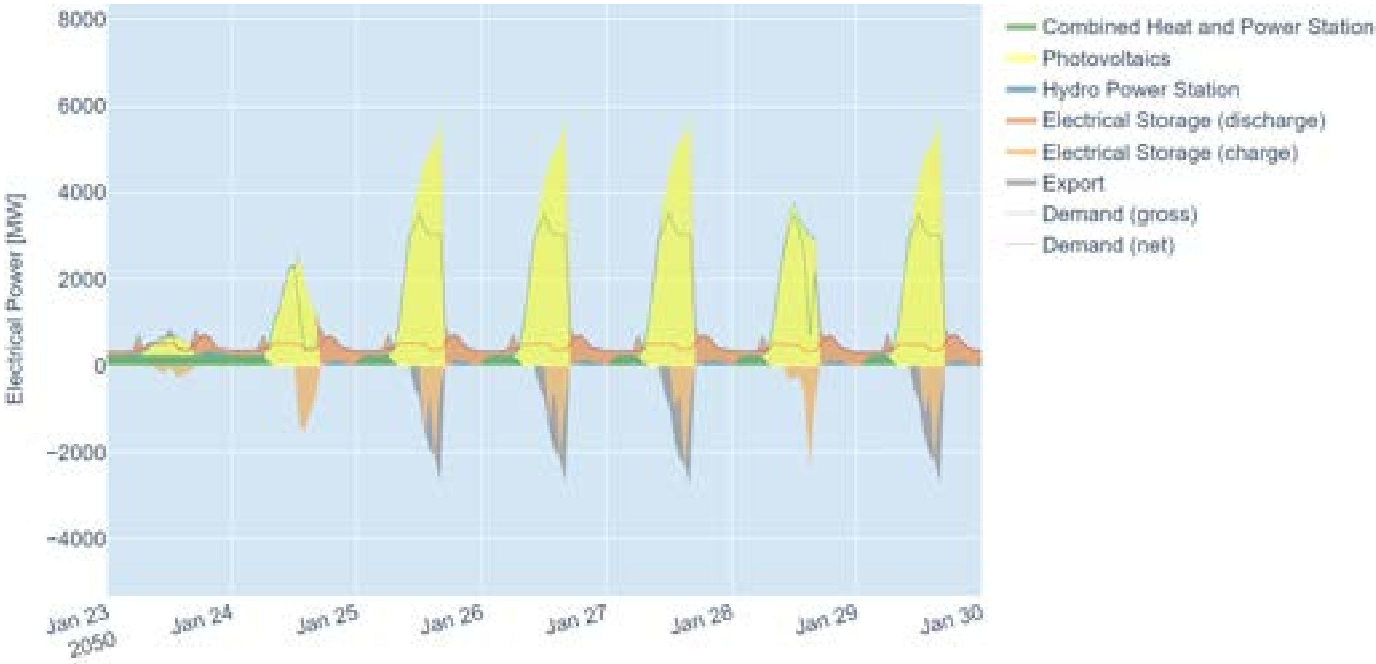


Figure 20: Time series for one week in January 2050 for electricity supply and demand for the leading scenario: hydropower fixed

In Figure 21 and Figure 22 electricity supply and demand for one week in April 2050 for both leading scenarios is shown. This is a week with high hydropower output in the hydropower fixed scenario (see Figure 22). Electricity supply is even higher with 7,124 MW in the least-costs scenario and 6,434 MW in the hydropower fixed scenario on April 19th. Hydropower supplies electricity constantly with a base load of 160 MW, which is the maximum output. In the hydropower fixed scenario, CHPs are running only once that week, in the night of April 22nd to April 23rd, as solar irradiation was low in April 22nd so little excess electricity could be produced that day to be used at night. In the least-costs scenario, they run every night.

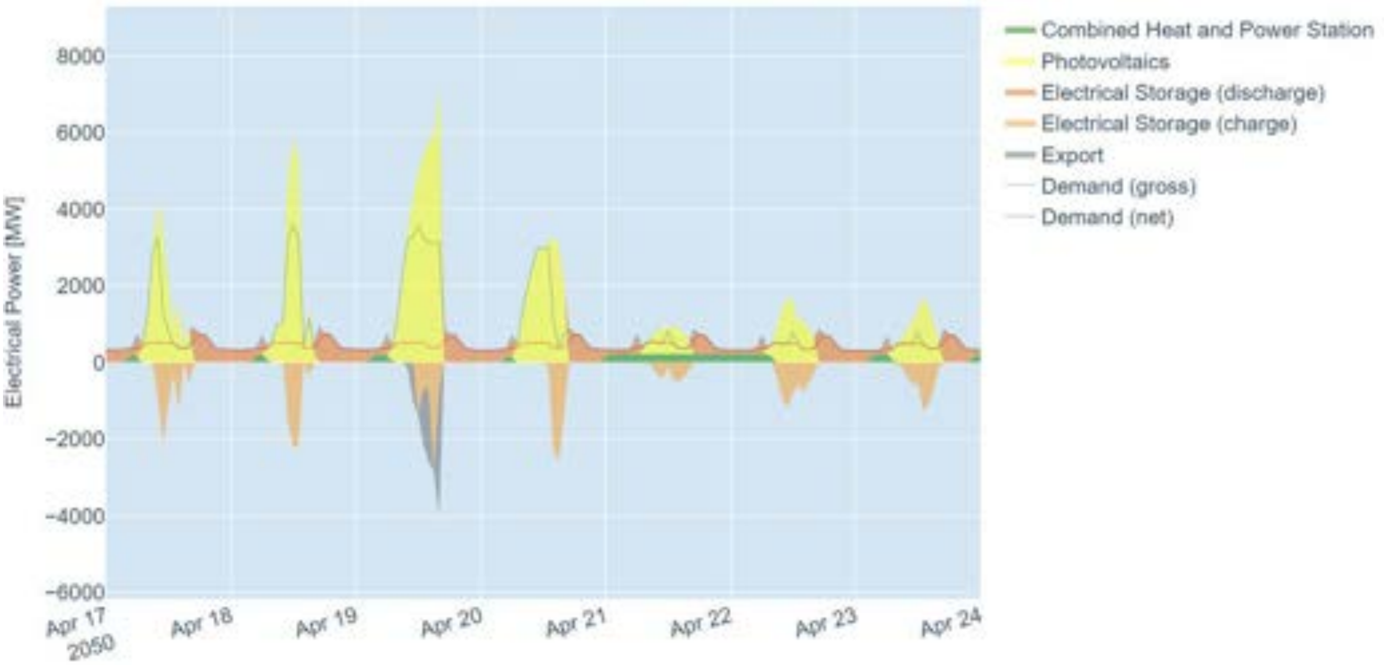


Figure 21: Time series for one week in April 2050 for electricity supply and demand for the leading scenario: least cost

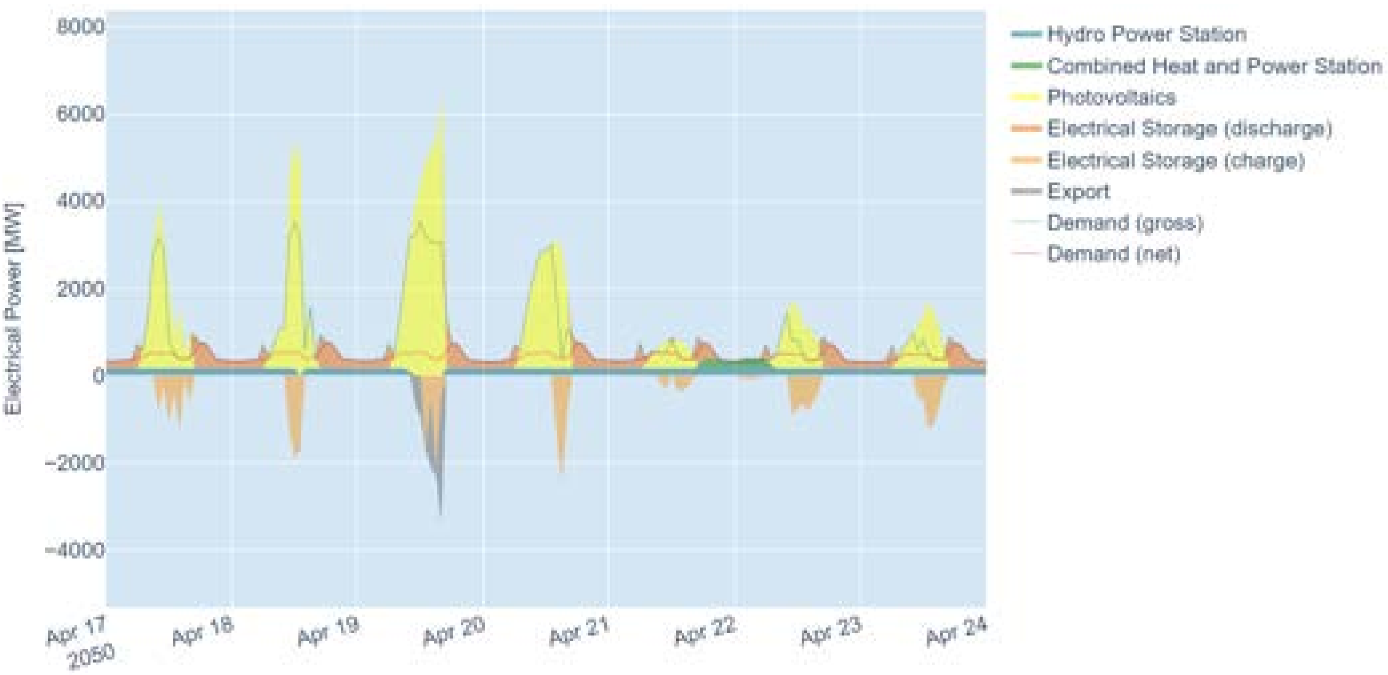


Figure 22: Time series for one week in April 2050 for electricity supply and demand for the leading scenario: hydropower fixed

6.2 Comparison of all scenarios

Overall, eight scenarios have been calculated. All results in table format can be found in Appendix C.

6.2.1 Energy supply

In Figure 23 the electricity supply in all scenarios is shown. In all 100 percent RE scenarios, PV covers the largest share of electricity demand: its highest share is in the low demand scenario with 100 %, and its lowest share is in the hydro and biomass fixed scenario with 74 %. In the business-as-usual (BAU) scenario, solar electricity is covering 1.4 % of electricity supply. As modeling results from this study - as well as many other studies that have been conducted in the last years (Kost et al. 2018; Lazard, Ltd. 2020; IRENA 2021) - show that PV is by far the cheapest supply technology, the reasoning why its use is not more extensive in the BAU scenario remains unclear. It is therefore highly recommended for the whole of Kenya to accelerate the expansion of PV as it is a cheap as well as a decentralized supply technology, allowing its use in remote areas and helping rural households to easily access electricity.
Biogas is used in CHPs, as well as biogas stoves, and covers around 2 % of electricity supply in all the scenarios except the low-demand and BAU scenarios. Hydropower supplies around 8 % when fixed, as in the hydropower fixed and the hydro and biomass fixed scenario. In addition, it is installed in the high demand scenario with a capacity of 43 MW (27 % of total potential). In all other scenarios it is not installed.

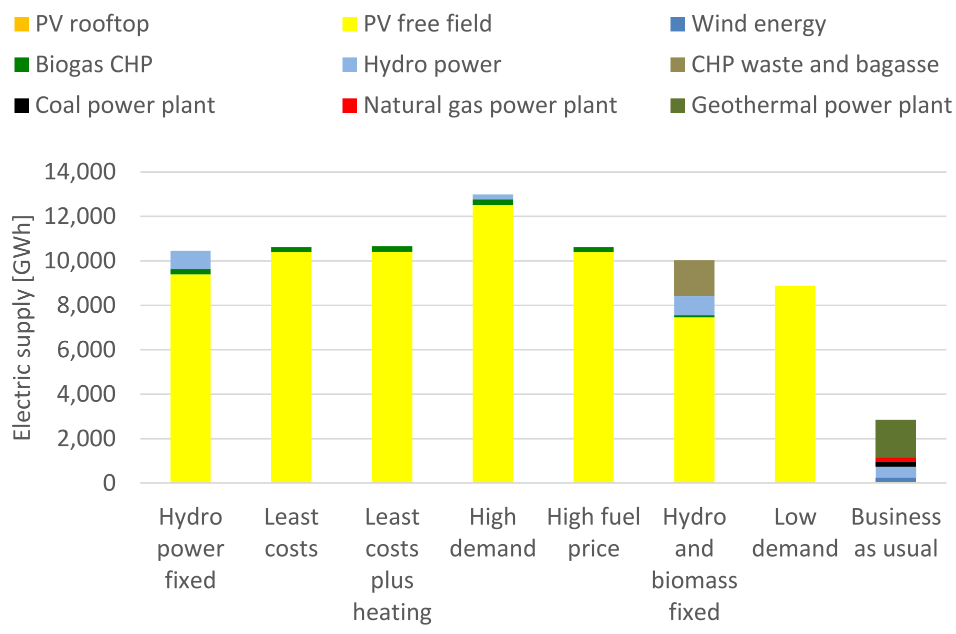


Figure 23: Comparison of electricity supply in all scenarios

In the majority of the scenarios electric stoves take the largest share of energy supply with shares between 79 % (least cost and high fuel price) and 86 % (least cost plus heating and high demand). In the hydro and biomass fixed scenario the full biomass potential is used; the share of energy supply for cooking provided by biomass is 52 %, as potentials are restricted and electric stoves are used to cover the rest of the demand. In the low demand scenario the electricity demand is only half as high as in the mean demand scenario and is fully covered with photovoltaics (see Figure 23). Because of that, biomass can be fully used to cover energy for cooking demand, which results in a higher share of 78 % biomass stoves (biogas, ethanol and wood). In the BAU scenario no biogas

CHPs are installed (see definition in section 5.6) and therefore biogas is fully used to cover energy for cooking demand.

Figure 24: Comparison of cooking supply in all scenarios

6.2.2 Usage of potentials

The goal of 100% renewables can be reached in all calculated scenarios, including the high-demand scenarios. An assessment of the used potentials helps to understand whether 100 percent RE would still be possible, if demand were even higher in the future. Figure 25 shows the percent of potential used for PV, hydropower, and biomass and municipal waste under all scenarios.

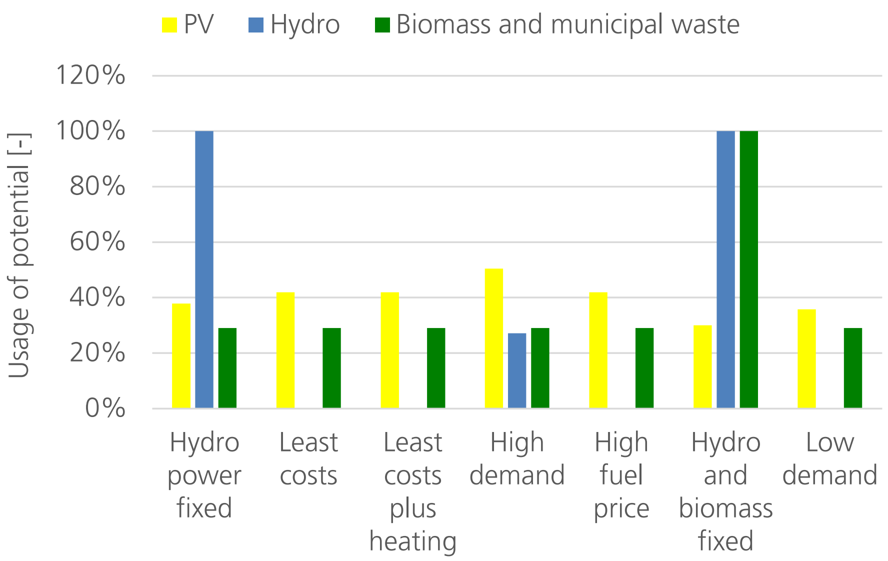


Figure 25: Used potentials PV and Wind in all 100% RE scenarios normalized to the maximum potential

As the absolute potentials from the three different resources are quite different the usage of total potential cannot be read out of this graph. Hydropower, bagasse and municipal waste are only fully used when it they are fixed in the scenarios. Biogas, wood and ethanol are used fully in all scenarios. The PV potential used is between 30% (hydro and biomass fixed) and 50% (high demand) of the total resources available. When biomass, municipal waste and hydropower potentials are fully used, naturally less electricity supply from PV is needed to cover the remaining demand. While in the high demand scenario the higher demand has to be covered which is mainly done by installing more PV power plants as other resources are already fully used.
Table 22 shows the used potential summed across all types of renewable energies, and percentage of this total potential used. The percentage of used potential varies between 34 % in low demand scenario and 48 % in high demand scenario, while the largest part of unused potential is photovoltaics (see also sub-section 4.2.10). In addition, it is shown how much space is needed to install all free field photovoltaic power plants in the different scenarios, in relation to the total area of Kisumu. This share varies from 2.17 % to 3.12 %.

Table 22: Used potential of all renewable energy types in Kisumu and used area for free field photovoltaics

	Used potential primary energy supply [GWh]	**Used potential total [%]**	**Used area PV free field power plants [m²]**	**Percentage of total area of Kisumu [%]**
Hydropower fixed	10,458	39.45%	297.27	2.34%
Least cost	10,446	39.40%	329.19	2.59%
Least cost plus heating demand	10,455	39.44%	329.51	2.59%
High demand	12,725	48.00%	396.39	3.12%
High fuel price	10,446	39.40%	329.19	2.59%
Hydro and biomass fixed	10,021	37.80%	275.82	2.17%
Low demand	9,008	33.98%	281.26	2.21%

6.2.3 Costs

Figure 26 depicts the levelized costs of electricity (LCOE) and heat (LCOH) of all technologies being installed in the scenarios. These levelized costs of energy describe the costs for producing one kWh of energy with one technology. The lowest LCOE belongs to biogas CHPs with 1.8 €ct/kWh electricity produced (2.33 KSH/kWh), but they reach this figure only if heat is produced and fully used. The reason is that capital, maintenance as well as fuel costs are split up between electricity and heat production in that case. If only electricity is produced costs are higher for electricity production resulting in 4 €ct/kWh (5.25 KSH/kWh) for biogas CHPs. PV power plants have an LCOE of 2.8 €ct/kWh (3.55 KSH/kWh). Additional costs occur for batteries to balance supply and demand which results in additional costs for PV of 1.1 €ct/kWh (1.47 KSH/kWh).
Wind power, coal power plants, geothermal power plants and natural gas power plants are only installed in the BAU scenario. Wind power and geothermal power plants do not

have any potential in Kisumu, prices are calculated out of mean costs and mean full load hours for the technologies (see Table 18 for used sources). All types of biomass stoves are cheaper than electric stoves, which is why their potential is fully used in all scenarios. Electric stoves are more expensive because electricity has higher costs than other fuels. The electricity price taken here is the weighted mean LCOE by all installed technologies in the respective scenarios.

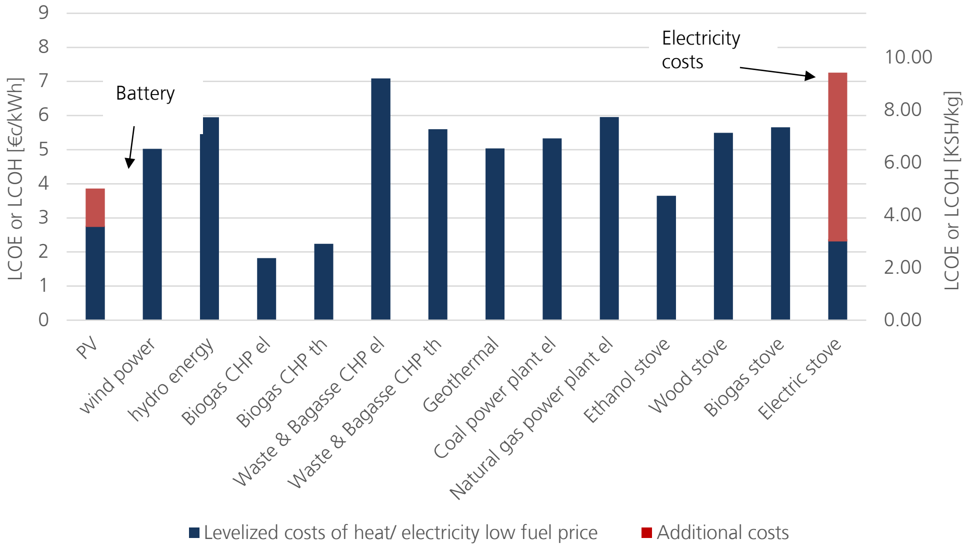


Figure 26: Levelized costs of energy for the different technologies

Figure 27 shows the overall system costs in all scenarios normalized to the costs of the hydropower fixed scenario. The least cost scenario is even cheaper, but only by 0.2 %, which can be rated as effectively equal, especially in view of the uncertainties in the cost projections 30 years in the future. In addition, the least cost scenario with heating demand has 0.2 % higher cost than the least cost scenario without industrial heating demand. While in the least cost scenario excess heat from CHP thermal processes, as well as from the electrolysis process, has to be curtailed, it can be used in the least cost plus heating scenario to cover the heating demand in the industrial sector. The operation of the CHPs and electrolyzers is adapted accordingly, but it has no major influence on the overall system structure. The high demand scenario - with 30% more energy demand - is also about 30% more expensive, while the low demand scenario - with 15% lower energy demand - is 12% less expensive. Therefore, the relation between demand and costs is quite linear, at least in the examined range. This means that efficiency measures and a resulting lower energy demand directly lead to lower energy system costs. The most expensive scenario is the BAU scenario. These costs are mainly driven by fossil fuels used in the transport sector as still 80 % of all vehicles depend on fossil fuels in the BAU scenario in 2050. At the same time these costs are the most uncertain costs. As the BAU scenario is highly dependent on fossil fuels, cost prediction is difficult. Kenya imports fossil fuels and prices are dependent on worldwide developments which cannot be controlled. It must be noted that the costs for technology development can be projected quite well based on economies of scale. The main energy source in the 100 percent RE scenarios - and therefore the main cost driver - is PV, which is independent from fuels and whose cost is therefore easier to predict. This independence is also an advantage when using local energy resources.

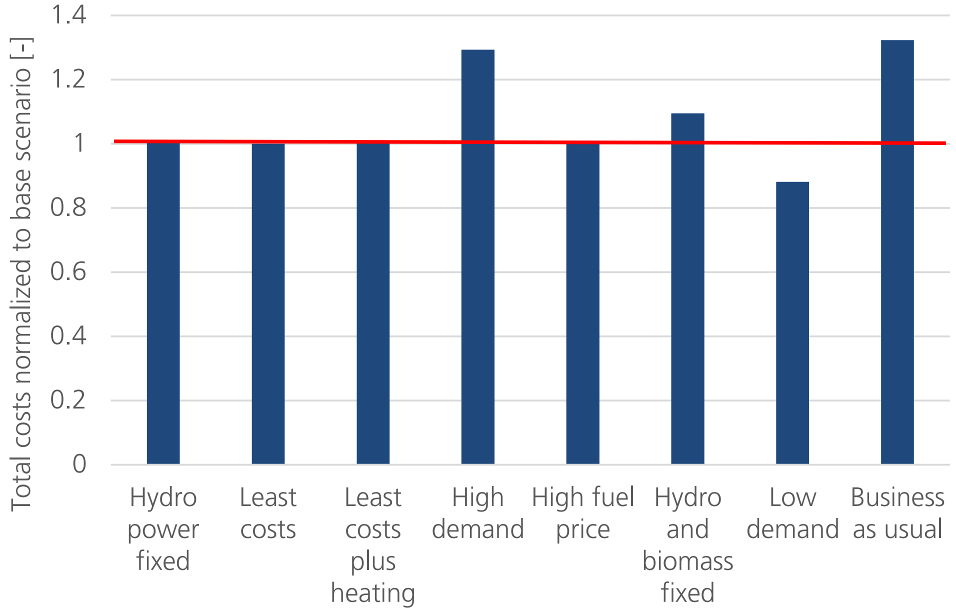


Figure 27: Total system costs in all scenarios normalized

6.2.4 Carbon dioxide equivalent emissions

The direct CO_2e (carbon dioxide equivalent) emissions in all scenarios are depicted in Figure 28. Direct CO_2e emissions are only emissions from burning fuel, no carbon dioxide equivalents from the production of different power plants are included. In most of the 100 percent RE scenarios the direct CO_2e emissions are the same, as the same amount of biomass is used and PV and hydropower do not emit direct CO_2e emissions. As in the hydro and biomass fixed scenario waste and bagasse are used; in addition, the direct CO_2e emissions are higher. The BAU scenario has 27 times higher direct CO_2e emissions than the leading scenarios, emissions which result mainly from diesel and gasoline used in the transport sector and from coal and natural gas used in thermal power plants to supply electricity.

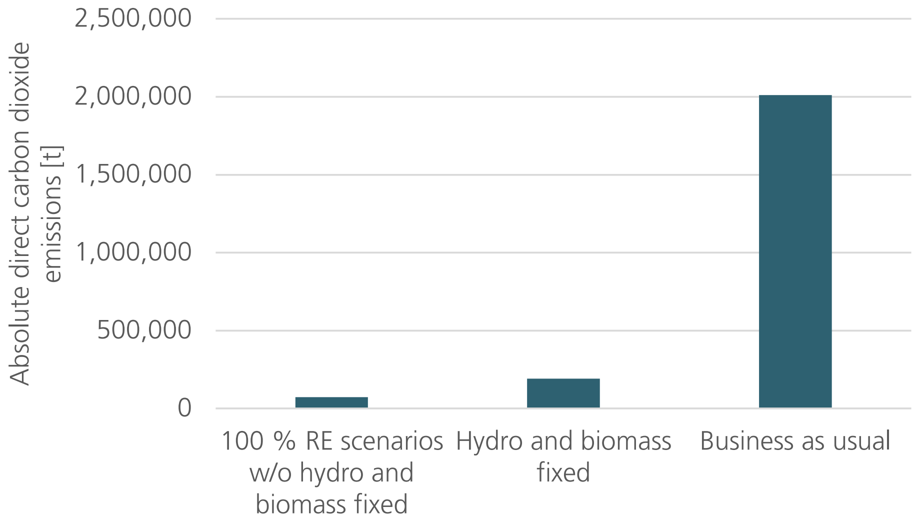


Figure 28: Direct CO_2e emissions in all scenarios

6.3 Transition plan

The elaboration of a detailed transition plan will be a key part of the ongoing 100% Renewables Cities and Regions Roadmap project, but some first insights into possible transformation pathways for Kisumu's energy system shall be already given here. These can show the amount of new energy technologies and generation capacity that must be deployed every year in order to reach 100% renewable status by 2050. For example, Figure 29 shows one possible pathway for electricity generation to reach the leading scenario with hydropower in the year 2050. It is considered to be very important that the right investment decisions are made from now on, which means that ideally, no investments in fossil technologies shall be made anymore, as these investments would be stranded eventually. This means that private households should also be incentivized to invest into renewable energy technologies such as biogas stoves and photovoltaics. The usage of LPG stoves could be an option for the upcoming years as they have already a much higher efficiency than traditional stoves types and produce less harmful Particulate matter emissions.

Electricity demand is projected to rise by 10 times in the mean demand scenario (including electricity demand for transport and cooking) until 2050. New power plant capacities must be installed quite soon to cover growing electricity demand. Today 80 MW of hydropower as well as 21 MW of biomass CHP in sugar cane factories are installed. 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 five years, as soon as biogas production plants have been built up. It is assumed that the additional 80 MW of hydropower is installed in 2035. As electricity demand will grow rather slowly in the first years and then increases more steeply, and additionally because hydrogen production is only assumed to start in 2032, most of the PV capacity only has to be installed after 2030, when prices will be even lower than today. Already today no import of electricity is necessary and more electricity is produced than needed, as also one gas power plant is installed producing around 100 GWh of electricity every year (Buma 2021). It is assumed that this gas power plant will stop its operation in 2027 (10 years after its commissioning) and from that moment on only renewable energy technologies are being used. Excess electricity, especially from PV. can be exported to regions with uncovered demands or can be (partly) curtailed if not needed somewhere.

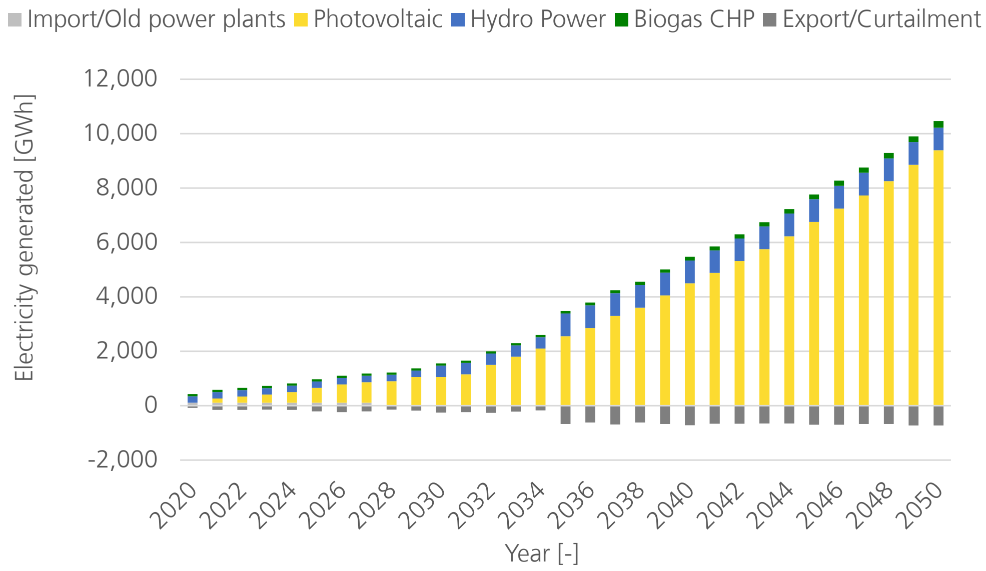


Figure 29: Generated electricity in the years 2020-2050 in the leading scenario

Figure 30 shows the share of different drive train concepts from today until 2050, aggregated for all vehicle types.

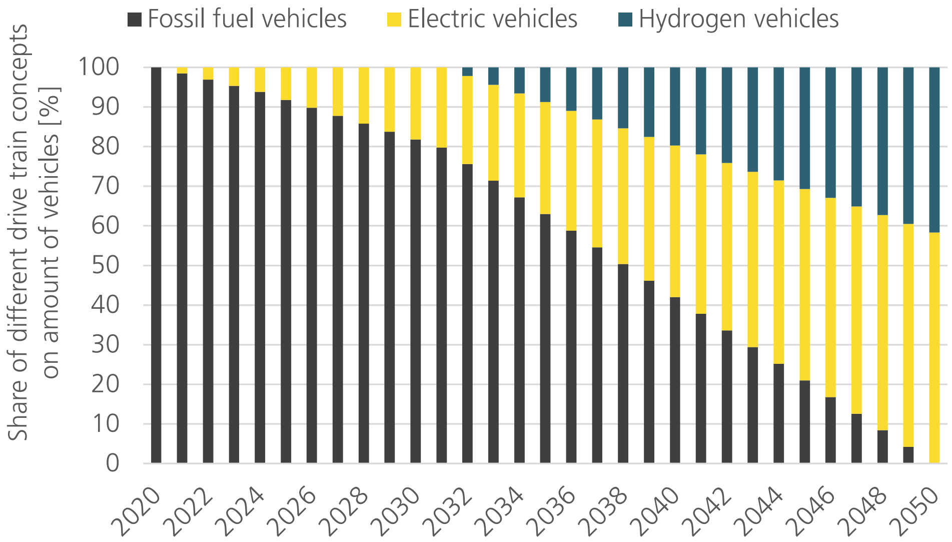


Figure 30: Share of different drive train concepts over all vehicle types in the leading scenario from today until 2050

The first vehicles that are assumed to be electrified are motorcycles, since this technology is already available, cheaper than electric cars, and used for short distances, meaning that no comprehensive charging infrastructure is needed. Cars are the next vehicles type to become electrified, while trucks and busses are last, with hydrogen production only starting in 2032. Simultaneously with the adoption of the new vehicles, charging and refueling infrastructure has to be installed in Kisumu. As vehicles will also drive from Kisumu to other counties, a critical consideration is the supply of electricity and hydrogen to vehicles which travel outside of Kisumu, which means that in transport sector a local solution without any collaboration is not possible. This is one of the threats to the transformation of the transport sector to 100 % renewables. Secondly, in Kenya, as well as many other parts of Africa, cars are bought used, often from Europe. This means that electric and especially hydrogen vehicles are potentially not available at large scale in Kenya and secondly not affordable for the majority of the people. Internal discussions in the project team with local stakeholders have also revealed doubts about the usage of hydrogen as fuel in Kisumu as it is assumed in the scenario. These doubts are justified, as at the moment electrification of trucks and busses is still being tested and range will most probably increase in the coming years. But it will only come clear in the next years whether the range will be large enough to transport goods for long distances under given time constraints. Anyway, the usage of electrified trucks to transport goods to and from Kisumu requires charging infrastructure not only in Kisumu but everywhere these trucks go to and come from. In summary, the transport sector is seen as the most critical sector when it comes to a transformation to 100 percent RE.

Today's cooking technologies (mainly wood and charcoal) shall be replaced with modern stoves which have a higher efficiency and generate less harmful smoke. As lifetime of cooking stoves is rather short (less to equal 10 years), they can simply be replaced when they have reached the end of their lifetime. In the transition plan shown in Figure 31, it is assumed that the last old cooking stoves are replaced in 2035 and from that moment on additional demand is met with additional modern cooking technologies. Cooking supply and therefore demand increases from today until the year 2050 in the households as well as in the commercial sector. The increase is correlated to the increase of population. The largest energy supplier in the cooking sector is electric cooking because of restricted biomass potentials (wood, biogas and ethanol are fully used). Electric stoves have a minor share today, which means that many households will have to switch their cooking fuels and have to adapt their cooking habits. This means that capacity building about modern electric cook stoves should be an important part of the ongoing actions towards 100 percent RE in Kisumu.

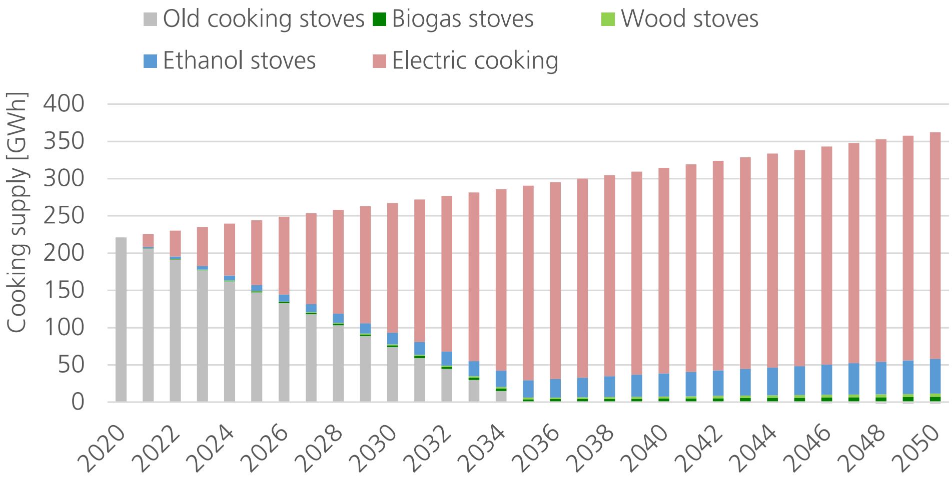


Figure 31: Share of biogas and old cooking stoves on overall cooking supply in the leading scenario from today until 2050

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 the installed storages and the longest period where little to no renewable energy from fluctuating renewables is produced because of low solar irradiation. In the model battery storages are implemented as storage technologies. Other storage options like compressed air reservoirs or hydrogen could be additional options to increase supply security. Hydrogen is produced anyway for transport sector and could be used in fuel cells to produce electricity when needed as back up technology.
- 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 used decentrally and therefore also help more remote areas to have access to clean, affordable, and secure electricity supply
- In this study, for the sake of simplicity, biogas was assumed to be the only form of bioenergy for all scenarios. Whether the direct burning of biomass or the conversion of biomass to biogas is the better option in Kisumu shall be assessed via detailed feasibility studies
- Biogas production should start soon so that it is available to use in biogas cooking stoves in households as well as in biogas CHPs. To produce biogas, biomass residues and manure must be collected and brought to the biogas production facilities. It is beneficial if biomass and manure must only be transported for short distances, as the calorific value is low before the biogas production process. Transport costs should be kept at a minimum to keep biogas price low. The best locations for biogas production must therefore be found by taking into account the agricultural used areas, 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 fewer power plant capacities must be installed and less fuel is needed. Projections of energy demand show that demand will most probably rise in the future. There are several reasons for this, such as electrification of households that are not yet connected to the grid and growing welfare in connected households, which leads to higher electricity demand. Efficient appliances and the thoughtful usage of electricity can be promoted or even subsidized.
- Fossil fuel power plants shall not be expanded in Kisumu as these will eventually become stranded assets. Electricity demand is increasing in the future and additional demand should be covered with renewable technologies directly.
- Kisumu isn't an island and electricity is currently traded between different parts of Kenya. In this project, the aim was to determine how much of Kisumus energy demand can be covered with local resources. Still, it might be beneficial to work together with other counties that could have better potentials for one technology (for example, geothermal and wind power plants) and where installation is more feasible than in Kisumu. Electricity can then be imported at certain times. But what should not be forgotten is that, as long as Kenya's entire energy supply is not fully based on renewables (see BAU scenario), importing electricity always means importing non-renewable electricity.

- Increasing electricity demand and expansion of PV in the rural parts of Kenya will make grid expansion necessary to prevent congestion and must be part of future planning processes for power plant expansion.

Transport sector:

- As Kisumu's vehicles are not only driving in Kisumu but to other counties or even neighboring countries, they must have the possibility to be charged somewhere else. A solely local solution in the transport sector is therefore not possible. This means that in transport sector nationwide solutions have to be found. Charging infrastructure has to be in place before electric vehicles driving longer distances can be widely applied. Therefore, the transport sector is seen as the sector where achieving 100 percent RE is fraught with the most risks
- One vehicle type that can be already used today and is not dependent on vast charging infrastructure is electric motorcycles, as they usually drive short distances and are available already today in Africa.
- One important question to be solved is about the availability of electric and hydrogen cars in Kenya and their price. Today electric and hydrogen cars are more expensive than fossil fuel driven cars and many countries have subsidies to increase their market diffusion. Also, the availability of hydrogen and electric cars on the secondhand car market is nonexistent until now, which could be a potential thread for the uptake in Kenya.
- The used projection 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 be solutions to have lower energy demand increase in the transport sector.
- The use of hydrogen in trucks and busses was seen as critical by the local stakeholders. This was justified by the fact that hydrogen cars are not widely available now and it is questionable if it is realistic that 50 % of all busses and trucks could be hydrogen vehicles in Kisumu in 2050. Biofuels cannot be produced locally in Kisumu as biomass potentials are restricted, not even covering energy for cooking demand and electricity demand in meaningful amounts. The other option would be to electrify trucks and busses fully. Whether this is realistic with these vehicle types is still discussed today, with distance driven being the main factor. But here, too, it is certain that a very good charging infrastructure will have to be in place if busses and trucks are to be 100% electric in 2050.

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 users 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 micro-credits can help people to adopt these new technologies.
- Today wood and charcoal are used by most households and institutions to cook, but deforestation is a large problem in Kisumu as well as the rest of Kenya. Therefore, it is seen as very important to stop using wood to the extent it is used today. For this reason, wood covers only a small amount of energy for cooking demand, as only sustainable wood use is assumed for the scenarios.

Fuels and heating supply in commercial and industrial sector

- During data collection process it was not possible to obtain information about heating demand in commercial and industrial sector;therefore, this heating demand could not be included in the model. One theoretical scenario was calculated assuming a certain heating demand to show the impact on the results. CHP power plants as well as electrolyzers, which produce excess heat as a by-product, are installed in nearly all scenarios, and this excess heat could be used to cover heating demands in commercial and industrial facilities. The usage of excess heat from electrolyzers and CHPs relies on spatial proximity; therefore, it is recommended to build up CHP power plants and electrolyzers close to commercial and industrial sites.
- It is recommended to collect data on commercial and industrial heating demand and use that data when planning the installation of CHPs and electrolyzers to take advantage of that synergy effect.

7 Conclusions

This study is able to show that, under the used boundary conditions, 100 percent renewable energy for Kisumu County, Kenya is possible for the following sectors: electricity, heating, cooking, as well as transport on land. The most important findings of the study are:

- 100 percent renewable energy is possible in all demand scenarios. Biogas from manure and crop residues, ethanol and sustainable wood are used fully in all scenarios and PV share of electricity production is at least 74 %, as other potentials are scarce.
- Photovoltaics is the technology with the highest electricity supply in all 100 % RE scenarios, varying from 75 % to 100 %, with levelized costs of electricity at 0.028 €/kWh (3.11 KSH/kWh). As PV supplies 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 0.039 €/kWh (4.33 KSH/kWh)
- Biogas potential is fully used, both in CHP power plants as well as biogas stoves for cooking. Biogas CHPs are the cheapest technology with low fuel price with LCOE at 0.0182 €/kWh (2.02 KSH/kWh) and LCOH at 0.0224 €/kWh (2.49 KSH/kWh), when heat from CHPs is not used costs for electricity are adding up to 0.0406 €/kWh (4.52 KSH/kWh). Waste and bagasse power plants have higher LCOE and LCOH and are not installed when not fixed in the scenario
- In the least cost scenario, no hydropower is installed but fixing hydropower in the scenario increases the costs by only 0.2 %, which can be rated as an economically equal solution. Therefore, it is recommended to install additional hydropower capacities in the future to diversify technology mix which can enhance supply security.
- The business-as-usual (BAU) scenario represents an energy system with much lower ambitions for RE deployment, with 85 % renewables for electricity supply, but only 20 % share of electric vehicles, while the rest still uses fossil fuels. The share of technologies for electricity supply comes from a national study and PV deployment lies only at 1.4 %. As PV is the cheapest electric supply technology, the BAU scenario is 32 % more expensive than the least cost scenario. At the same time, the carbon dioxide emissions are 27 times higher because of fossil fuel deployment in the transport sector.
- During the data collection process, it was not possible to obtain information about heating demand in the commercial and industrial sector and therefore heating demand could not be included in the model. One theoretical scenario was calculated assuming a certain heating demand to show the impact on the results. CHP power plants as well as electrolyzers, which produce excess heat as a byproduct, are installed in nearly all scenarios and this excess heat could be used to cover heating demands in commercial and industrial facilities. 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.

Recommendations for the transition of the energy system of Kisumu to 100 % renewables are described in section 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. 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 used decentral and therefore also help more remote areas to have access to clean, affordable, and secure electricity supply

- Fossil fuel power plants should not be expanded in Kisumu, as these are stranded assets eventually. Electricity demand is increasing in the future and additional demand should be covered with renewable technologies directly.
- Kisumu isn't an island, and electricity is traded between different parts of Kenya today. In this project, the aim was to determine how much of Kisumus energy demand can be covered with local resources. Still, it might be beneficial to work together with other counties that could have better potentials for one technology (for example, geothermal and wind power plants) and installation is more feasible there than in Kisumu. Electricity can then be imported at certain times. But what should not be forgotten is, as long as Kenya's energy supply is not fully based on renewables (see BAU scenario) importing electricity always means importing non-renewable electricity.
- As Kisumu's vehicles are not only driving in the county of Kisumu but to other counties or even neighbouring countries, they must have the possibility of being charged somewhere else. A solely local solution in the transport sector is therefore not possible. This means that in the transport sector nationwide solutions must be found. Charging infrastructure must be in place before electric vehicles driving longer distances can be widely applied. Therefore, the transport sector is seen as the sector in which achieving 100 percent RE is fraught with the most risks
- 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.

8 APPENDIX

A. Table of end energy demands today and in 2050

	Energy demand today	Energy demand base scenario 2050	Energy demand low demand scenario 2050	Energy demand high demand scenario 2050
All values in [GWh]				
cooking residential	196	321	321	321
cooking commercial	24	40	40	40
electricity demand	374	2,137	1,113	4,105
transport energy demand electric	0	1,735	1,735	1,735
transport energy demand hydrogen	0	3,499	3,499	3,499
transport energy demand fossil fuels	3,838	0	0	0
Sum	4,433	7,732	6,707	9,699

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

	End energy consumption of fuel vehicle [kWh/100 km]	End energy consumption of electric vehicle [kWh/100 km]	End 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: Hydropower fixed

	Capacity [MW]	Generation [GWh]	Generation [kt]	Full load hours [h]
PV	6,257	9,389		1,500
Hydropower	160	834		5,211
CHP Biogas crops el	239	239		1,000

CHP Biogas crops th				
CHP waste el				
CHP waste th				
Biogas stove	6.4	7		1,106
Electric stove	268	302		1,136
Wood stove	5.4	4		800
Ethanol stove	58	47		800
Electrolysis	2,673	0	105	2,050
Electrical storage	6,801			
Thermal storage	0			

Leading scenario: Least cost

	Capacity [MW]	Generation [GWh]	Generation [kt]	Full load hours [h]
PV	6,928	10,397		1,500
Hydropower	0	0		0
CHP Biogas crops el	223	223		1,000
CHP Biogas crops th	0	0		0
CHP waste el				
CHP waste th				
Biogas stove	23	26		1,097
Electric stove	251	283		1,139
Wood stove	5.4	4		800
Ethanol stove	58	47		800
Electrolysis	2,738	0	105	1,996
Electrical storage	8,905			
Thermal storage	0			

Least cost plus heating

	Capacity [MW]	Generation [GWh]	Generation [kt]	Full load hours [h]
PV	6,935	10,407		1,500
Hydropower	0	0		0
CHP Biogas crops el	215	245		1,069
CHP Biogas crops th	194	193		1,069
CHP waste el				
CHP waste th				
Biogas stove	0	0		0
Electric stove	275	309		1,131
Wood stove	5.4	43		800
Ethanol stove	58	47		800
Electrolysis	2,637	105	166	1,122
Electrical storage	9,525			
Thermal storage	0			

High demand

	Capacity [MW]	Generation [GWh]	Generation [kt]	Full load hours [h]
PV	8,343	12,519		1,500
Hydropower	43	228		5,266
CHP Biogas crops el	245	245		1,000

CHP Biogas crops th				
CHP waste el				
CHP waste th				
Biogas stove	0	0		0
Electric stove	274	309		1,136
Wood stove	5.4	43		800
Ethanol stove	58	47		800
Electrolysis	2,264		105	2,414
Electrical storage	21,025			
Thermal storage	0			

High fuel price

	Capacity [MW]	Generation [GWh]	Generation [kt]	Full load hours [h]
PV	6,928	10,397		1,500
Hydropower	0	0		0
CHP Biogas crops el	223	223		1,000
CHP Biogas crops th				
CHP waste el				
CHP waste th				
Biogas stove	23	26		1,097
Electric stove	250	283		1,139
Wood stove	5.4	43		800
Ethanol stove	58	47		800
Electrolysis	2,738		105	1,996
Electrical storage	8,905			
Thermal storage	0			

Hydro and biomass fixed

	Capacity [MW]	Generation [GWh]	Generation [kt]	Full load hours [h]
PV	4,970	7,458		1,500
Hydropower	160	850		5,312
CHP Biogas crops el	94	94		1,000
CHP Biogas crops th				
CHP waste el	203	1,616		7,960
CHP waste th				
Biogas stove	158	173		1,095
Electric stove	116	136		1,182
Wood stove	5.4	43		800
Ethanol stove	58	47		800
Electrolysis	2,453		105	2,228
Electrical storage	3,188			
Thermal storage	0			

Low demand

	Capacity [MW]	Generation [GWh]	Generation [kt]	Full load hours [h]
PV	5,920	8,883		1,500
Hydropower	0	0		0
CHP Biogas crops el	0	0		0
CHP Biogas crops th				
CHP waste el				

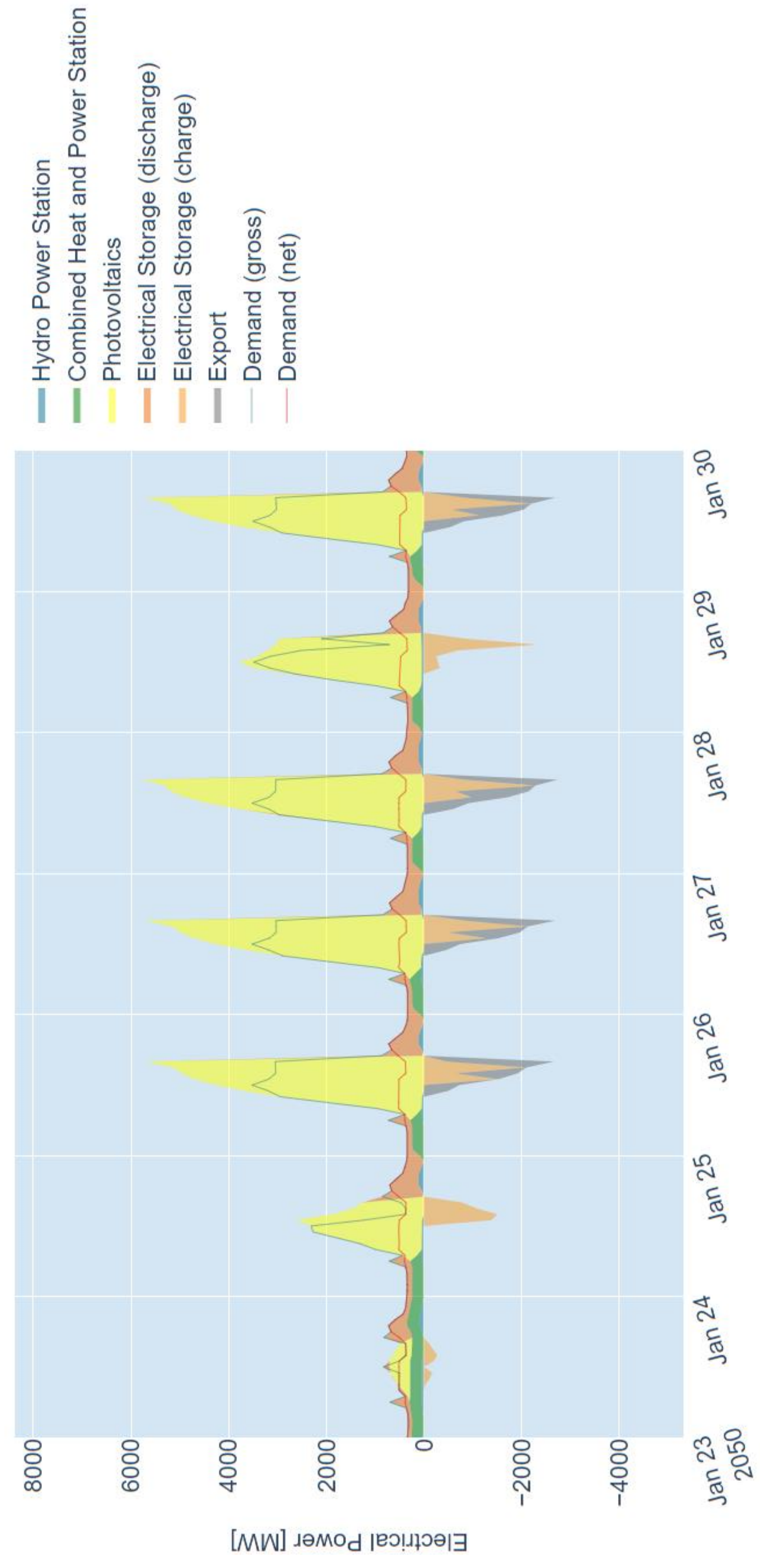
CHP waste th				
Biogas stove	253	279		1,104
Electric stove	21	296		1,451
Wood stove	5.4	43		800
Ethanol stove	58	47		800
Electrolysis	2,041		105	2,678
Electrical storage	12,730			
Thermal storage	0			

Business-as-usual

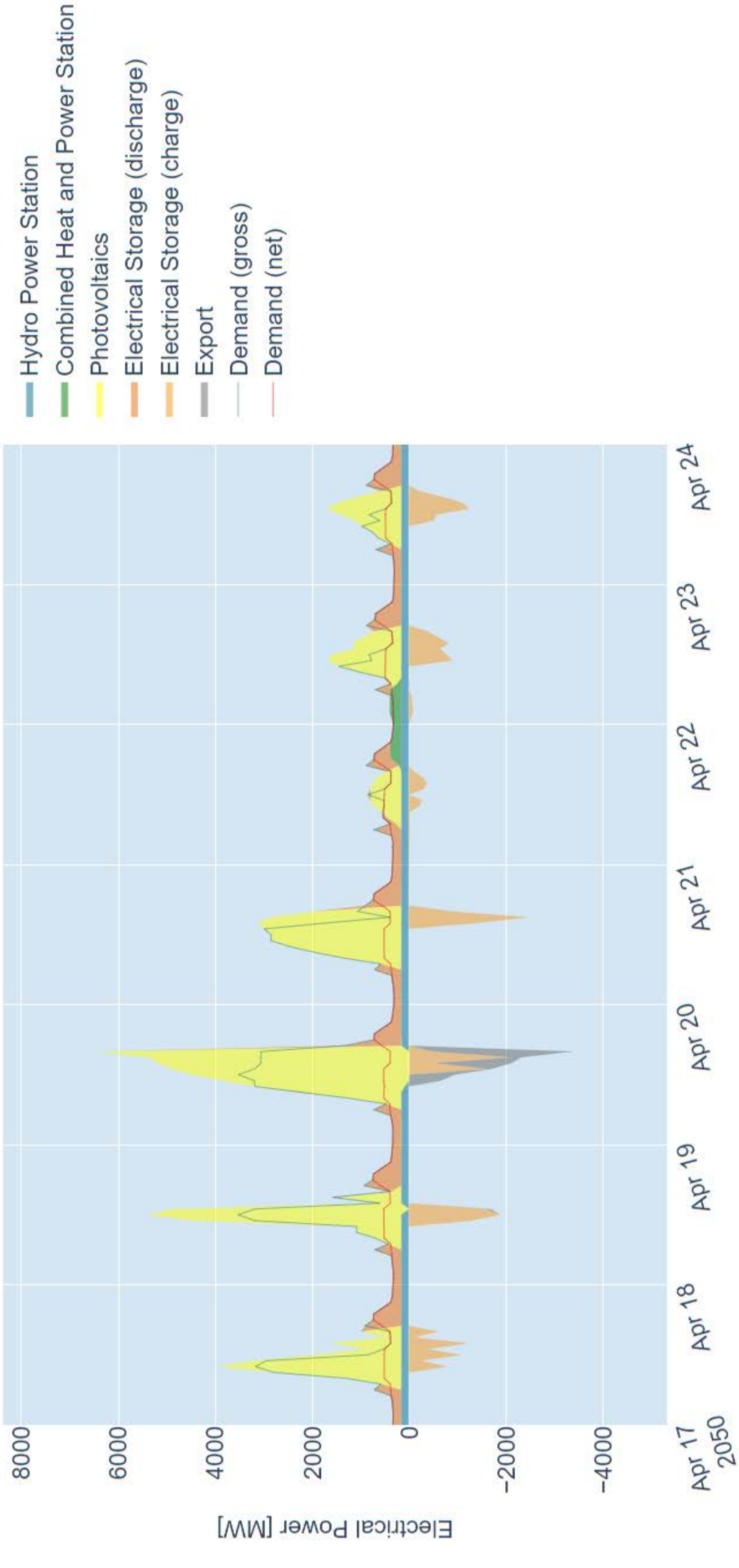
	Capacity [MW]	Genera-tion [GWh]	Genera-tion [kt]	Full load hours [h]
PV	25	38		1,500
Wind power	84	199		2,385
Hydropower	98	503		5,117
Geothermal	240	1,681		7,000
Coal power plant	25	199		8,000
Gas power plant	28	228		8,000
Biogas stove	247	280		1,135
Electric stove	70	76		1,102
Wood stove	4	43		1,095
Ethanol stove	0	0		0
Electrolysis	0	0	0	0
Electrical storage	0			
Thermal storage	0			

D. Time series of the leading scenarios in high resolution

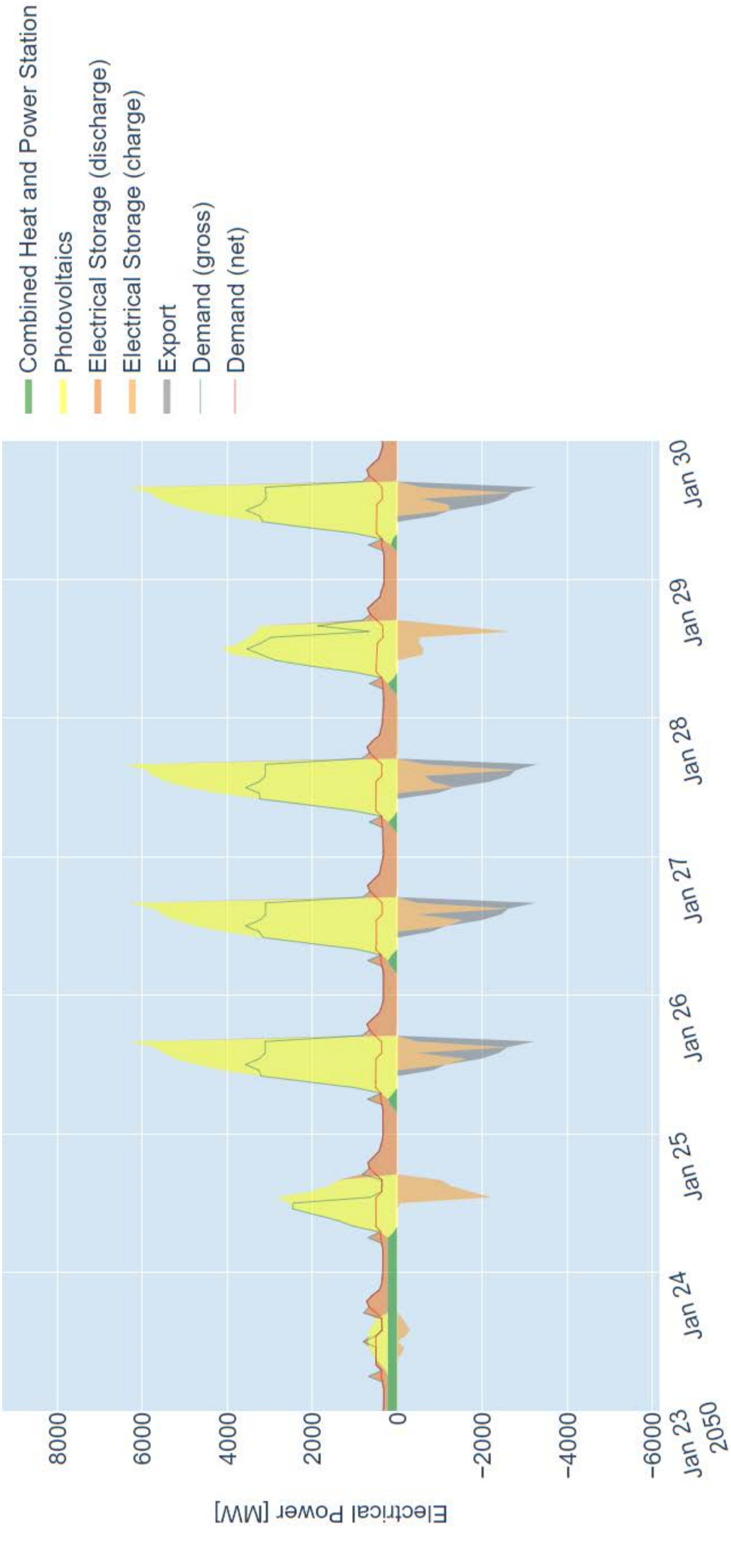
Hydropower fixed – week in January



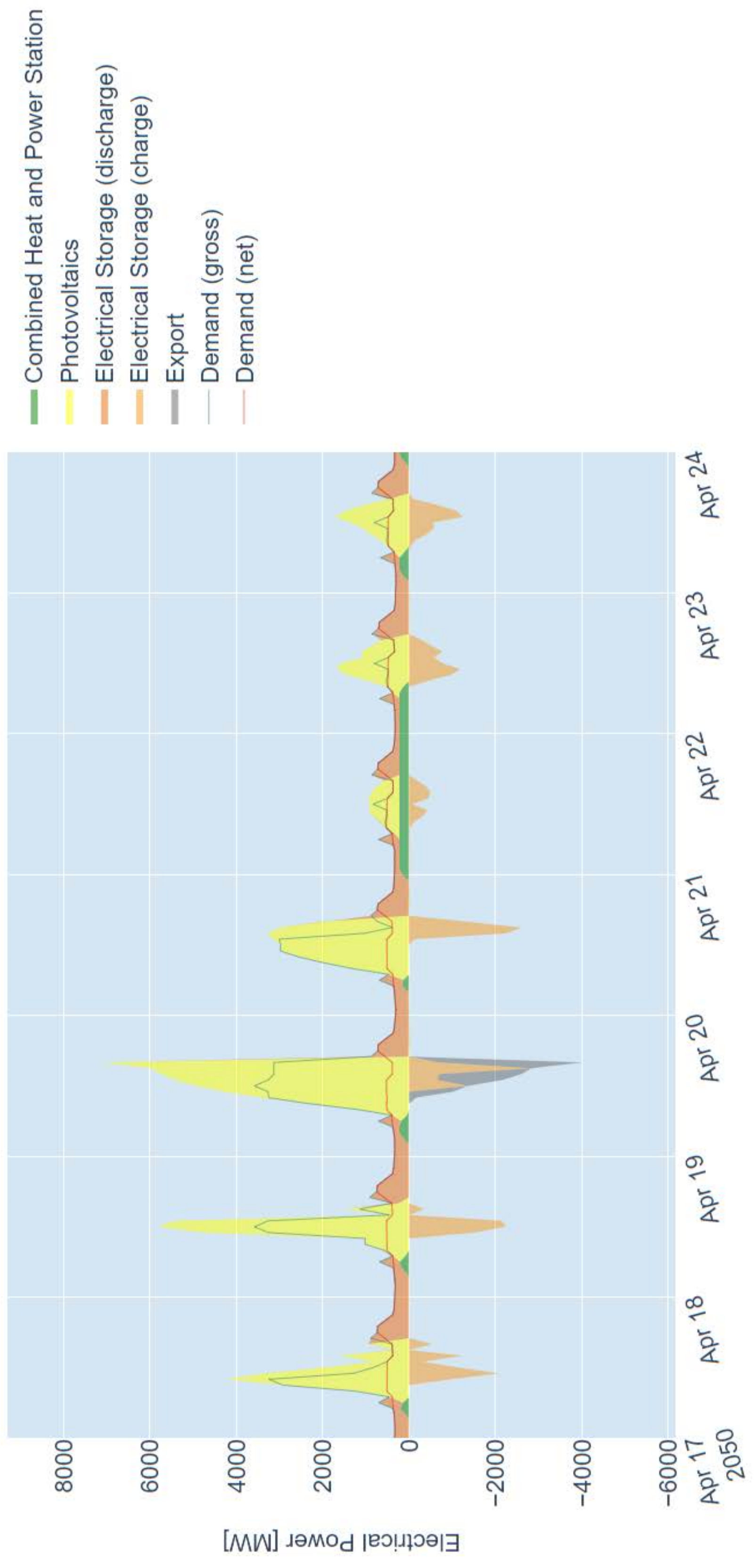
Hydropower fixed – week in April



Least cost – week in January



Least cost – week in April



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