UTS Institute for Sustainable Futures

Rwanda:
Energy Development Plan to decarbonize the Economy

prepared for Power Shift Africa

REPORT FOR PUBLIC CONSULTATION

by The University Technology Sydney
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The Institute for Sustainable Futures (ISF) was established by the University of Technology Sydney in 1996 to work with industry, government and the community to develop sustainable futures through research and consultancy. Our mission is to create change toward sustainable futures that protect and enhance the environment, human wellbeing and social equity. We seek to adopt an inter-disciplinary approach to our work and engage our partner organisations in a collaborative process that emphasises strategic decision-making.

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The energy scenario software for the long-term projections and economic parameters is based on the development of the German Aerospace Centre (DLR), Institute for Technical Thermodynamics, Pfaffenwaldring 38-40, 70569 Stuttgart/Germany and applied to over 100 energy scenario simulations for global, regional and national energy analysis.

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All conclusions and any errors that remain are the authors own.

DISCLAIMER

The authors have used all due care and skill to ensure the material is accurate as at the date of this report. UTS and the authors do not accept any responsibility for any loss that may arise by anyone relying upon its contents.

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Report for Public Consultation

The energy report ***'Rwanda: Energy Development Plan to decarbonize the Economy'*** is the preliminary result of a joint research by ***Power Shift Africa*** and the ***University of Technology Sydney – Institute for Sustainable Futures*** conducted between January and November 2023.

The task was to develop comprehensive energy scenarios for Rwanda which challenges the current government and private sector plan and provides new scientific input for future policies.

A focus of this work lies on the development of a 100% Renewable Energy Pathways to provide data for future National Determined Contribution (NDC) report for the UNFCCC.

The 100% Renewable Energy pathways are developed as robust, reliable and cost-effective energy plans and based on GIS based renewable energy potential analysis for solar and wind energy, hourly simulation to determine a high-level analysis of the required storage and grid expansion requirements.

The energy pathways aim to phase-out energy-related CO_2 emissions as fast as possible while implementing fast and ambitious energy access programs.

The energy demand analysis is based on the following assumptions:

1. Economic growth to facilitate high enough to develop towards a middle-income country
2. Increase energy demand for services and industries
3. Increased decarbonized transport sector
4. Access to reliable and affordable energy services for all households to achieve OECD household standards by 2050.

This report provides a detailed technical documentation of the energy scenario development and is part of the global 'One Earth Climate Model research program under leadership of the University of Technology Sydney – Institute for Sustainable Futures. Further details about the One Earth Climate Model are available at www.uts.edu.au/OECM

PSA's mission is to mobilize climate action in Africa, amplify African voices through increased visibility in media and public communications, and leveraging this voice internationally. As part of our work, PSA is helping to build dedicated platforms of African civil society organizations, technical experts and high-level leadership that will engage collectively to ensure a transformative, Africa-led efforts to accelerate and scale-up the harnessing of the continent's huge renewable energy potential. We seek to promote and support Africa to meet its short and long-term targets to achieve the 1.5C target through a just transition to 100% renewable energy.

This report is for PUBLIC CONSULTATION – feedback and comments are welcome.

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Introduction

This report focuses on the development of a 100% Renewable Energy Pathway for Rwanda. Here, the 100% Renewable Energy pathways is constructed with the aim to be robust and to proof the technical and financial feasibility. In addition, the 100% Renewable Energy pathways will be a clear demonstration of security of supply for Rwanda's industry, transport and residential sectors.

The scenarios for the energy pathways do not claim to predict the future, but provide a useful tool with which to describe and compare potential development pathways from the broad range of possible 'futures.' The Rwanda 1.5 °C (R-1.5°C) scenario is designed to calculate the efforts and actions required to achieve the ambitious objective of a 100% renewable energy system and to illustrate the options available to change the Rwanda's energy supply system into a truly sustainable one. It may serve as a reliable basis for further analyses of the possible ideas and actions required to implement pathways to achieve the desired results.

100% renewable energy scenarios for electricity generation, energy demand, energy supply, and transport are included. The investments required to achieve these scenarios and the policies that will enable them are described for the specific scenarios.

Finally, the report includes simulations of the national grid capacity required now and, in the future, and the necessary linkages between different parts of the country's power grid. The simulations support the assessment of the grid expansion requirements, the power-trade balance, and the investments required to strengthen the backbone of Rwanda's electricity infrastructure to ensure its reliability and resilience.

In this report, we aim to inform policymakers, researchers, and practitioners of the extent of the intervention required for Rwanda to reach its target of 100% renewable energy by 2050. The decade-by-decade scenarios can inform important milestones that will allow further sector-wise energy-related targets to be defined and tracked.

1 Research Scope

Since 2017, the University of Technology Sydney–Institute of Sustainable Future (UTS-ISF) has undertaken detailed country-specific energy analyses (see reference list), ranging from the global south, including Tanzania, to industrialized countries, including all the G20 countries and Switzerland.

All UTS-ISF energy analyses include the following aspects:

- A renewable energy resource analysis based on spatial GIS data under constrained land availability conditions (excluding protected areas, areas with a steep slope, and certain land-cover classes, such as closed forests, wetlands, snow and ice, and permanent water).
- The development of the future energy demands for 2025, 2030, 2035, 2040, 2045, and 2050, based on the latest available statistics—base year for energy demand is 2019 —broken down into the main energy sectors (power, buildings, industry, and transport).
- The sectorial energy demand (see above) is broken down to the level of provinces.
- The development of the following scenario:
    - 1.5 °C scenario[1]—100% renewable energy plan to decarbonize the energy sector by 2050 within the carbon budget required to achieve a temperature rise of 1.5 °C with 66% certainty (based on IPCC AR6, 2021).
    - Compared to Reference scenario.
- These scenarios are combined with renewable energy scenarios with different variable power generation shares (solar photovoltaic [PV], wind, bioenergy, and hydropower).
- Based on the different power demand-and-supply scenarios, a projection of the required load from industry, commercial, and residential demands is compared with the available power generation capacity —to stress-test the security of supply.
- The power generation capacity is simulated at 1-hour resolution for seven provinces with regional long-term average meteorological data for solar and onshore wind.
- Current and future required national grid capacities are simulated, together with the required linkages between different parts of the country's national power grid and import/export transactions with neighbouring countries.

This simulation is particularly important regarding the role of 24/7 power generation and power flows between regions and neighbouring countries. Included are the:

- Grid expansion and storage requirements.
- Visualization of the hourly demand and supply curves;
- Carbon emissions (annual and cumulative);
- Investment required in additional power generation capacity—including fuel costs and fuel cost savings, and operation and maintenance costs for all power generation capacities;
- The power sector trade balance (electricity and fuel) with neighbouring countries.
- A cost comparison of all scenarios.

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[1] 1.5 °C scenario: Series of scenarios with total global carbon budget of 400 $GtCO_2$ to limit the global mean temperature rise to a maximum of 1.5 °C with 67% likelihood, as defined in IPCC AR6.

2 Scenario Assumptions

2.1 RWANDA: COUNTRY OVERVIEW

Rwanda is a small land-locked country of 26,338 km^2 in area with a population of 13.2 million people, (NISR 2022[2]). It is a densely populated country in comparison to other African countries. In 2022, Rwanda's GDP was USD 13.31 billion (Worldbank 2023)[3], 2,365 USD per capita. Since 2000, Rwanda's per capita GDP grew around 5% on average. After a COVID related GDP decrease by 5.7% in 2020, the economy recovered with a growth rate of 8.3% in 2021 and 5.7% in 2022.

2.1.1 POLITICAL CONTEXT

The latest energy policy document available was published in 2015, at a time when Rwanda's per capita GDP was at 643 USD, 70% lower than today. This research aims to support Rwanda's energy policy debate and the further development of the Economic Development and Poverty Reduction Strategy (EDPRS II) published in the same year.

According to the Rwanda Energy Policy 2015 document published by the Ministry of Infrastructure of the Republic of Rwanda on the 17th March 2015[4], the energy policy '*is founded upon three essential government principles:*

I. A resolve for transparent and effective sector governance

ii. Easing doing business and reducing barriers to private investment.

iii. Enhancing institutional, organizational, and human capacities as well as the legal and regulatory framework.

The Energy Policy and the Energy Sector Strategic Plan (ESSP) are mutually reinforcing. Whereas the policy outlines a long-term vision, provides high-level goals, and recommends clear and coordinated approaches for achieving that vision, the ESSP outlines targets and an implementation framework against which to measure progress towards the realization of the policy. In this way, the policy can guide the actualization of aligned implementation strategies, while the ESSP outlines the priority strategies and actions that give practical thrust to the policy.' (…)

The policy needs to address the following critical sector challenges:

i. Energy security and a sound demand-supply balance.

ii. Dramatic increase in access to modern energy services.

iii. Improvement and streamlining of stakeholder coordination to ensure effective partnership and delivery on set targets;

iv. Need for a robust legal and regulatory framework required.

v. Necessity for an institutional, organizational, and human capacity development.

vi. Inadequate infrastructure requiring huge investment.

vii. High cost of fuel for electricity generation.

viii. Vulnerability to climate change.

In addition, the development of relevant policies for the energy sector mandates that, the key issues that affect the supply and demand of energy in Rwanda be delineated. Broad issues of the energy sector in Rwanda include the following:

I. Inadequate co-ordination and information sharing between/or among the various projects, government bodies, the private sector and civil society organizations.

ii. Lack of investment.

iii. Inadequate energy planning information system (energy supply and demand analysis);

iv. Lower rate of access to modern energy.

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[2] National Institute of Statistics of Rwanda (NISR), GPD National Accounts 2022 (https://www.statistics.gov.rw/publication/1914)

[3] Worldbank online database, data in current US$, assessed November 2023, https://data.worldbank.org/indicator/NY.GDP.PCAP.PP.KD?locations=RW

[4] Rwanda Energy Policy, Ministry of Infrastructure, Republic of Rwanda, 17th March 2015, https://rura.rw/fileadmin/Documents/Energy/RegulationsGuidelines/Rwanda_Energy_Policy.pdf

v. Inadequate financial resources to plan for and monitor the energy sector and carry out appropriate research and development (R&D);

vi. Lack for appropriate curricula in energy studies at many institutions of higher learning.

vii. Inadequate human resource and institutional capacity.

For each of the energy-sub sectors there are specific issues to consider, which are given below. The various energy sub-sectors include the following:

- *Electricity;*
- *Petroleum;*
- *Biomass;*
- *Energy Efficiency and Demand Side Management*

This research aims to provide detailed new information about Rwanda's future energy demand in the residential and industry sector as well as transport. Furthermore, a renewable energy resource assessment has been added. Therefore, this research adds another energy subsector: **'Renewables'.**

While the Energy Policy 2025 document is based on forms of energy production, this report suggests using a division into consumption sectors:

- Residential sector
- Services and Industry
- Transport

2.1.2 POPULATION DEVELOPMENT

In comparison with neighbouring countries, such as Kenya and Tanzania, Rwanda is considered to be a small country in terms of land area with 26,338km^2 , consisting of five provinces. The Fifth Rwanda Population and Housing Census (RPHC5) reported that Rwanda's population was 13,246,394 as of August 2022, indicating a 2.3% growth from 2012. The population density of the country is 503 (National Institute of Statistics of Rwanda, 2023)[5].

Figure 1: Rwanda

Source: GIS Geography

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[5] National Institute of Statistics of Rwanda, 5th Population and housing Census, Rwanda, 2022, https://www.statistics.gov.rw/publication/main_indicators_2022

2.1.3 ECONOMIC CONTEXT

Rwanda faces significant vulnerabilities in achieving inclusive and sustainable growth.[6] The global disruptions caused by the COVID-19 pandemic have been compounded by structural constraints for Africa, such as slow domestic job creation, high vulnerability to natural disasters, climate change, environmental degradation, and large infrastructure gaps. Furthermore, the pandemic has triggered a surge in debt levels, which must be addressed. However, strong economic growth is assumed for the development of the energy scenario. The future energy supply is seen as a perquisite for strong economic growth in the future. This research aims to find the most cost effective and sustainable energy sector to provide stable and affordable energy supply.

Population and economic development projections until 2050

The population and gross domestic product (GDP) shown in Table 2 are based on projections of the Rwanda's Government, which have been used for the NDC and the long-term energy plan. The GDP values – both in total as well as per capita – are in US Dollar values of the year 2015 to harmonize values of different databases. Thus, the values in Table 1 differ from the values in section 2.1 which are in current US Dollar values.

Table 1: Rwanda's population and GDP projections until 2050 – USD in values based on 2015 – not current US$ value)

Rwanda	Units	2021	2025	2030	2035	2040	2045	2050
Population	[individuals]	13,464,539	14,519,600	16,375,704	18,040,220	19,724,007	21,391,577	23,030,046
Population Growth	[%/a]	2.4%	2.2%	2.0%	1.9%	1.7%	1.6%	1.5%
GDP (US$ 2015)	[US$ billion]	11.99	15.74	21.06	28.18	35.63	42.11	47.41
GDP Growth	[%/a]	9.46%	6.00%	6.00%	6.00%	4.00%	3.00%	2.00%
GDP/Person (calculated)	[US$/capita]	903	1211	1621	2174	2757	3276	3715

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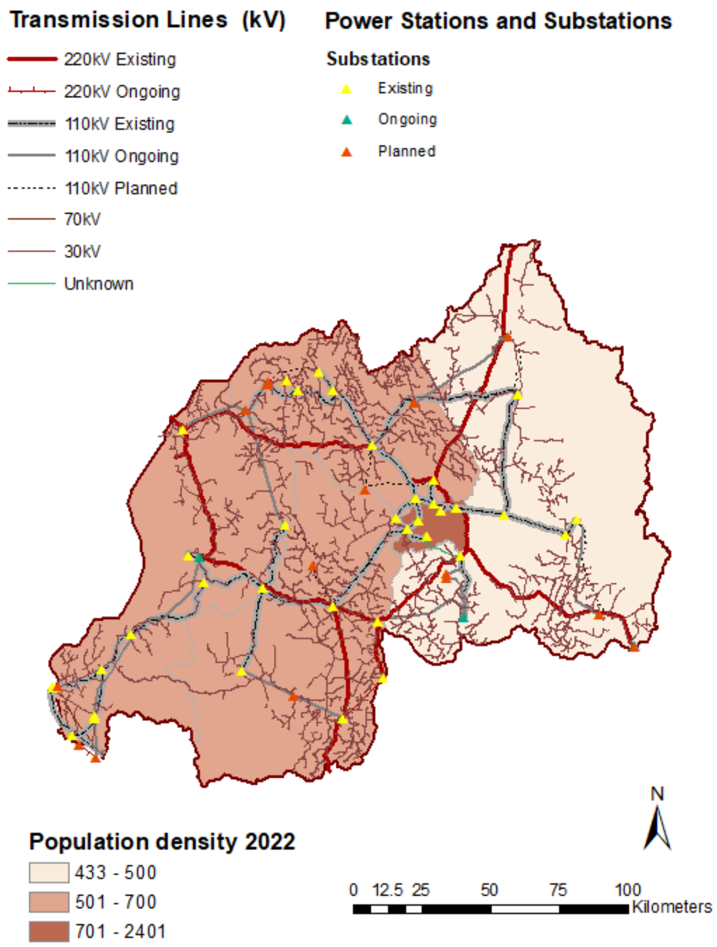
[6] World Bank 2022, Country Overview Rwanda, database from 2022.

2.2 ELECTRICITY INFRASTRUCTURE AND ENERGY ACCESS

For this analysis, Rwanda's power sector is modelled on the national level and not divided into regions. However, regional distribution of the population and the availability of the energy infrastructure correlate with the socio-economic situation in all regions. The following map provides an overview of the locations of power lines and power plants, a regional breakdown of energy pathways, and a power sector analysis (Chapter 6).



Source: Substations and transmission lines — Electric network operation facility dashboard

Figure 2: Distribution of population and the existing electricity infrastructure in Rwanda

Figure 2 also shows the population density of Rwanda. The highest population concentrations are shown in dark red and the lowest in white. The map clearly shows the high population densities in the metropolitan areas of Kigali. The existing constructed electricity infrastructure (power lines, power plants, and sub-stations), with their different types of grids, are shown as lines, and the differently coloured dots mark grid-connected power plants—each colour represents a specific technology, identified in the legend. The lines represent power transmission lines with different voltage levels. The figure visualizes the distribution of the grid, power plants, and population density, but does not claim to be complete.

Electricity access

According to the Rwanda Energy Group, 'as of end September 2023, the cumulative connectivity rate in Rwanda is 74.40% of Rwandan households including 54.19% connected to the national grid and 20.21% accessing through off-grid systems (mainly solar). During the elaboration of the EDPRS II, the Government of Rwanda took a clear policy decision to diversify the sources of electricity from traditional dominant grid to include even off-grid connections. Subsequently, Households far away from the planned national grid coverage have been encouraged to use alternatively cheaper connections such as Mini-grids and Solar Photovoltaics (PVs) to reduce the cost of access to electricity whilst relieving constraints on historical government subsidies' (REG 2023)[7].

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[7] Rwanda Energy Group, online information assessed in November 2023, https://www.reg.rw/what-we-do/access/

2.3 ENERGY DEMAND—DEVELOPMENT SINCE 2005

It is necessary to analyse the development of the past energy demand in order to project that of the future. Therefore, the statistical data for Rwanda's energy demand between 2005 and 2019 have been analysed (IEA 2022)[8].

Figure 3 shows Rwanda's final energy demand development between 2005 and 2019. The overall energy demand grew constantly, despite years of reduced demand due to reduced economic activity. The gross final energy demand has grown by about 32% since 2005 to around 107 petajoules per annum (PJ/a). The main energy demand is required in the residential sector, whereas only 7% of the energy is for industry use and 8% for the transport sector.

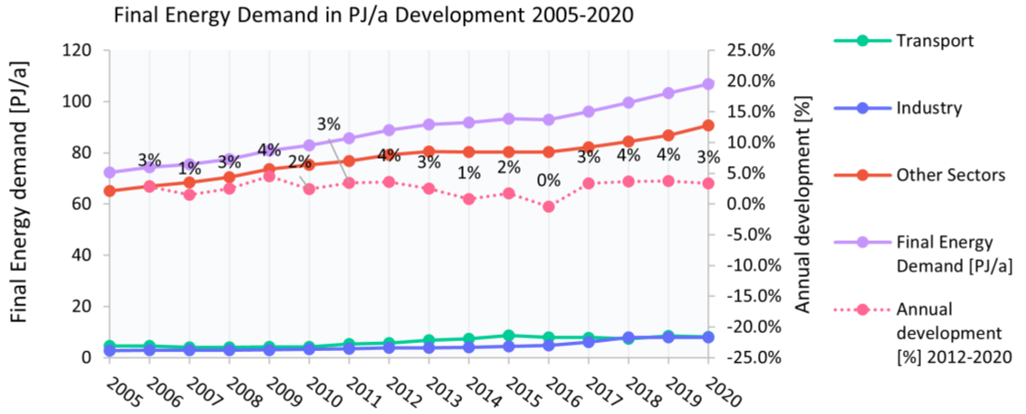

Figure 3: Final energy demand development in Rwanda from 2005 to 2019

The electricity demand has increased significantly faster than the final energy demand. By 2019, the annual electricity demand was close to 1 billion kilowatt-hours (1 TWh/a), up from 0.2 TWh/a in 2005 (Figure 4), growing by a factor of 3. Again, the residential sector grew fastest, followed by the industry sector, and the electricity demand for transport was almost negligible. However, with the increased electrification of vehicles, the electricity demand for transport is expected to rise significantly.

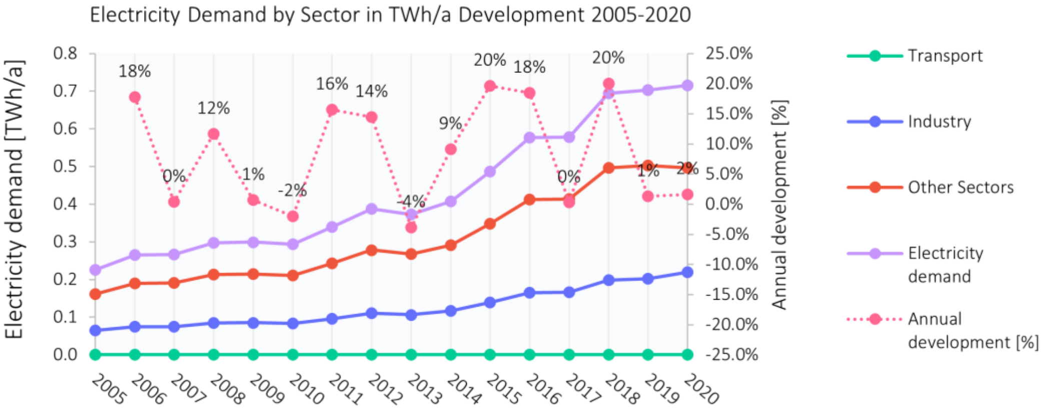

Figure 4: Electricity demand development in Rwanda from 2005 to 2020

However, Rwanda's electricity demand is currently 55 kWh per capita, one of the lowest in the world (IBN 2011), where the global average consumption is 2,500 kWh per annum (World Bank 2019)[9].

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[8] IEA 2022, Advanced World Energy Balances, Rwanda.

[9] World Bank Database 2019, https://data.worldbank.org/indicator/EG.USE.ELEC.KH.PC?locations=IN-PK-BD-LK-NP-AF&name_desc=true

2.3.1 ENERGY SUPPLY

The primary energy supply is dominated by biomass (over 98 %), used mainly for cooking and heating, as shown in Table 2, whereas electricity is almost entirely supplied by Hydro energy (53 %). If the primary energy supply continues according to its development over the past 5 years (by 2% annually), the primary energy demand will increase by almost 60% to 290 PJ/a by 2050.

Table 2: Rwanda's primary energy supply between 2005 and 2019 (IEA World Energy Balances 2021)

Primary Supply -	Units	2005	2006	2007	2008	2009	2010	2011	2012	2013	2014	2015	2016	2017	2018	2019	2020
Annual development		3%	2%	2%	5%	3%	2%	3%	3%	3%	2%	1%	3%	3%	3%	2%	3%
Primary energy	[PJ/a]	127	131	133	136	142	146	149	154	157	161	165	166	172	178	183	187
Net Export (–) /Import (+)	[PJ/a]	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Fossil fuels	[PJ/a]	10	10	9	9	10	11	11	12	13	14	16	16	17	19	20	18
Coal	[PJ/a]	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Lignite	[PJ/a]	0	0	0	0	0	0	0	0	0	0	0	1	1	1	1	1
Oil	[PJ/a]	10	10	9	9	10	11	11	12	13	14	15	15	15	16	17	15
Gas	[PJ/a]	0	0	0	0	0	0	0	0	0	0	0	1	1	2	2	2
Nuclear	[PJ/a]	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Conventional Renewables	[PJ/a]	117	121	124	127	132	135	138	142	145	147	148	150	153	157	162	167
Hydro	[PJ/a]	0	0	0	1	1	0	1	1	1	1	1	1	1	1	1	2
Wind	[PJ/a]	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Solar	[PJ/a]	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Biomass	[PJ/a]	117	120	123	127	132	135	138	142	144	146	147	149	152	156	160	166
Geothermal	[PJ/a]	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Ocean energy	[PJ/a]	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Conventional Renewables Share:	[%]	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%
New Renewables Share	[%]	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%

(A) Solar is not zero because it is used in various on- and off-grid applications. However, the overall energy generation is < 0.1 PJ/a

Definition of renewable energy

The Intergovernmental Panel on Climate Change (IPCC) is the leading international body assessing climate change. In its Special Report on Renewable Energy Sources and Climate Change Mitigation,[10] the IPCC defines the term 'renewable energy' as follows:

'RE is any form of energy from solar, geophysical, or biological sources that is replenished by natural processes at a rate that equals or exceeds its rate of use. RE is obtained from the continuing or repetitive flows of energy occurring in the natural environment and includes resources such as biomass, solar energy, geothermal heat, hydropower, tide and waves, ocean thermal energy and wind energy. However, it is possible to utilize biomass at a greater rate than it can grow or to draw heat from a geothermal field at a faster rate than heat flows can replenish it. On the other hand, the rate of utilization of direct solar energy has no bearing on the rate at which it reaches the Earth. Fossil fuels (coal, oil, natural gas) do not fall under this definition, as they are not replenished within a time frame that is short relative to their rate of utilization.'

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[10] Arvizu, D., T. Bruckner, H. Chum, O. Edenhofer, S. Estefen, A. Faaij, M. Fischedick, G. Hansen, G. Hiriart, O. Hohmeyer, K. G. T. Hollands, J. Huckerby, S. Kadner, Å. Killingtveit, A. Kumar, A. Lewis, O. Lucon, P. Matschoss, L. Maurice, M. Mirza, C. Mitchell, W. Moomaw, J. Moreira, L. J. Nilsson, J. Nyboer, R. Pichs-Madruga, J. Sathaye, J. Sawin, R. Schaeffer, T. Schei, S. Schlömer, K. Seyboth, R. Sims, G. Sinden, Y. Sokona, C. von Stechow, J. Steckel, A. Verbruggen, R. Wiser, F. Yamba, T. Zwickel, 2011: Technical Summary. In IPCC Special Report on Renewable Energy Sources and Climate Change Mitigation [O. Edenhofer, R. Pichs-Madruga, Y. Sokona, K. Seyboth, P. Matschoss, S. Kadner, T. Zwickel, P. Eickemeier, G. Hansen, S. Schlömer, C. von Stechow (eds), Cambridge University Press, Cambridge, UK and New York, NY, USA.

2.4 DEVELOPMENT OF THE RESIDENTIAL ENERGY DEMAND

To develop a projection for the residential electricity demand in Rwanda over the coming 30 years to achieve the Rwanda 1.5 °C (R-1.5°C) scenario, a bottom-up electricity demand analysis was performed.
The R-1.5°C aims to increase the access to energy—especially electricity—for all by 2050, while increasing the electrification and comfort standards to the levels of OECD countries. The growing economy requires a reliable power supply for small and medium businesses, industry, and the transport sector. It is assumed that households will use modern energy-efficient applications, according to the highest efficiency standards, to slow the growth of the power demand and to allow the parallel expansion of the energy infrastructure and the construction of renewable power plants. Electrification will be organized from the 'bottom up' in a new and innovative approach developed by UTS-ISF.

2.4.1 DISTRIBUTION OF HOUSEHOLDS BY HABITAT

The first step to develop a household energy demand projection of the coming 3 decades is to evaluate the current situation in the country. Rwanda's Fifth Rwanda Population and Housing Census of 2022 provides a detailed database[11].

Table 3: Distribution (%) of the private households by type of habitat and District (The Fifth Rwanda Population and Housing Census)

Province/District	Total	Umudugudu (Planned rural settlement)	Integrated Model Village	Old settlement	Dispersed / Isolated housing	Modern planned urban housing	Spontaneous /squatter housing	Other type of housing
Rwanda	**100**	**65.4**	**0.8**	**2.3**	**14.9**	**6.9**	**8.9**	**0.8**
City of Kigali	**100**	**3.8**	**1.2**	**2.8**	**8**	**42.4**	**40.1**	**1.7**
Nyarugenge	100	2.8	0.9	2.3	11.3	28.3	53.2	1.1
Gasabo	100	5.9	1	2.7	10.2	37.7	41.1	1.4
Kicukiro	100	0.8	1.6	3.4	1.5	61.8	28.4	2.5
Southern Province	**100**	**72.3**	**1**	**1.3**	**20.2**	**0.7**	**3.7**	**0.9**
Nyanza	100	70.3	0.5	1.1	23.3	0.6	3.5	0.7
Gisagara	100	77.3	1.1	1.2	17.7	0.1	0.8	1.8
Nyaruguru	100	82.7	1.2	0.7	13.8	0	1.1	0.5
Huye	100	82	1.6	1	11.6	0.6	2.8	0.4
Nyamagabe	100	69.2	0.4	0.7	26.2	0.1	1.5	2
Ruhango	100	61.2	0.7	2.8	31.6	0.1	3.4	0.4
Muhanga	100	67.5	1.2	1.3	14.3	0.7	14.3	0.6
Kamonyi	100	70.3	1.1	1.3	21.9	2.4	2.4	0.6
Western Province	**100**	**70.5**	**0.9**	**3.7**	**18.3**	**1.2**	**4.6**	**0.8**
Karongi	100	56.9	1.4	1.4	33.2	0.2	3.6	3.3
Rutsiro	100	80.5	0.5	2.2	15.1	0	1.2	0.4
Rubavu	100	70.7	0.5	6.7	4.9	5.4	11.5	0.3
Nyabihu	100	61.8	0.9	13.6	18.1	0	5.5	0.1
Ngororero	100	60.4	0.8	1.9	33.3	0.1	2.6	0.8
Rusizi	100	85.4	1.1	0.7	7.4	0.7	4.6	0.1
Nyamasheke	100	74.5	1.3	0.5	22.2	0	1	0.5
Northern Province	**100**	**70.5**	**0.6**	**1.7**	**22.3**	**0.5**	**4.1**	**0.3**
Rulindo	100	52.8	0.9	0.9	40.2	0.4	4.4	0.4
Gakenke	100	85.5	0.5	0.3	13.1	0.1	0.3	0.2
Musanze	100	76.4	0.7	4	7.7	1.6	9.3	0.2
Burera	100	83.9	0.6	2.2	12.1	0	1	0.2
Gicumbi	100	54.8	0.4	0.5	39.6	0.3	4	0.4
Eastern Province	**100**	**86.5**	**0.5**	**2.2**	**7.4**	**0.7**	**2**	**0.6**
Rwamagana	100	82.8	0.7	0.9	10.9	1.9	2.3	0.5
Nyagatare	100	84.4	0.3	1.7	10.5	0.3	2.3	0.5
Gatsibo	100	80.5	0.5	1	13.8	0.1	2.6	1.5
Kayonza	100	91.8	0.4	0.7	5.4	0.4	0.8	0.5
Kirehe	100	87.8	0.4	9.7	1	0.3	0.1	0.5
Ngoma	100	96.3	0.5	0.2	2.1	0.1	0.7	0.1
Bugesera	100	85.6	1	1.6	5.4	1.7	4.2	0.6

2.4.2 HOUSEHOLD ELECTRICITY DEMAND

The current and future developments of the electricity demand for Rwanda's households were analysed from the second half of 2023 onwards under the leadership of the Power Shift Africa. The future development of the household demand

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[11] Fifth Rwanda Population and Housing Census, Main Indicators Report, Ministry of Finance and Economic Planning, National Institute of Statistics of Rwanda, February 2023, https://statistics.gov.rw/file/13787/download?token=gjjLyRXT

has been discussed in a multiple-stakeholder dialogue with representatives from Rwanda’s academia, civil society, and government.

Table 4 shows the electricity demand and the electrical appliances used by households in Rwanda in 2020 and the projected ‘*phases*’, with increased demand in the case of increased electrification. It is assumed that households with an annual consumption indicated under the household type in ‘phase 1’ will increase their demand to ‘phase 2’ or ‘phase 3’ values over time. There are currently three household types, separated according to their annual electricity demand: rural households, which have an average annual electricity demand of just under 340 kWh; semi-rural households, which consume around 500 kWh per year; and urban households, with an annual consumption of 840 kWh.

The electricity demand will gradually increase as the electric applications for each of the three household types progress from those households with very basic needs, such as light and mobile phone charging, to a household standard equivalent to that of industrialized countries. The different levels of electrification and the utilization of appliances are described with the affixes ‘phase 1’, ‘phase 2’, and ‘phase 3’ for rural households. In contrast, semi-urban and urban households have two groups: one for the basic level and one for the more-advanced stage of electrification. The households will develop over time, from the basic group towards the more advanced group.

The third phase of a rural household includes an electric oven, refrigerator, washing machine, air-conditioning, and entertainment technologies, and aims to provide the same level of comfort as households in urban areas in industrialized countries. Adjustments will be made to the levels of comfort in households in city and rural areas to prevent residents—especially young people—from leaving their home regions and moving to big cities. The phase-out of unsustainable biomass and liquefied pressurized gas (LPG) for cooking is particularly important in decarbonizing Rwanda’s household energy supply. A staged transition towards electrical cooking is assumed (see Section 2.1.8.2).

Table 4: Household types used in all scenarios and their assumed annual electricity demands

		Rwanda—Annual household electricity demands	
Household Type	Group		Annual electricity demand
			[kWh/a]
Rural	Phase 1	- Very-low-income rural household - Low-income rural household	337
	Phase 2	- Lower-middle-income rural household	1021
	Phase 3	- Upper-middle-income rural household	2210
Semi-Urban	Basic	- Low-to-middle-income semi-urban household	501
	Advanced	- Middle-income semi-urban household	1763
Urban - Apartment	Basic	- Low-to-middle-income urban household (apartment)	836
	Advanced	- Middle-income urban household (apartment)	2422
Urban House	Basic	- Middle-income urban household (house)	2405
	Advanced	- Middle-to-high-income urban household (house)	2477

The typical household electricity demands are compared with:

i) Regional countries in South Asia: India, Sri Lanka, Pakistan, and Bhutan;
ii) Example of an OECD country. The authors have chosen Switzerland for its well-documented electricity demands and good representation of energy-efficient but highly electrified households among the OECD countries.

OECD household: Switzerland

Table 5 shows an example of the electricity demands of different household types in the OECD country of Switzerland. The example of Switzerland was chosen because of its well-documented electricity demands and its good representation of the energy-efficient and highly electrified households among the OECD countries. In predicting the future development of Rwanda's electricity demand, we assume that the level of electrification and household appliances used will be similar to those in industrialized countries. Although the electricity demand of households in industrialized countries—excluding electric mobility—can be reduced through technical efficiency measures and more-efficient appliances by improving technical standards, the current demand provides an orientation for the future demands in developing countries.

Table 5: Standard household demand in an industrialized country (Switzerland)

Standard Household—OECD	Apartment			Separate House			
Category	2 People	Additional person	4 People	2 People	Any additional person/s	4 People	Calculated Urban Family 2
	[kWh/a]	[kWh/a]	[kWh/a]	[kWh/a]	[kWh/a]	[kWh/a]	[kWh/a]
Cooking/baking including special equipment, e.g., coffee maker	300	80	460	300	80	460	0
Dishwasher	250	25	300	250	25	300	
Refrigerator with or without freezer compartment	275	40	355	325	60	445	340
Separate freezer	275	25	325	350	25	400	
Lighting	350	90	530	450	125	700	198
Consumer electronics (TV, video, hi-fi, various players, etc.)	250	60	370	275	80	435	110
Home office (PC, printer, modem, comfort phone, etc.)	200	60	320	200	80	360	
Div. Nursing and small appliances including humidifier	250	45	340	325	60	445	272
Washing machine	225	65	355	250	78	405	127
Laundry dryer (about 2/3 of the laundry, with a tumbler)	250	85	420	275	88	450	
General (building services)	400		400+	900	150	1200	
Total	**3025**	**575**	**4175**	**3900**	**850**	**5600**	**1047**
Climatization							1,013
Total, including climatization	3025	575	4175	3900	850	5600	2060

Source: Der typische Haushalt-Stromverbrauch Energieverbrauch von Haushalten in Ein- und Mehrfamilienhäusern/Schweiz, https://www.werkezuerichsee.ch/dl.php/de/0dn3t-3gjac9/Typischer_Haushaltstromverbrauch-SEV0719.pdf

The development of the country-wide shares of the electricity demand in Rwanda according to the various household types is presented in Table 6. Electrification starts with basic household types, such as rural, semi-urban, and urban (apartments or houses) and moves to better-equipped households. Thus, the proportion of fully equipped households grows constantly, while the proportion of basic households increases in the early years and decreases towards the end of the modelling period. By 2050, most households will have a medium-to-high level of comfort equipment. The authors of this report have deliberately chosen a high standard for Rwanda's households to close the gap between households in OECD countries and countries in the global south, to achieve greater equity.

Table 6: Household types—development of household shares of the electricity demand country-wide in Rwanda

Household type	Country-wide electricity shares [%] (rounded)			
	2020	**2030**	**2040**	**2050**
No access to electricity	25.00%	4.00%	2.00%	0%
Rural —Phase 1	60.00%	72.00%	65.00%	55.00%
Rural—Phase 2	4.00%	8.00%	9.00%	15.00%
Rural—Phase 3	0.00%	3.00%	4.00%	10.00%
Semi-Urban—basic	10.00%	4.00%	3.00%	5.00%
Semi-Urban—advanced	0.00%	2.00%	0.00%	0.00%
Urban Apartment—basic	0.00%	0.00%	0.00%	0.00%
Urban Apartment—advanced	0.00%	4.00%	8.00%	10.00%
Urban House—basic	0.00%	2.00%	5.00%	1.00%
Urban House—advanced	1.00%	1.00%	4.00%	4.00%
Total	100%	100%	100%	100%

Source: PSA and UTS-ISF research

While 74% of Rwanda's households have access to electricity (see 2.2), some households might not have access to reliable and uninterrupted electricity. Here, rapidly expanding cities are problematic because the infrastructure for transport and energy supply and the requirements of residential apartment buildings cannot match the demand, often leading to social tensions. Mini grids for remote areas have proven a successful technology option for bringing energy services to remote communities, helping villages develop local economies, and providing alternative opportunities for young people to establish careers outside the metropolitan areas.

2.4.3 HOUSEHOLD FUEL DEMAND—COOKING

The main energy demand for Rwanda's households is for cooking. Biomass in the form of firewood is the main energy source for households. Table 7 provides an overview of the most important cooking technologies and their key technical and economic parameters (WFC 2019).[12] The data are taken from a comprehensive analysis of cooking technologies and the sustainability and cost-effectiveness of electric cooking. One key finding of this analysis was that cooking with electricity (whether with solar home systems [SHS] or in a mini-grid context) using high-efficiency appliances could make cooking even cheaper than it is many households currently using firewood and charcoal. The World Bank's bottom-up research from across Sub-Saharan Africa indicated that households use on average US$1–31 per month on cooking fuels (World Bank 2014)[13]. With slow cookers and pressure cookers enabling household cooking costs of between USUS$15–21/month for SHS and US$3.56–9.53/month for mini-grids, the economics of cooking with high-efficiency cooking appliances is becoming increasingly compelling (WFC 2019).

Based on the current cooking energy usage, a transition scenario from fuel-based cooking to electric cooking (e-cooking) has been developed for the R-1.5°C scenario (**Error! Reference source not found.**). However, with an increasing population and a growing number of households, the overall fuel demand is likely to remain at high levels, and a phase-out of emissions and fuel demand cannot be achieved with this measure. Rwanda's households use traditional cooking stoves (53%) and open fire stoves (16% of used appliances).[14]

Table 7: Basic data on technologies and energy use

Appliance	Cost range [EUR]	Median Cost [EUR]	Median Cost [RWF]	Watts (range)	Approximate Daily Household Consumption (in Wh/day for electric options or in kg/day for solid and gas-based fuels)	Approximate Daily Household Consumption [MJ/day]
Three Stones (Wood)	0	0	0	N/A	4.15–20.76 kg/day	68.48–342.54
Traditional Cooking Stove (Wood)	0–5	2.5	3,375	N/A	3.32–8.3 kg/day	54.78–136.95
Improved Cooking Stove (Wood)	5–65	35	47,250	N/A	2.08–5.53 kg/day	34.32–91.25
Three Stones (Charcoal)	0	0	0	N/A	1.92–4.81 kg/day	54.72–137.09
Traditional Cooking Stove (Charcoal)	0–10	5	6,750	N/A	1.6–4.01 kg/day	45.60–114.29
Improved Cooking Stove (Charcoal)	5–65	35	47,250	N/A	1.2–2.4 kg /day	34.20–68.40
Improved Cooking Stove (Wood-based Biomass Pellets)	16–80	48	64,800	N/A	1.76–3.96 kg/day	30.41–68.43
Improved Cooking Stove (Agro-waste Pellets)	16–80	48	64,800	N/A	2.42–5.44 kg/day	30.49–68.54
Single Burner Hot Plate	8–35	21.5	29,025	600–2000	1200–4000 Wh/day	4.32–14.40
Induction Hot Plate	45–95	67.5	91,125	1000–2300	2000–4600 Wh/day	7.20–16.56
Slow Cooker / Rice Cooker / Crock Pot	10–130	70	94,500	120–300	175–700 Wh/day	0.63–2.52
Electric Pressure Cooker	19–140	79.5	107,325	500–1000	160–340 Wh/day	0.58–1.22
Microwave Oven	50–100	75	101,250	600–1200	100–1200 Wh/day	0.36–4.32
Gas Stove (single burner)	20–60	40	54,000	N/A	0.3 kg/day	13.7
Gas Stove (double burner)	30–90	60	81,000	N/A	0.3 kg/day	13.7
Gas Stove (four burners)	40–100	70	94,500	N/A	0.3 kg/day	13.7

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[12] WFC 2019, Beyond fire—How to achieve electric cooking; Toby D. Couture (E3 Analytics); Dr. David Jacobs (IET– International Energy Transition GmbH), Eco Matser and Harry Clemens (Hivos), Anna Skowron (WFC) and Joseph Thomas (E3 Analytics), World Future Council, Lilienstrasse 5–9, 22095 Hamburg, Germany, May 2019–costs are converted from Euro to US$ with the exchange rate of 25th August 2022: 1 Euro = US$1

[13] World Bank 2014, Clean and Improved Cooking in Sub-Saharan Africa: Second Edition. World Bank, Washington, DC. Available at: http://documents.worldbank.org/curated/en/164241468178757464/pdf/98664-REVISED-WP-P146621-PUBLIC-Box393185B.pdf

[14] https://mecs.org.uk/wp-content/uploads/2021/10/Policy-and-market-review-for-modern-energy-cooking-in-Rwanda.pdf

Table 8: Cooking energy demand by technology and household type in 2021, Rwanda

	Demand per Household and Day [MJ/day]	Demand per Household and Year [MJ/year HH]								
		Rural—Phase 1	Rural—Phase 2	Rural—Phase 3	Semi-Urban 1	Semi-Urban 2	Urban Apartment 1	Urban Apartment 2	Urban House 1	Urban House 2
Wood + Bioenergy Fuel based cooking	96	3,504	4,380	5,840	17,520	4,380	4,380	4,380	5,840	8,760
Gas / NLG Fuel based cooking	13.7	500	625	833	2,500	625	625	625	833	1,250
Electric cooking	3.3	120	151	201	602	151	151	151	201	301

The daily and annual energy demands for the three main cooking technologies groups are shown in Table 8. Based on these, a scenario for transitioning from fuel-based cooking to electricity-based cooking was developed (Table 9).

On average, 1% of all wood and bio energy fuel-based cooking applications will be gradually phased out and replaced with electric cooking appliances. The total phase-out of traditional bio energy-based systems will be for environmental and economic reasons. Fuel-based cooking requires fuel that generates emissions, and the fuel supply is, in most cases, not sustainable. Collecting fuel wood puts forests under pressure, is time-consuming, and has a negative economic impact on the country's productivity. Burning LPG causes CO_2 emissions, and its production is based on fossil gas, which must be phased-out by 2050 to remain within the global carbon budget to limit the global mean temperature rise to a maximum of +1.5 °C. The remaining wood and bio energy-based cooking in 2050 is sustainable charcoal. Electric-cooking can be supplied by renewable energy sources and will therefore be emissions-free.

Table 9: Transition scenario from fuel-based to electricity-based cooking in Rwanda under the R-1.5°C pathway

Phase-out of Fossil Fuel-based Cooking 2020–2050											
	Share of Household with Wood and Bioenergy Fuel-based Cooking		Rural—Phase 1	Rural—Phase 2	Rural—Phase 3	Semi-Urban 1	Semi-Urban 2	Urban Apartment 1	Urban Apartment 2	Urban House 1	Urban House 2
Average energy demand by HH (Based on World Future Council 2019)			3,504	4,380	5,840	17,520	4,380	4,380	4,380	5,840	8,760
2020	98%	[MJ/a HH]	3,434	4,292	5,723	17,170	4,292	4,292	4,292	5,723	8,585
2025	96%	[MJ/a HH]	3,364	4,205	5,606	16,819	4,205	4,205	4,205	5,606	8,410
2030	90%	[MJ/a HH]	3,154	3,942	5,256	15,768	3,942	3,942	3,942	5,256	7,884
2035	75%	[MJ/a HH]	2,628	3,285	4,380	13,140	3,285	3,285	3,285	4,380	6,570
2040	50%	[MJ/a HH]	1,752	2,190	2,920	8,760	2,190	2,190	2,190	2,920	4,380
2045	20%	[MJ/a HH]	701	876	1,168	3,504	876	876	876	1,168	1,752
2050	15%	[MJ/a HH]	526	657	876	2,628	657	657	657	876	1,314
	Share of Household with Gas / NLG Fuel-based Cooking		Rural—Phase 1	Rural—Phase 2	Rural—Phase 3	Semi-Urban 1	Semi-Urban 2	Urban Apartment 1	Urban Apartment 2	Urban House 1	Urban House 2
Average energy demand by HH (Based on World Future Council 2019)			500	625	833	2,500	625	625	625	833	1,250
2020	1%	[MJ/a HH]	6	7	9	28	7	7	7	9	14
2025	1%	[MJ/a HH]	6	8	10	31	8	8	8	10	16
2030	2%	[MJ/a HH]	0	0	0	1	0	0	0	0	0
2035	2%	[MJ/a HH]	10	13	17	50	13	13	13	17	25
2040	2%	[MJ/a HH]	10	13	17	50	13	13	13	17	25
2045	2%	[MJ/a HH]	10	13	17	50	13	13	13	17	25
2050	0%	[MJ/a HH]	0	0	0	0	0	0	0	0	0
	Phase-in of Electric Cooking 2020–2050										
	Share of Households with Electric Cooking		Rural—Phase 1	Rural—Phase 2	Rural—Phase 3	Semi-Urban 1	Semi-Urban 2	Urban Apartment 1	Urban Apartment 2	Urban House 1	Urban House 2
Average energy demand by HH (Based on World Future Council 2019)			120	151	201	602	151	151	151	201	301
2020	1%	[kWhelectric/a HH]	1	1	2	5	1	1	1	2	3
2025	3%	[kWhelectric/a HH]	3	4	6	17	4	4	4	6	8
2030	8%	[kWhelectric/a HH]	10	12	16	48	12	12	12	16	24
2035	23%	[kWhelectric/a HH]	28	35	46	139	35	35	35	46	69
2040	48%	[kWhelectric/a HH]	58	72	96	289	72	72	72	96	145
2045	78%	[kWhelectric/a HH]	94	117	157	470	117	117	117	157	235
2050	85%	[kWhelectric/a HH]	102	128	171	512	128	128	128	171	256

According to 'Plan of Action: Rwanda's transition to modern energy cooking' published in December 2022[15], the government of Rwanda aims to phase-out the use of traditional biomass cooking, which the authors of this analysis support. The reports states:

'The government of Rwanda has developed several policies, including the national forest policy, Rwandan energy policy, Rwanda biomass strategy among others, to tackle the biomass fuel use, form 79.9% households in 2017 to 42% by 2024, and establish a clear pathway to clean and modern energy cooking. In addition to improved cookstoves, pellets and briquettes stoves, Rwanda has selected modern energy cooking (LPG, electricity, and biogas) as alternatives for traditional biomass energy cooking. LPG received a more pronounced focus, going further at producing an LPG master plan, which sets the national target at 40% of households using LPG by 2024.'

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[15] Plan of Action: Rwanda's transition to modern energy cooking; Working paper, December 2022, Main author: Saulve Divin Ntivunwa, Energy 4 Impact; https://mecs.org.uk/wp-content/uploads/2023/01/Plan-of-Action-Rwandas-transition-to-modern-energy-cooking.pdf

Is Liquefied Petroleum Gas (LPG) clean?

Traditional biomass-based cooking has significant negative impacts on the environment, public health and indoor air quality. The United Nations Department of Economic and Social Affairs published a policy brief 'Acceleration Sustainable Development Goal (SDG) 7'[16] – which addresses 'Affordable and Clean Energy'.

The report defines clean and modern cooking solutions as follows:

'Improving indoor air quality requires defining "clean" for health at point of use. The most recent WHO Guidelines for indoor air quality: household fuel combustion (the Guidelines) set new standards for clean burning in the home based on systematic reviews of scientific literature and robust mathematical models.
Any type of fuel-technology combination is considered "clean" if its emissions meet WHO Guidelines. Currently available options that are clean at point of use include electricity, gas, ethanol, solar and the highest performing biomass stoves. In order to provide the greatest health benefit, clean fuels and technologies should be used exclusively.'

While LPG burns with less air pollution than traditional biomass, gas is a fossil fuel with considerable energy-related CO_2 emissions. The Intergovernmental Panel on Climate Change (IPCC) released the Sixth Assessment Report of Working Group I in August 2021, which focuses on the physical science basis of climate change (IPCC 2021A)[17]. One of the key headline statements for policy makers is that '*from a physical science perspective, limiting human-induced global warming to a specific level requires limiting cumulative CO_2 emissions, reaching at least net zero CO_2 emissions, along with strong reductions in other greenhouse gas emissions. Strong, rapid and sustained reductions in CH_4 emissions would also limit the warming effect resulting from declining aerosol pollution and would improve air quality*' (IPPC2021B)[18].

The global energy transition to decarbonize the energy sector requires a phase-out of fossil fuels by 2050. LPG is a fossil fuels and therefore only an interim solution. The authors of this report recommend to move directly to electric cooking instead of LPG to avoid possible stranded infrastructure investment. Therefore, the clean cooking scenario shown in Table 9 does not include the increase of LPG to replace traditional biomass for cooking but suggests a direct transition to electric cooking.

However, there are some challenges to the introduction of electric cooking stoves:

- Firewood remains freely available.
- In relative terms, the initial investment and monthly costs are high.
- Concerns exist about the safety of the technology.
- (Initial) concerns exist around the learnability of new appliances.
- In the cold climate in mountainous regions, fire from cooking also heats the rooms.
- The use of e-cooking is perceived to be expensive in its utilizations.
- Quality concerns on the appliances
- It's a new technology that requires learning in order to operate it
- The current business models of distribution are not well suited to cater for low-income households. Most vendors use the model of payment upfront rather than other innovative model like pay as you go which have proven beneficial in many other technologies.
- Perceived and/or actual differences in taste and quality between food prepared using biomass vs e-cooking.

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[16] ACCELERATING SDG 7 ACHIEVEMENT POLICY BRIEF 02, ACHIEVING UNIVERSAL ACCESS TO CLEAN AND MODERN COOKING FUELS, TECHNOLOGIES AND SERVICES, 2018, https://sustainabledevelopment.un.org/content/documents/17465PB2.pdf

[17] IPCC. Climate Change 2021: The Physical Science Basis. Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge University Press; 2021.

[18] IPCC. Summary for Policymakers. In: Climate Change 2021: The Physical Science Basis. Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge University Press; 2021.

There are already numerous electric cooking devices on Rwanda’s market, including:

- Induction stoves
- Electric pressure cookers
- Electric ovens
- Hot plates
- Microwave ovens
- Electric and gas hobs
- Roti makers
- Infrared stoves
- Rice cookers
- Slow cookers
- Electric frying pans
- Air fryers
- Electric kettles

Among these, the most viable energy-efficient appliances are:

- Induction stoves
- Infrared stoves
- Rice cookers
- Electric pressure cookers

The supply-side barriers to e-cooking are:

- Electric cooking stoves do not seem to be manufactured locally.
- After-sales service is poor (i.e., poor access to repairs and maintenance).
- Concern exist around the quality and stability of the electricity supply.

Technical challenges of e-cooking for electric utilities and energy service companies:

The increase in the peak load during meal times will require an upgrade of the electricity distribution grid in terms of load management and the ability of the power grid to supply higher loads. The introduction of electric vehicles to replace fossil fuels will further increase the electric loads and require grid expansion and reinforcement to be implemented by electric grid operators.

Furthermore, current household electricity connections are often limited to 5-ampere meters, which significantly limits the load for each household, and the parallel operation of multiple appliances is not possible when electric stoves are used. Moreover, the technical standard of household wiring is low; cables are often not properly installed, or the lack of protective earthing compromises electrical safety.

Policy and social challenges in promoting electric cooking

Local-level governments in Rwanda already have formulated policy frameworks, such as specific energy policies, acts, procedures, and/or guidelines, to support the increased utilization of electric cooking devices. These policies include support for additional renewable electricity generation to supply stoves.

However, the implementation of sustainable cooking technologies is challenging for rural households in regard to get access to those technologies, technology standards as well as financing.

Therefore, the development of clean cooking programs is lagging behind the actual targets. Finally, the general awareness of the benefits of e-cooking—particularly in rural areas—is still low because the access to the necessary information is unavailable. Finally, this lack of information means that the acceptance of e-cooking devices in the supply chain—specialized kitchenware and hardware shops—is low. Therefore, awareness programs for retail staff are required.

2.5 INDUSTRY AND BUSINESS DEMANDS

The analysis of Rwanda's economic development is based on a breakdown of the fiscal year 2019 and assumes that the overall structure of the economy will not change, and that all sectors will grow at a rate equal to that of GDP over the entire modelling period.

Figure 5 shows that in the fiscal year 2020/21, agriculture, forestry and fishing services contributed most strongly to the growth of GDP (in the basic price), whereas machinery and transport, food, beverages and tobacco, textiles and clothing and chemicals sectors contributed least. The contribution of the industry (including construction) to the economic growth rate in that fiscal year (FY) was 19 %, and the manufacturing was 8 %.

In addition, Figure 6 presents the annual GDP growth rate from 2005 to 2020.

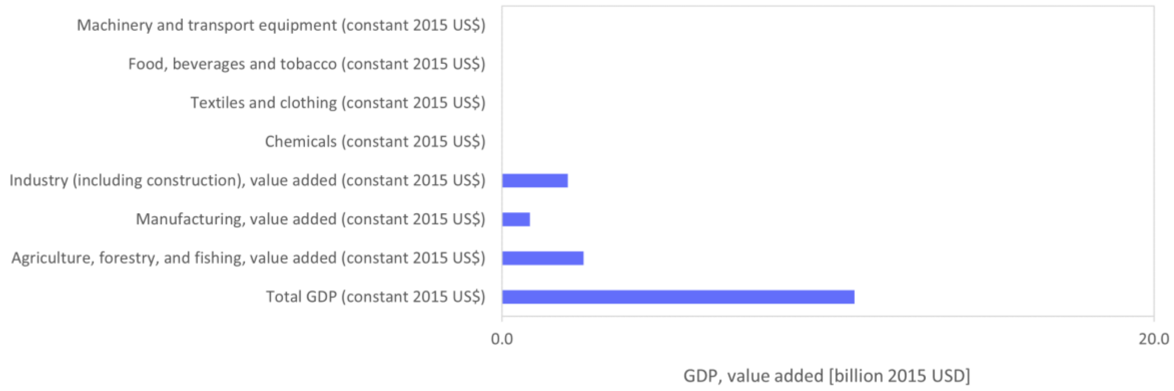

Figure 5: Contributions of sub-sectors to GDP growth

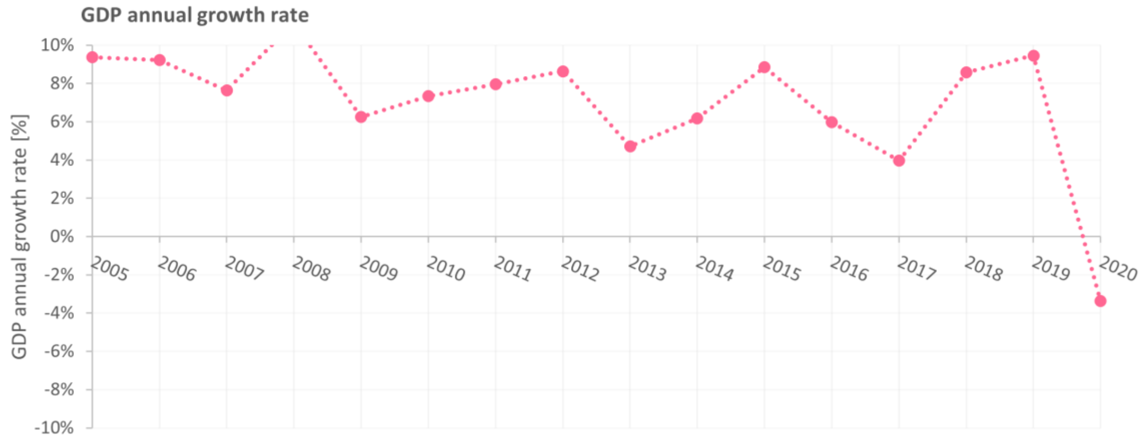

Figure 6: Gross domestic product (GDP) growth rate

2.6 TRANSPORT DEMAND

Rwanda's transport sector is currently dominated by motorcycles, which account for 51 % of all registered vehicles, whereas cars, pick-up trucks, and vans represent around 45 % of the vehicle fleet. Only 5% of all registered vehicles are buses or mini-buses. The remaining 1 % includes construction and industry vehicles, such as trailers and other vehicles (Figure 77).

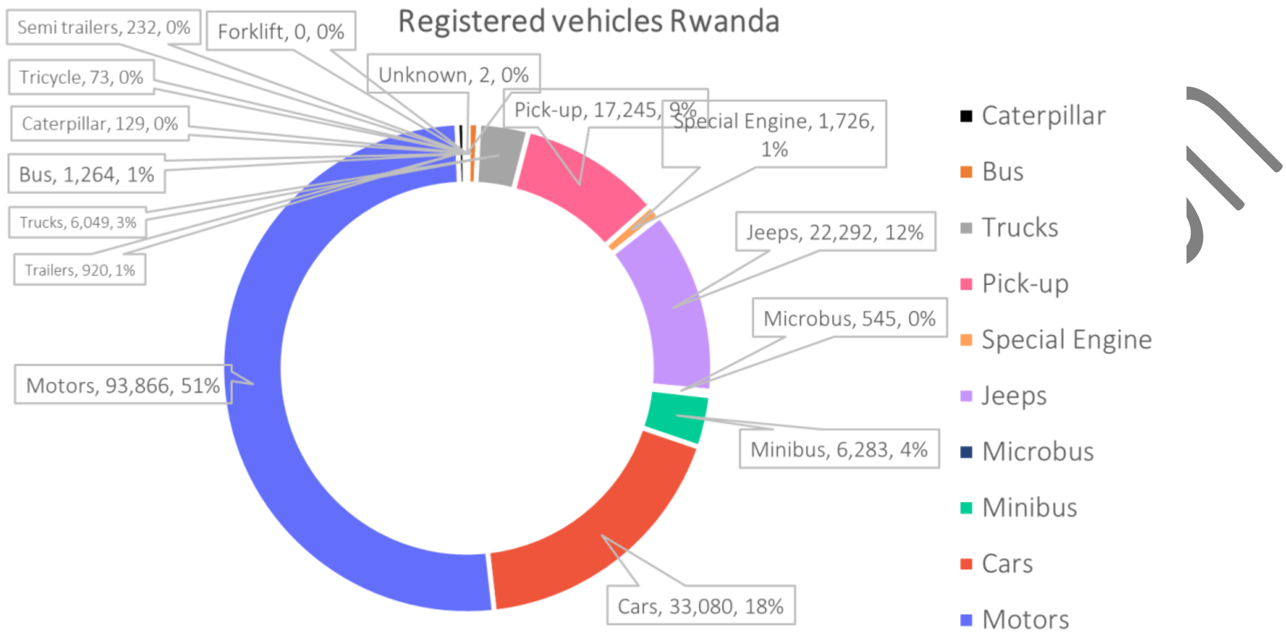

Figure 7: Categories of registered vehicles, with the percentages of the total number of registered vehicles (Year 2017). Source: Statistical yearbook, The Republic of Rwanda[19]

To develop a future transport scenario, the technical parameters of all vehicle options are required to project the energy demands. The following section provides an overview of the vehicular energy intensities for passenger and freight transport. Based on these, the actual utilization—in terms of annual kilometres per vehicle—was estimated to calculate the energy demand over time until 2050.

The energy intensities for the different vehicle types and each available drive train play an important role in calibrating the transport modes and projections. Each transport mode has different vehicular options. Each of the vehicles has different drive-train and efficiency options. The technical variety of passenger vehicles, for example, is extremely large. The engine sizes for five-seater cars range between around 20 kW to > 200 kW.

Furthermore, drive trains can use a range of fuels, from gasoline, diesel, and bio-diesel to hydrogen and electricity. Each vehicle has a different energy intensity in megajoules per passenger kilometre (MJ/pkm). Therefore, the energy intensities provided in the following tables are average values.

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[19] Republic of Rwanda, Statistical yearbook, https://www.statistics.gov.rw/publication/statistical-yearbook-2017

2.6.1 TECHNICAL PARAMETERS—INDIVIDUAL TRANSPORT

Passenger transport by road is the commonest and most important form of travel (TUMI 2021)[20]. There are numerous technical options to 'move people with vehicles': bicycles, motorcycles, tricycles, city cars, and 4four-wheel-drive SUVs. Each vehicle has a very different energy intensity per km. Although this research project aims for high technological resolution, simplifications are required. Table 10 shows the energy intensities for the main vehicle types (electric and with internal combustion engines [ICE]), and forms the basis for the energy scenario calculations.

Table 10: Energy intensities of individual transport—road transport

Individual Transport			Passengers		Vehicle Demand	Consumption per Passenger	Energy demand
			Average Passengers per Vehicle	Assumed Occupation Rate	Average	Average	Assumption for Scenario Calculation
		Fuels			litre/100 km	litre/100 pkm	[MJ/pkm]
Scooters & motorbikes	2-wheeler	Gasoline	1	1	3.0	3.0	1.21
		Electricity			kWh$_{el}$/100 km	kWh$_{el}$/100 pkm	[MJ/pkm]
E-bikes	2-wheeler	Battery	1	1	1.0	1.0	0.04
Scooters	2-wheeler	Battery	1	1	1.8	1.9	0.06
Motorbikes	2-wheeler	Battery	1	1	4.8	4.8	0.17
Rickshaw	3-wheels	Battery	3	2	8.0	4.0	0.14
Cars		Fuels	0	0	litre/100 km	litre/100 pkm	[MJ/pkm]
	small	ICE–oil	2	1.8	5.0	2.8	1.12
	medium	ICE–oil	4	2	7.5	3.8	1.51
	large	ICE–oil	5	2	10.5	5.3	2.11
	small	ICE–gas	2	1.8	4.5	2.5	0.63
	medium	ICE–gas	4	2	7.0	3.5	1.41
	large	ICE–gas	5	2	10.0	5.0	1.25
	small	ICE–bio	2	1.8	5.0	2.8	0.91
	medium	ICE–bio	4	2	7.5	3.8	1.51
	large	ICE–bio	5	2	10.5	5.3	1.72
	small	Hybrid–oil	2	1.8	4.0	2.2	0.89
	medium	Hybrid–oil	4	2.5	6.0	2.4	0.96
	large	Hybrid–oil	5	2.5	8.5	3.4	1.37
		Electricity			kWh$_{el}$/100 km	kWh$_{el}$/100 pkm	[MJ/pkm]
	small	Battery	2	1.8	16.0	8.9	0.32
	medium	Battery	4	2	25.0	12.5	0.45
	large	Battery	5	2	32.5	16.3	0.59
	large	Fuel Cell	4	2	37.5	18.8	1.36

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[20] TUMI (2021), Teske, S., Niklas, S., Langdon, R., (2021), TUMI Transport Outlook 1.5°C - A global scenario to decarbonize transport; Report prepared by the University of Technology Sydney for the Deutsche Gesellschaft für Internationale Zusammenarbeit (GIZ) GmbH; Published by TUMI Management, Deutsche Gesellschaft für International Zusammenarbeit (GIZ) GmbH, Friedrich-Ebert-Allee 36 + 40, 53113 Bonn, Germany; https://www.transformative-mobility.org/assets/publications/TUMI-Transport-Outlook.pdf

2.6.2 TECHNICAL PARAMETERS—PUBLIC TRANSPORT

There is a huge variety of public transport vehicles—from rickshaws to taxis and mini-buses to long-distance trains. The occupation rates for those vehicles are key factors in calculating the energy intensity per passenger per kilometre. For example, a diesel-powered city bus transporting 75 passengers uses, on average, about 27.5 litres per 100 kilometres. If the bus operates at full capacity during peak hour, the energy demand per passenger is as low as 400 ml per kilometre, lower than almost all fossil-fuel-based road transport vehicles. However, if the occupancy drops to 10%—e.g., for a night bus—the energy intensity increases to 3.7 litres, equal to that of a small energy-efficient car. Occupation rates vary significantly and depend on the time of day, day of the week, and season.

There are also significant regional differences, even within a province. Again, the parameters shown in Table 11 are simplified averages and are further condensed for the scenario calculations. Although high technical resolution is possible for the scenario model, it would pretend an accuracy that does not exist because the statistical data required for this resolution are not available at the regional level.

Table 11: Energy intensities for public transport—road & rail transport

Public Transport			Passengers		Vehicle Demand	Consumption per Passenger	Energy Demand
			Average Passengers per Vehicle	Assumed Occupation Rate	Average	Average	Assumption for Scenario Calculation
Buses		Fuels			litre/100 km	litre/100 pkm	[MJ/pkm]
	small	Diesel	12	40%	8.8	1.8	0.73
	small	Bio	12	40%	8.8	1.8	0.60
	12 m	Diesel	75	40%	27.5	0.9	0.37
	12 m	Bio	75	40%	27.5	0.9	0.30
	large	Diesel	135	40%	57.5	1.1	0.43
		Electricity	0	0	kWh_{el}/100 km	kWh_{el}/100 pkm	[MJ/pkm]
	small	Battery	12	40%	31	6.4	0.23
	small	Fuel Cell	12	40%	77	15.9	0.57
	12 m	Battery	75	40%	143	4.8	0.17
	12 m	Fuel Cell	75	40%	358	11.9	0.43
	large	Overhead lines	135	40%	263	4.9	0.18
Trains		Fuels	0	0	litre/100 km	litre/100 pkm	[MJ/pkm]
	Metros	Diesel	400	40%	150	0.9	0.38
	Metros	Bio	400	40%	150	0.9	0.31
	Commuter Trains	Diesel	600	40%	300	1.3	0.50
	Commuter Trains	Bio	600	40%	300	1.3	0.41
		Electricity	0	0	kWh_{el}/100 km	kWh_{el}/100 pkm	[MJ/pkm]
	Trams	Electric	300	40%	495	4.1	0.14
	Metros	Electric	300	40%	1,200	10.0	0.14
	Commuter Trains	Electric	600	40%	1,950	8.1	0.17

2.6.3 TECHNICAL PARAMETERS—FREIGHT TRANSPORT

The energy intensity data for freight transport are not as diverse as those for passenger transport because the transport vehicle types are standard and the fuel demands are well known. However, the utilization rates of the load capacities vary significantly, and consistent data are not available for the calculated regional and global levels. Therefore, the assumed utilization rate greatly influences the calculated energy intensity per tonne–km (tkm). The average energy intensities per tkm used in the scenario are shown in Table 12 and are largely consistent with those from other sources in the scientific literature (EEA, 2021)[21]. The assumed energy intensities for electric and fuel cell/hydrogen freight vehicles are only estimates because this technology is still in the demonstration phase. Therefore, none of the scenarios factor in large shares of electric freight transport vehicles before 2035.

Table 12: Energy intensities freight transport—road & rail transport

Freight Transport			Maximum Load Capacity (tonnes)	Assumed Utilization Rate	Vehicle Demand	Consumption per tonne	Energy Demand
					Average	Average	Assumption for Scenario Calculation
Trucks		Fuels			litre/100 km	litre/tkm	[MJ/tonkm]
	3.5 t	Diesel	3.5	40%	11	7.9	3.16
	3.5 t	Bio	3.5	40%	11	7.9	2.57
	7.5 t	Diesel	7.5	40%	20	6.5	2.61
	7.5 t	Bio	7.5	40%	20	6.5	2.13
	12.5 t	Diesel	12.5	40%	25	5.0	2.01
	12.5 t	Bio	12.5	40%	25	5.0	1.64
		Electricity			kWh_{el}/100 km	kWh_{el}/ton-km	[MJ/tonkm]
	3.5 t	Battery	3.5	40%	19	13.6	1.34
	3.5 t	Fuel Cell	3.5	40%	46	33.2	1.33
	7.5 t	Battery	7.5	40%	41	13.6	0.49
	7.5 t	Fuel Cell	7.5	40%	100	33.2	1.19
	12.5 t	Battery	12.5	40%	68	13.6	0.49
	12.5 t	Fuel Cell	12.5	40%	166	33.2	1.19
Trains		Fuels			litre/100 km	litre/ton-km	[MJ/tonkm]
	Freight–740 m	Diesel	1,000	40%	300	0.8	0.30
	Freight–740 m	Bio	1,000	40%	300	0.8	0.25
		Electricity			kWh_{el}/100 km	kWh_{el}/ton-km	[MJ/tonkm]
	Freight–740 m	Electric	1,000	40%	5,840	14.6	0.53

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[21] European Environment Agency, https://www.eea.europa.eu/publications/ENVISSUENo12/page027.html

2.6.4 UTILIZATION OF VEHICLES

In the second step, the utilization of vehicles must be analysed to develop a projection into the future. No up-to-date surveys are available. The annual passenger–kilometres (pkm) and tonne–kilometres (tkm) for freight transport are calculated based on the current energy demand and the energy intensities of the vehicles in use. The average energy intensity across all passenger vehicles is assumed to have been 1.5 MJ per kilometre in 2020—which reflects the current vehicle fleet of motorcycles (average of 1.2–1.3 MJ/pkm), cars (average of 1.5 MJ/pkm), and SUVs and pick-up trucks with an energy demand of 2–6 MJ/pkm. The assumed average energy intensity for freight vehicles is calculated accordingly, assuming vans and mini-vans are the main transport vehicles. It is also assumed that internal combustion engines (ICEs) and not electric drives are in use.

Table 13: Rwanda—projected passenger and freight transport demand under the R-1.5°C scenario

		2019	2020	2025	2030	2035	2040	2045	2050
Road: **Passenger** Transport Demand	[PJ/a]	9	8	7	6	3	3	2	2
Annual passenger kilometres	[million pkm]	2,395	2,271	2,424	2,082	1,834	1,658	1,499	1,355
Average energy intensity—passenger vehicles.	[MJ/pkm]	2.50	2.50	1.88	1.75	1.71	1.66	1.63	1.60
Annual demand variation:	[%/a]	-	-	-1.00%	-3.00%	-2.50%	-2.00%	-2.00%	-2.00%
kilometres per person per day	[km/person day]	566	520	470	339	252	284	189	153
Road: **Freight** Transport Demand	[PJ/a]	3	2	3	3	2	2	1	1
Annual freight kilometres	[million tkm]	1,705	1,617	2,377	2,261	2,150	2,045	1,756	1,508
Average energy intensity—freight vehicles	[MJ/tkm]	1.51	1.51	1.20	1.14	1.11	1.08	1.07	1.06
Annual demand Variations	[%/a]	-	-	8.00%	-1.00%	-1.00%	-1.00%	-3.00%	-3.00%

The total amount of passenger and freight kilometres is the basis for the projection of the future transport demand. The contraction of the transport demand in 2020 due to COVID is expected to end. It is anticipated that the pre-COVID transport demand of 2019 will be reached by 2023, and the transport demand will increase with population growth and GDP. It is assumed that the annual passenger kilometres will increase by 3% annually until 2050, whereas the freight transport demand will increase by 2% annually. All assumptions and calculated energy demands are shown in Table 13. The energy intensities for all vehicles are assumed to decrease over time with the implementation of more-efficient engines, the phase-out of fossil-fuel-based drives, and their replacement with electric drives. To achieve the terms of the Paris Climate Agreement, all energy-related CO_2 emissions must be phased out by 2050. Therefore, all fossil-fuel-based vehicles must be phased out, and electric drives will dominate, supplemented with a limited number of biofuel-based vehicles.

However, it is assumed that the share of cars will grow at the expense of two-wheeler vehicles—which will increase the average energy intensity per kilometre. Although electric drives are significantly more efficient, the increased vehicle size combined with more public transport options—mainly buses—will limit the increase in the energy demand. On average—across all passenger vehicle types—the energy intensity will decrease from around 1.5 MJ per passenger kilometre to 1.07 MJ in 2030 and to 0.54 MJ in 2050.

The energy required by freight vehicles to move 1 tonne for 1 kilometre will decrease from around 1.5 MJ to 1.11 MJ by 2030 and to 0.68 MJ by 2050. Both reductions will only be possible with high shares of electric drives. Figure 8 and Figure 9 show the development of drive trains for passenger and freight transport vehicles over time. The electrification of large parts of these fleets is unavoidable if the transport sector is to be decarbonized. The supply of—sustainably produced—biofuels will be limited and will be directed to large commercial vehicles, buses, and the large trucks used in remote rural areas where the required charging infrastructure for electric vehicles is unlikely to be developed in the next two decades.

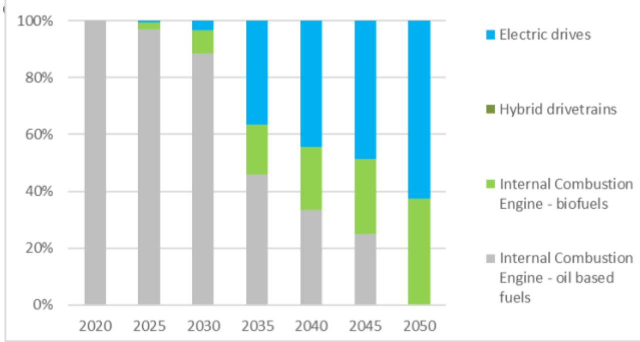

Figure 8: Passenger transport—drive trains by fuel

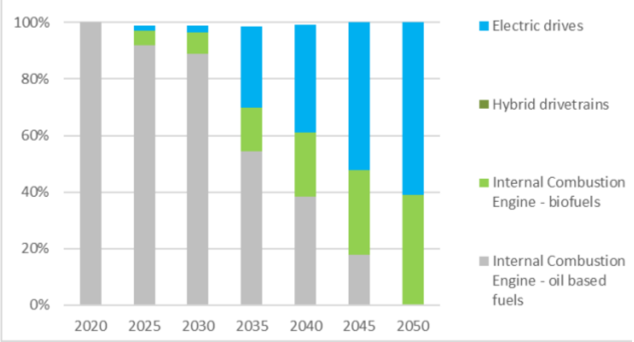

Figure 9: Freight transport—drive trains by fuel

The assumed trajectory for the transport sector (Figure 8 and Figure 9) is consistent with the National Determined Contribution (NDC) (NDC-Rwanda 2020)[22]of the Government of Rwanda published in May 2020, which identified the following goals:

Rwanda's transport sector is dominated by land transport due to the improved national and districts road network and increased investment in public transport. Transport is mainly undertaken by road with a current classified road network consisting of national roads (2,749 km), district roads class 1 (3,906 km) district roads class 2 (9,706 km) and other

unclassified roads. With increasing demand for travel, the number of vehicles has increased dramatically over the past decade. Based on number of registrations, total vehicle numbers are estimated to have grown from 47,631 in 2006 to 161,925 in 2015, representing an increase of over 300%1. Motorcycles accounted for around 51% of total vehicles in 2015, followed by passenger cars (34%), and other vehicles including buses and trucks (15%).

To reduce the number of accidents on Rwanda's roads, motor vehicle inspection centres has been created. To reduce atmospheric pollution levels from the transport sector, the government has also committed to reducing the number of imported used cars by increasing taxes and plans the introduction of electric vehicles from 2020 onwards as part of its 'e-mobility' program. Other key transport strategies include bus promotion as part of public transport development, replacement of minibuses by modern buses and the promotion of mass rapid transportation.'

Based on these lifespans for motorcycles and cars, a country-wide overall market share of electric drives for the entire existing car fleet may not exceed 5% by 2030 for passenger and freight cars. Furthermore, it is assumed that the railway system will not be expanded beyond the current plans after 2030.

Supply-side barriers to e-vehicles

Currently, most e-vehicles are imported. The infrastructure required for electric mobility, in terms of maintenance and service centres and charging stations across urban and rural areas, is lagging. The resilience and reliability of the electricity supply—especially in rural areas—is still under development and faces challenges. Therefore, a rapid expansion of the charging infrastructure, which will increase the load even further, will depend on the progress of electricity services. However, the decarbonization of Rwanda's energy sector will require increased electrification of the transport sector, and the expansion of a resilient power supply based on sustainable power generation technologies is essential.

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[22] Republic of Rwanda, Updated National Determined Contribution, May 2020, https://unfccc.int/sites/default/files/NDC/2022-06/Rwanda_Updated_NDC_May_2020.pdf

2.7 TECHNOLOGY AND FUEL COST PROJECTIONS

All cost projections in this analysis are based on a recent publication by Teske et al. (2019)[23]. Section 5.2 is based on Chapter 5 of that book, written by Dr. Thomas Pregger, Dr. Sonja Simon, and Dr. Tobias Naegler of the German Aerospace Center/DLR. The parameterization of the models requires many assumptions about the development of the characteristic technologies, such as specific investments and fuel costs. Therefore, because long-term projections are highly uncertain, we must define plausible and transparent assumptions based on background information and up-to-date statistical and technical information.

The speed of an energy system transition also depends on overcoming economic barriers. These largely involve the relationships between the cost of renewable technologies and of their fossil and nuclear counterparts. For our scenarios, the projection of these costs is vital to ensure a valid comparison of energy systems. However, there have been significant limitations to these projections in the past in terms of investment and fuel costs.

Moreover, efficiency measures generate costs that are usually difficult to determine, which depend on technical, structural, and economic boundary conditions. Therefore, in the context of this study, we have assumed uniform average costs of 3 cents per kWh of electricity consumption avoided in our cost accounting.

During the last decade, fossil fuel prices have seen huge fluctuations.

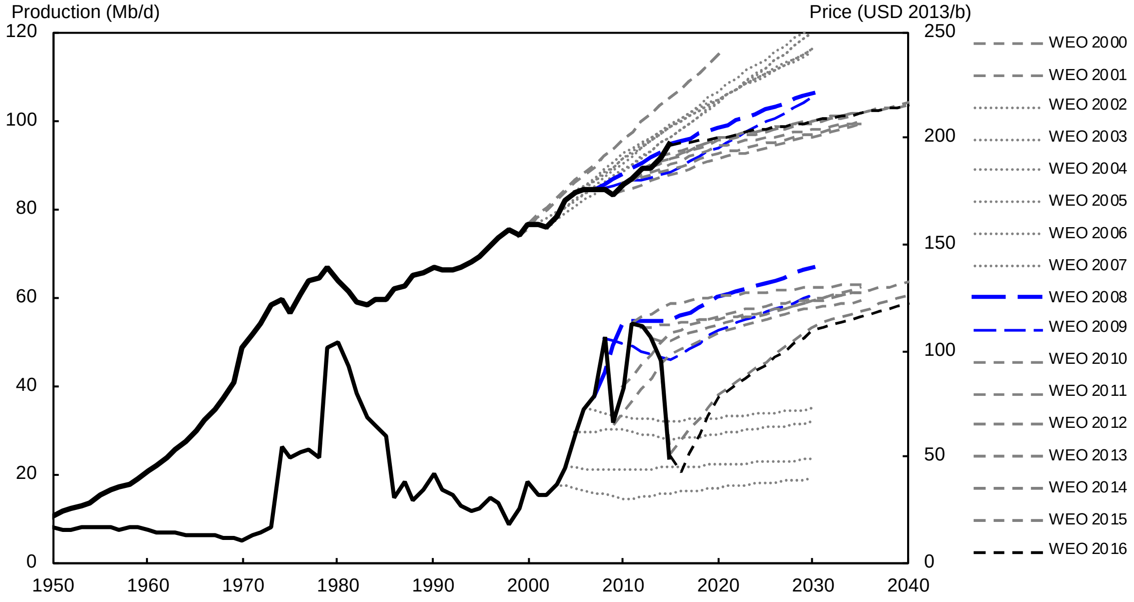

Figure 10 shows the oil prices since 1997. After extremely high oil prices in 2012, we are currently in a low-price phase. Gas prices saw similar fluctuations (IEA 2017)[24]. Therefore, fossil fuel price projections have also seen considerable variations (IEA 2017[24]; IEA 2013[25]) and this has influenced the scenario results.

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[23] Teske S (2019), Achieving the Paris Climate Agreement Goals—Global and Regional 100% Renewable Energy Scenarios with Non-energy GHG Pathways for +1.5 °C and +2.0 °C, ISBN 978-3-030-05842-5, Springer, Switzerland 2019.

[24] IEA (2017): IEA (2017) World Energy Outlook 2017. International Energy Agency, Organization for Economic Co-operation and Development, Paris.

[25] IEA 2013: IEA (2013) World Energy Outlook 2013. International Energy Agency, Organization for Economic Co-operation and Development, Paris.

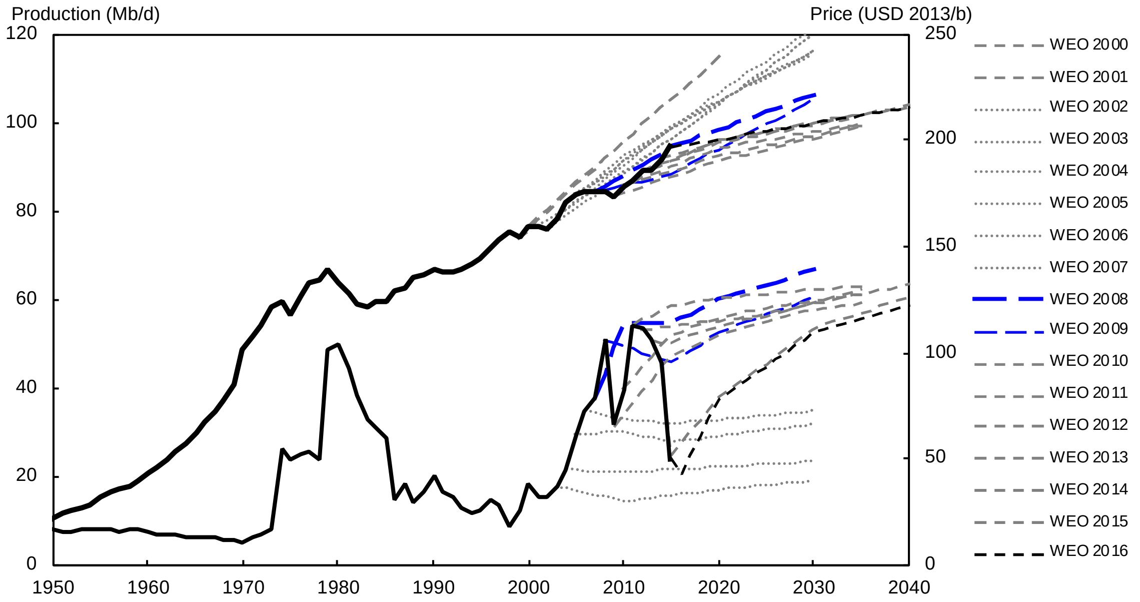

Figure 10: Historical development and projections of oil prices (bottom lines) and historical world oil production and projections (top lines) by the World Energy Outlook (WEO) published by the International Energy Agency (IEA), according to Wachtmeister et al. (2018)

Although oil-exporting countries have provided the best oil price projections in the past, institutional price projections have become increasingly accurate, with the IEA leading the way in 2018 (Roland Berger 2018)[26]. An evaluation of the oil price projections of the IEA since 2000 by Wachtmeister et al. (2018)[27] showed that price projections have varied significantly over time. Whereas the IEA's oil production projections seem comparatively accurate, oil price projections showed errors of 40%–60%, even when made only 10 years ahead. Between 2007 and 2017, the IEA price projections for 2030 varied from US$70 to US$140 per barrel, providing significant uncertainty regarding future costs in the scenarios. Despite this limitation, the IEA provides a comprehensive set of price projections. Therefore, we based our scenario assumptions on these projections, as described below.

However, because most renewable energy technologies provide energy without fuel costs, the projections of investment costs become more important than fuel cost projections, and this limits the impact of errors in the fuel price projections. It is only for biomass that the cost of feedstock remains a crucial economic factor for renewables. These costs range from negative costs for waste wood (based on credit for the waste disposal costs avoided), through inexpensive residual materials, to comparatively expensive energy crops. Because bio-energy has significant market shares in all sectors in many regions, a detailed assessment of future price projections is provided below.

Investment cost projections also pose challenges for scenario development. Available short-term projections of investment costs depend largely on the data available for existing and planned projects. Learning curves are most commonly used to assess the future development of investment costs as a function of their future installations and markets (McDonald and Schrattenholzer 2001[28]; Rubin et al. 2015[29]). Therefore, the reliability of cost projections largely depends on the uncertainty of future markets and the availability of historical data.

Fossil fuel technologies provide a large cost data set featuring well-established markets and large annual installations. They are also mature technologies, so many cost-reduction potentials have already been exploited.

For conventional renewable technologies, the picture is more mixed. For example, like fossil fuels, hydropower is well established and provides reliable data on investment costs. Other technologies, such as solar PV and wind, are experiencing tremendous installation and cost-reduction developments. However, solar PV and wind are the focus of cost monitoring, and big data are already available on existing projects. However, their future markets are not readily

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[26] Roland Berger (2018) 2018 oil price forecast: who predicts best? Roland Berger study of oil price forecasts. https://www.rolandberger.com/en/Publications/pub_oil_price_forecast_2015.html. Accessed 10.9.2018 2018.

[27] Wachtmeister H, Henke P, Höök M (2018) Oil projections in retrospect: Revisions, accuracy and current uncertainty. Applied Energy 220:138-153. doi:https://doi.org/10.1016/j.apenergy.2018.03.013

[28] McDonald A, Schrattenholzer L (2001) Learning rates for energy technologies. Energy Policy 29 (4):255–261. doi:https://doi.org/10.1016/S0301-4215(00)00122-1

[29] Rubin ES, Azevedo IML, Jaramillo P, Yeh S (2015) A review of learning rates for electricity supply technologies. Energy Policy 86:198–218. doi:https://doi.org/10.1016/j.enpol.2015.06.011

predictable, as seen in the evolution of IEA market projections over recent years in the World Energy Outlook series (compare, for example, IEA 2007, IEA 2014, and IEA 2017). Small differences in cost assumptions for PV and wind lead to large deviations in the overall costs, also cost assumptions must be made with particular care.

Furthermore, many technologies have only relatively small markets, such as geothermal, modern bio-energy applications, and concentrated solar power (CSP), for which costs are still high and for which future markets are insecure. The cost reduction potential is correspondingly high for these technologies. This is also true for technologies that might become important in a transformed energy system but are not yet widely available. Hydrogen production, ocean power, and synthetic fuels might deliver important technology options in the long term after 2040, but their cost reduction potential cannot be assessed with any certainty today.

Thus, cost assumptions are a crucial factor in evaluating scenarios. Because costs are an external input into the model and are not internally calculated, we assume the same progressive cost developments for all scenarios. In the next sections, we present a detailed overview of our assumptions for power and renewable heat technologies, including the investment, fuel costs, and potential CO_2 costs in the scenarios.

2.7.1 POWER TECHNOLOGIES

The focus of cost calculations in our scenario modelling is the power sector. We compared the specific investment costs estimated in previous studies (Teske et al. 2015)[30], which were based on a variety of studies, including the European Commission-funded NEEDS project (NEEDS 2009), projections of the European Renewable Energy Council (Zervos et al. 2010)[31], investment cost projections by the IEA (IEA 2014), and current cost assumptions by IRENA and IEA (IEA 2016c). We found that investment costs generally converged, except for PV. Therefore, for consistency, the power sector's investment and operation and maintenance costs are based primarily on the investment costs within WEO 2016 (IEA 2016c) up to 2040, including their regional disaggregation. We extended the projections until 2050 based on the trends in the preceding decade.

For renewable power production, we used investment costs from the 450-ppm scenario from IEA 2016c. For technologies not distinguished in the IEA report (such as geothermal combined heat and power [CHP]), we used cost assumptions based on our research (Teske et al. 2015). Because the cost assumptions for PV systems by the IEA do not reflect recent cost reductions, we based our assumptions on a more recent analysis by Steurer et al. (2018)[32], which projects lower investment costs for PV in 2050 than does the IEA. The costs for onshore wind were adapted from the same source (Steurer et al. 2018) to reflect more recent data. Table 14 summarizes the cost trends for power technologies derived from the assumptions discussed above for Rwanda. It is important to note that the cost reductions are, in reality, not a function of time but of cumulative capacity (production of units), so dynamic market development is required to achieve a significant reduction in specific investment costs. Therefore, overall, we might underestimate the costs of renewables in the REFERENCE scenario compared with the *With the Existing Measures* (WEM) scenario and the R-1.5°C pathway.

Table 14: Investment cost assumptions for power generation plants US Dollars (US$) and the local currency (RWF/kW) by kW until 2050

Assumed Investment Costs for Power Generation Plants										
	2020		2025		2030		2040		2050	
Technology	[US$/kW]	[RWF/kW]	[US$/kW]	[RWF/kW]	[US$/kW]	[RWF/kW]	[US$/kW]	[RWF/kW]	[US$/kW]	[RWF/kW]
Coal power plants	2,018	2,421,329	2,018	2,421,329	2,018	2,421,329	2,018	2,421,329	2,018	2,421,329
Diesel generators	908	1,089,598	908	1,089,598	908	1,089,598	908	1,089,598	908	1,089,598
Gas power plants	504	605,332	504	605,332	504	605,332	504	605,332	676	811,145
Oil power plants	938	1,125,918	918	1,101,704	898	1,077,491	865	1,038,145	827	992,745
Conventional Renewables										
Hydropower plants*	2,674	3,208,260	2,674	3,208,260	2,674	3,208,260	2,674	3,208,260	2,674	3,208,260
New renewables										
PV power plants	989	1,186,451	744	893,244	736	883,785	565	677,972	474	569,012
Onshore Wind	1,594	1,912,850	1,559	1,870,476	1,523	1,828,103	1,463	1,755,463	1,412	1,694,930
Biomass power plants	2,371	2,845,061	2,346	2,814,794	2,320	2,784,528	2,220	2,663,461	2,129	2,554,502

*Values apply to both run-of-the-river and reservoir hydropower.

However, our approach is conservative when we compare the REFERENCE scenario with the more ambitious renewable energy scenarios under identical cost assumptions. Fossil-fuel power plants have limited potential for cost reductions because they are at advanced stages of technology and market development. The products of gas and oil plants are relatively cheap, at around US$670/kW and US$822/kW, respectively. In contrast, several renewable technologies have seen considerable cost reductions over the last decade. This is expected to continue if renewables are deployed extensively. Hydropower and biomass have remained stable in terms of costs. Tremendous cost reductions are still expected for solar energy and wind power, even though they have experienced significant reductions already. Whereas CSP might deliver dispatchable power at half its current cost in 2050, variable PV costs could drop to 35% of today's costs.

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[30] Teske S, Sawyer S, Schäfer O, Pregger T, Simon S, Naegler T, Schmid S, Özdemir ED, Pagenkopf J, Kleiner F, Rutovitz J, Dominish E, Downes J, Ackermann T, Brown T, Boxer S, Baitelo R, Rodrigues LA (2015) Energy [R]evolution - A sustainable world energy outlook 2015. Greenpeace International.

[31] Zervos A, Lins C, Muth J (2010) RE-thinking 2050: a 100% renewable energy vision for the European Union. European Renewable Energy Council (EREC).

[32] Steurer M, Brand H, Blesl M, Borggrefe F, Fahl U, Fuchs A-L, Gils HC, Hufendiek K, Münkel A, Rosenberg M, Scheben H, Scheel O, Scheele R, Schick C, Schmidt M, Wetzel M, Wiesmeth M (2018) Energiesystemanalyse Baden-Württemberg: Datenanhang zu techoökonomischen Kenndaten. Ministerium für Umwelt Klima und Energiewirtschaft Baden-Württemberg, STrise: Universität Stuttgart, Deutsches Zentrum für Luft- und Raumfahrt, Zentrum für Sonnenenergie- und Wasserstoff-Forschung Baden-Württemberg, Stuttgart.

2.7.2 HEATING TECHNOLOGIES

Assessing the costs in the heating sector is even more challenging than for the power sector. Costs for new installations differ significantly between regions and are interlinked with construction costs and industrial processes, which are not addressed in this study. Moreover, no data are available to allow the comprehensive calculation of the costs for existing heating appliances in all regions. Therefore, we have concentrated on the additional costs of new renewable applications in the heating sector.

Our cost assumptions are based on a previous survey of renewable heating technologies in Europe, which focused on solar collectors, geothermal energy, heat pumps, and biomass applications. Biomass and simple heating systems in the residential sector are already mature. However, more-sophisticated technologies that can provide higher shares of heat demand from renewable sources are still under development and rather expensive. Market barriers will slow the further implementation and cost reductions of renewable heating systems, especially for heating networks. Nevertheless, significant learning rates can be expected if renewable heating is increasingly implemented, as projected in all scenarios.

Table 15 presents the investment cost assumptions for heating technologies, disaggregated by sector. Geothermal heating shows the same high costs in all sectors. In Europe, deep geothermal applications are being developed for heating purposes at investment costs ranging from €500/kW$_{\text{thermal}}$ (shallow) to €3000/kW$_{\text{thermal}}$ (deep), with the costs strongly dependent on the drilling depth. The cost reduction potential is assumed to be around 30% by 2050. No data are available for the specific situation in Rwanda. However, geothermal power and heating plants are not assumed to be built under any scenario.

Heat pumps typically provide hot water or space heat for heating systems with relatively low supply temperatures, or they supplement other heating technologies. Therefore, they are currently mainly used for small-scale residential applications. Costs currently cover a large bandwidth and are expected to decrease by only 20% to US$1450/kW by 2050.

We assume the appropriate differences between the sectors for biomass and solar collectors. There is a broad portfolio of modern technologies for heat production from biomass, ranging from small-scale single-room stoves to heating or CHP plants on an MW scale. Investment costs show similar variations: simple log-wood stoves can be run for US$100/kW, but more sophisticated automated heating systems that cover the whole heat demand of a building are significantly more expensive to run. The running costs of log-wood or pellet boilers range from US$500–1300/kW, and large biomass heating systems are assumed to reach their cheapest cost in 2050 at around US$480/kW for industry. For all sectors, we assume a cost reduction of 20% by 2050.

In contrast, solar collectors for households are comparatively simple and will become cheap, at US$680/kW, by 2050. The costs of simple solar collectors for service water heating might have been optimized already, whereas their integration into large systems is neither technologically nor economically mature. For larger applications, especially in heat-grid systems, the collectors are large and more sophisticated. Because there is not yet a mass market for such grid-connected solar systems, we assume there will be a cost reduction potential until 2050.

Table 15: Specific investment cost assumptions (in US$2015) for heating technologies in the scenarios until 2050

Investment Costs for Heat Generation Plants									
		2020		2030		2040		2050	
		[US$/kW]	[RWF/kW]	[US$/kW]	[RWF/kW]	[US$/kW]	[RWF/kW]	[US$/kW]	[RWF/kW]
Solar collectors	Industry	820	984,000	730	876,000	650	780,000	550	660,000
	In heat grids	970	1,164,000	970	1,164,000	970	1,164,000	970	1,164,000
	Residential	1,010	1,212,000	910	1,092,000	800	960,000	680	816,000
Geothermal		2,270	2,724,000	2,030	2,436,000	1,800	2,160,000	1,590	1,908,000
Heat pumps		1,740	2,088,000	1,640	1,968,000	1,540	1,848,000	1,450	1,740,000
Biomass heat plants		580	696,000	550	660,000	510	612,000	480	576,000
Commercial biomass heating systems	Commercial scale	810	972,000	760	912,000	720	864,000	680	816,000
Residential biomass heating stoves	Small scale / Rural	110	132,000	110	132,000	110	132,000	110	132,000

2.7.3 RENEWABLE ENERGY COSTS IN RWANDA IN 2021

The following tables provide an overview of the specific renewable energy costs in Rwanda. This information is based on information from Power Shift Africa.

Table 16: Solar Home System costs

Solar Home Systems	[RWF]	[$]	[$\text{US\$/kW}_{peak}$]
10 W	55,200	46	4,572
20 W	103,200	86	4,322
50 W	190,800	159	3,186
55 W	207,600	173	3,152
60 W	220,800	184	3,059
80 W	252,000	210	2,629
100 W	300,000	250	2,495
Institutional Solar Power Systems	[RWF]	[$]	[$\text{US\$/kW}_{peak}$]
1000 W	2,732,400	2,277	2,277
2000 W	4,579,200	3,816	1,908

Table 17: Costs – Solar Dryers

Solar Dryers [1 sqft = 0.0929 m^2]	[RWF]	[$]	[$\text{US\$/m}^2$]
3–6 sqft (household) [	309,600	258	617
10–15 sqft (household)	703,200	586	505
> 21 sqft (institutional)	1,087,200	906	464

Table 18: Costs – Solar Cooker

Solar Cookers	[RWF]	[$]
Parabolic—household	235,200	196
Parabolic—institutional	1,440,000	1,200

Table 19: Cost – biomass stoves

Biomass Stoves	[RWF]	[$]
Institutional improved stove—type 1	466,800	389
Institutional improved stove—type 2	489,600	408
Institutional improved stove—type 3	582,000	485
Natural draft stove	42,000	35
Forced draft stove	85,200	71
Improved metallic stove	116,400	97

2.7.4 FUEL COST PROJECTIONS

Fossil Fuels

Although fossil fuel price projections have seen considerable variations, as described above, we based our fuel price assumptions up to 2040 on *World Energy Outlook 2017* (IEA 2017). Beyond 2040, we extrapolated the price developments between 2035 and 2040 and present them in Table 27. Although these price projections are highly speculative, they provide prices consistent with our investment assumptions. Fuel prices for nuclear energy are based on the values in the Energy [R]evolution report 2015 (Teske et al. 2015)[30], corrected by the cumulative inflation rate for the Eurozone between 2012 and 2015 of 1.82%.

Table 20: Development projections for fossil fuel prices in US$2015 based on World Energy Outlook 2023 (STEPS) (IEA 2023)

Development Projections for Fossil Fuel Prices										
All Scenarios	2019		2025		2030		2040		2050	
	[US$/GJ]	[RWF/GJ]	[US$/GJ]	[RWF/GJ]	[US$/GJ]	[RWF/GJ]	[US$/GJ]	[RWF/GJ]	[US$/GJ]	[RWF/GJ]
Oil	8.5	10,200	12	14,400	11	13,200	10	12,000	10.5	12,600
Gas	9.8	11,760	20	24,000	10	12,000	11	13,200	12	14,400
Coal	3.2	3,840	3.5	4,200	4	4,800	3.8	4,560	3.5	4,200

2.7.5 BIOMASS PRICES

Biomass prices depend on the quality of the biomass (residues or energy crops) and the regional supply and demand. The global variability is large. Lamers et al. (2015)[33] reported a price range of €4–4.8/GJ for forest residues in Europe in 2020, whereas agricultural products might cost €8.5–12/GJ. Lamers et al.[33] modelled a range for wood pellets from €6/GJ in Malaysia to €8.8/GJ in Brazil. IRENA modelled a cost supply curve on a global level for 2030, ranging from US$3/GJ for a potential of 35 EJ/yr up to US$8–10/GJ for a potential of up to 90–100 EJ/yr (IRENA 2014) (and up to US$17/GJ for a potential extending to 147 EJ).

Bioenergy prices in Rwanda in 2021

Table 21: Biogas prices—small quantities—in Rwanda by region (estimation)

Biogas	2 m^3		4 m^3		6 m^3		8 m^3	
	[RWF]	[$]	[RWF]	[$]	[RWF]	[$]	[RWF]	[$]
Household— low cost assumption	493,200	411	704,400	587	811,200	676	907,200	756
Household— average cost	577,200	481	776,400	647	898,200	749	979,800	817
Household— high cost assumption	661,200	551	848,400	707	985,200	821	1,052,400	877

Source: UTS/ISF own research – March 2023

Table 22: Biogas prices—medium quantities—in Rwanda by region (estimation)

Biogas	12.5 m^3		40 m^3		60 m^3		100 m^3	
	[RWF]	[$]	[RWF]	[$]	[RWF]	[$]	[RWF]	[$]
Household— low cost assumption	2,605,200	2,171	7,506,000	6,255	9,964,800	8,304	14,534,400	12,112
Household— average cost	2,851,800	2,377	7,969,200	6,641	11,466,000	9,555	16,705,800	13,922
Household— high cost assumption	3,098,400	2,582	8,432,400	7,027	12,967,200	10,806	18,877,200	15,731

Source: UTS/ISF own research – March 2023

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[33] Lamers P, Hoefnagels R, Junginger M, Hamelinck C, Faaij A (2015) Global solid biomass trade for energy by 2020: an assessment of potential import streams and supply costs to North-West Europe under different sustainability constraints. GCB Bioenergy 7 (4):618–634. doi:https:// doi.org/10.1111/gcbb.12162

3 Rwanda: Renewable Energy Potential

Rwanda's solar and wind potential was assessed as an input for energy scenario development. In this section, we assess the technical potential under space-constrained conditions.

3.1 THE [R]E SPACE METHODOLOGY

GIS mapping was used to ascertain Rwanda's renewable energy resources (solar and wind). It was also used in the regional analysis of geographic and demographic parameters and the available infrastructure that could be leveraged in developing the scenarios. Mapping was performed with the software ESRI ArcGIS10.6.1, which allows spatial analysis and maps the results. It was used to allocate solar and onshore wind resources and for the demand projections for the country. Population density, access to electricity infrastructure, and economic development projections are key input parameters in an analysis of Rwanda's future energy situation, to clarify the requirements for additional power grid capacities and/or micro-grids.

The [R]E Space methodology is part of the One Earth Climate Model (OECM) methodology to map solar energy potential and onshore energy potential. Open-source data and maps from various sources were collected and processed to visualize the country. Further demographic data related to the population and poverty were plotted on the maps together with transmission networks and power plants. The main data sources and assumptions made for this mapping are summarized in Table 23.

Table 23: Rwanda—[R]E 24/7—GIS-mapping—data sources

Data	Assumptions	Source
Land cover	Land cover classes suitable for solar energy and wind energy production were identified from Copernicus Global Land Cover 2019.	Copernicus Global Land Cover - 2019[34]
Digital Elevation Model (DEM)	For both wind and onshore solar analyses, any land with a slope of > 30% was excluded from all scenarios.	SRTM Digital Elevation Data Version 4[35]
Population and Population Density	A population census was conducted in 2022 by the National Institute of Statistics of Rwanda.	Fifth Rwanda Population and Housing Census, 2022[36]
Protected Areas	All protected areas designated national parks, wildlife reserves, hunting reserves, conservation areas, or buffer zones were excluded from all scenarios.	World Database on Protected Areas[37]
Power Plants, Transmission Lines, and Network	Solar and wind potential of areas ≤ 10 km from transmission lines was considered (Scenario 2).	Electric network operation facility dashboard[38]
Solar Irradiance (direct normal irradiation: DNI)	The average yearly direct normal insolation/irradiation (DNI) values range from 1 to 5 MWh/m^2 per year (2.7–13.6 kWh/m^2 per day).	Global Solar Atlas[39]
Wind Speeds	Wind speeds ≥ 5 m/s were considered at a height of 100 m.	Global Wind Atlas [40]

The [R]E Space mapping procedure is summarised in Figure 11. The land areas available for potential solar and onshore wind power generation were calculated and visualized at the national and provincial levels using ArcGIS. The land-cover map, elevation (digital elevation model: DEM), World database of protected areas, solar irradiation (direct normal irradiation: DNI) and wind speed data were obtained from the website cited above as raster data, and were all converted into binary maps (0 = area not suitable as a potential area, 1 = area suitable as a potential area) against all the assumptions in Table 23, and then combined into one binary map by overlaying all the raster data. This map integrates all the criteria listed cited above in one map with a value of 1 (land included in the potential area) or a value of 0 (land not included in the potential area).

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[34] Copernicus Global Land Cover – 2019: https://land.copernicus.eu/global/products/lc
[35] SRTM Digital Elevation Data Version 4: https://srtm.csi.cgiar.org/
[36] 5th Population and housing Census Rwanda, 2022, National Institute of Statistics of Rwanda:https://www.statistics.gov.rw/publication/main_indicators_2022
[37] World Database on Protected Areas: https://www.protectedplanet.net/en/thematic-areas/wdpa?tab=WDPA
[38] Electric network operation facility dashboard: https://euclgis.reg.rw/portal/apps/opsdashboard/index.html#/0e19ddea1f53465d8437098f3c2102e3
[39] Global Solar Atlas: https://globalsolaratlas.info/map
[40] Global Wind Atlas: https://globalwindatlas.info/en

Data on transmission lines and protected areas exist as vector data. All protected areas were excluded from the above value 1 area in the integrated raster data using a mask layer generated from the 'erase' function. For scenario 2 (see Figure 21), buffer layers were generated from transmission line (10 km) data, and then the raster data without protected areas were clipped by these buffer layers to generate potential area maps under Scenario 2. This input was fed into the calculations for the [R]E 24/7 model, as described below.

Disclaimer: The environmental criteria used to identify suitable areas for utility scale solar and wind projects do not reflect the current legislation in Rwanda, and the potential provided is a conservative estimate and may ultimately be larger.

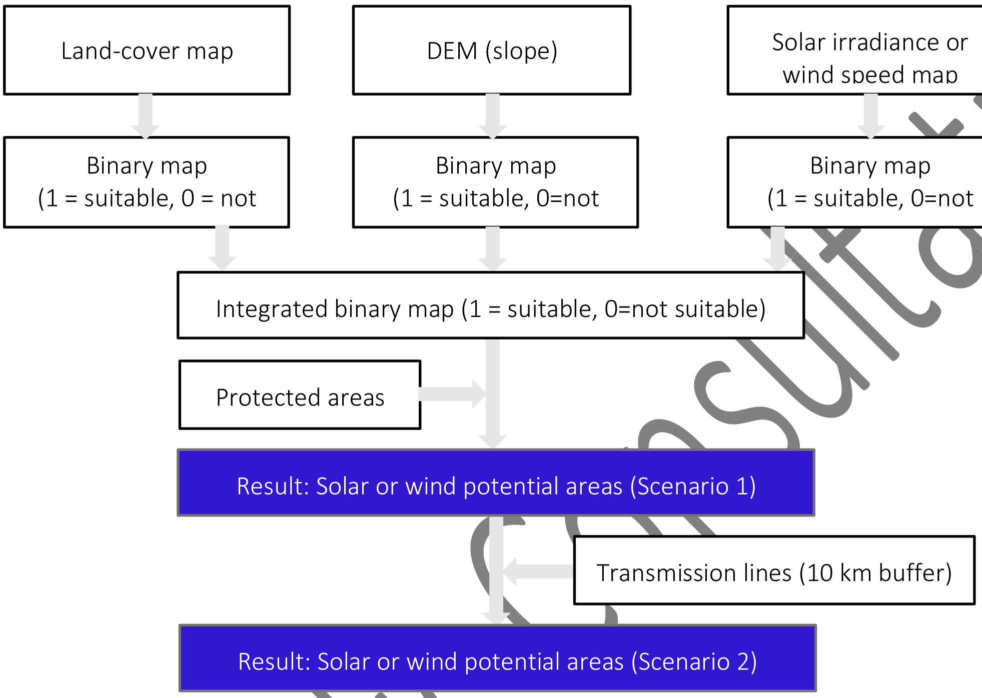

Figure 11: [R]E Space methodology—solar potential analysis and onshore wind potential analysis

3.2 MAPPING RWANDA

Rwanda's energy generation mix is characterized by a significant share of renewable energy sources, mostly hydropower and small percentage of solar energy. Electricity constitutes only 2 % of the total power consumption of the country. However, hydro accounts for 45% of the installed capacity, followed by diesel (non- renewable, 27%), methane (13.9%), peat (7%) and solar (5.6%)[40]. The installed capacity of solar is 12MW - solar power emerges as a promising option, especially as an off-grid solution, providing electricity access without necessitating substantial grid expansion investments) [41]. On the other hand, exploration of wind power potential has been relatively limited in Rwanda, indicating low suitability for conventional generation.

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[41] Bolson, N. and Patzek, T., 2022. Evaluation of Rwanda's energy resources. Sustainability, 14(11), p.6440.

3.2.1 SOLAR POTENTIAL

The yearly totals of solar irradiation (DNI) level in Rwanda is 608– 1468 kWh/m^2 (Global Solar Atlas).Rwanda's solar potential has been mapped for a national level under two different scenarios.

Scenario 1. Available land—excluding protected areas (PA), extreme topography (slope > 30% (mountainous areas, S30), and certain land-cover classes, including closed forests, wetlands, moss and lichen, snow and ice, and water (permanent water bodies) (LU).

Scenario 2. See 1, with additional restriction that excludes areas ≤ 10 km from existing transmission lines (PT10).

Table 24: Rwanda's potential for utility-scale solar photovoltaic

	1. LU + PA + S30		2. LU + PA + S30 + PT10	
Rwanda	Solar Potential Area (km^2)	Solar Potential (MW)	Solar Potential Area (km^2)	Solar Potential (MW)
TOTAL	16,177	404,420	15,540	388,497

Table 25 and Figure 12 shows the results of a spatial analysis indicating the solar potential areas under Scenario 1 (LU + PA + S30) in Rwanda. The scenario provides 16,177 km^2 of areas with solar potential and a total potential for utility-scale solar PV capacity of 404,420 MW (0.4 GW). Scenario 1 excludes all protected areas and areas with slopes > 30%, because installing and maintaining solar panels in steep areas is unrealistic. Open forests, shrubs, herbaceous vegetation, bare/spare vegetation, agricultural land, and urban/built-up land-cover classes in the Copernicus Global Land Cover 2019 dataset are included. However, certain land-cover classes (e.g., closed forests, wetlands, water bodies, snow and ice) are excluded in the scenarios selected for the consideration of solar energy potential.

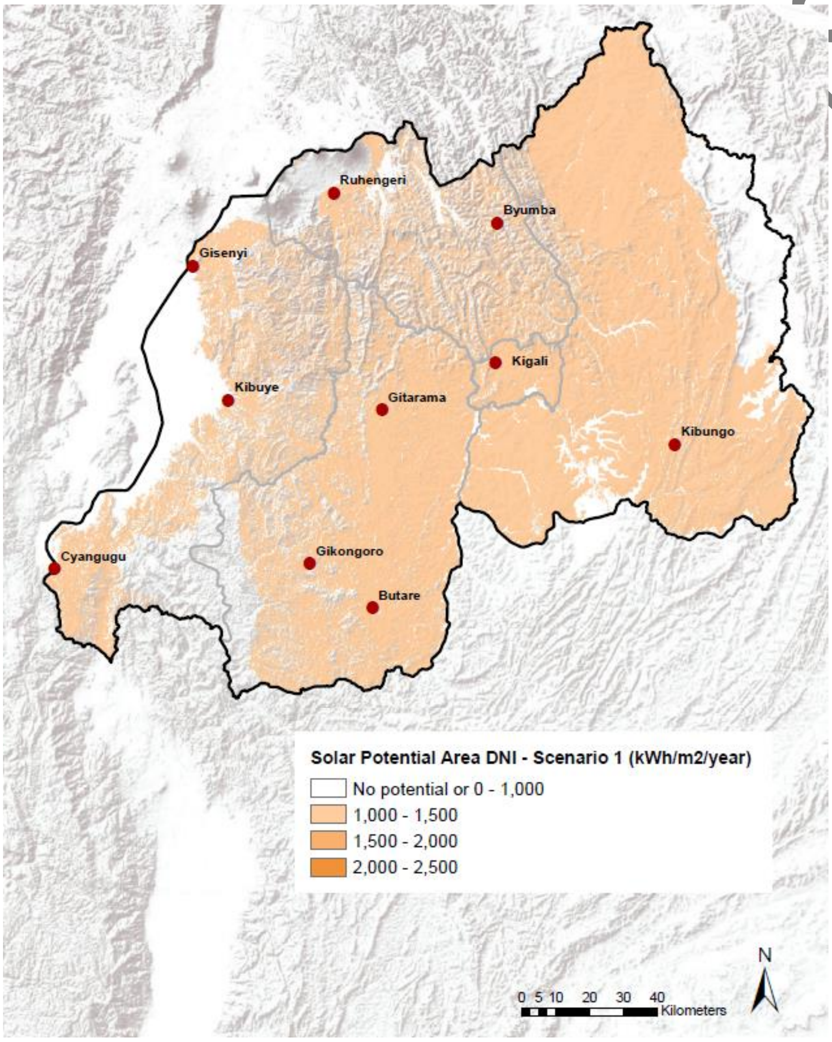

Figure 12: Rwanda—Solar Potential Areas (Scenario 1: LU + PA + S30)

Figure 13 shows the solar potential areas for Scenario 2 (LU + PA + S30 + PT10). When the land area is restricted by its proximity to power lines (10 km), the potential solar areas decrease to 15,540 km^2. Under Scenario 2, utility-scale solar farms in Rwanda can potentially harvest 388,497 MW (0.4 GW) of solar PV.

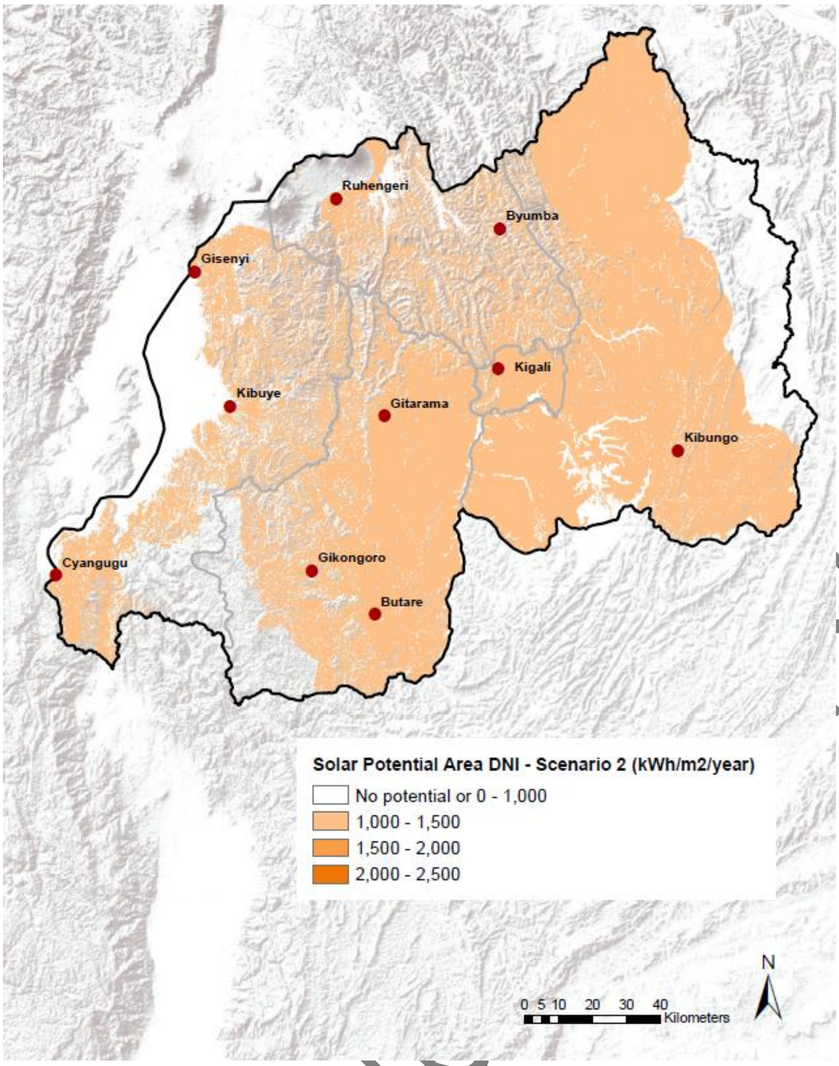

Figure 13: Rwanda- Solar Potential Areas (Scenario 2: LU + PA + S30 + PT10)

3.2.2 ONSHORE WIND POTENTIAL

The overall wind resources on land are significantly low in Rwanda compared with the solar potential. The wind speeds in Rwanda range from 1.1 to 10.6 m/s at 100 m height, while the country's average wind speed is relatively low - only 3.3 m/s (Global Wind Atlas). In this analysis, we have included only areas with an average annual wind speed of ≥ 5 m/s. Rwanda's wind potential has been mapped under two different scenarios.

'Scenario 1': Available land—restricted by protected areas (PA), topography (slope > 30% [mountain areas], S30), and existing land use, including forests and urban areas (LU).

'Scenario 2': See 1, with the additional restriction excluding areas ≤ 10 km from existing transmission lines (PT10).

Open forest, shrubs, herbaceous vegetation, bare/sparse vegetation, and agricultural land were included in the available land (LU) for the two wind scenarios, whereas the land-cover classes closed forests, wetland, moss and lichen, urban/built up areas, snow and ice, and permanent water bodies were excluded in this analysis of wind potential.

Table 25 shows that the overall total onshore wind potential under all restrictions is only 1,443 MW for Scenario 1 and 1,425 MW for Scenario 2. Overall, the spatial analysis identified very limited wind potential in Rwanda, because of very limited areas with an annual wind speed of ≥ 5 m/s within the country.

Table 25: Rwanda's potential for utility-scale wind power

Scenarios	1. LU + PA + S30		2. LU + PA + S30 + PT10	
Rwanda	Onshore Wind Potential Area (km^2)	Onshore Wind Potential (MW)	Onshore Wind Potential Area (km^2)	Onshore Wind Potential (MW)
TOTAL	289	1,443	285	1,425

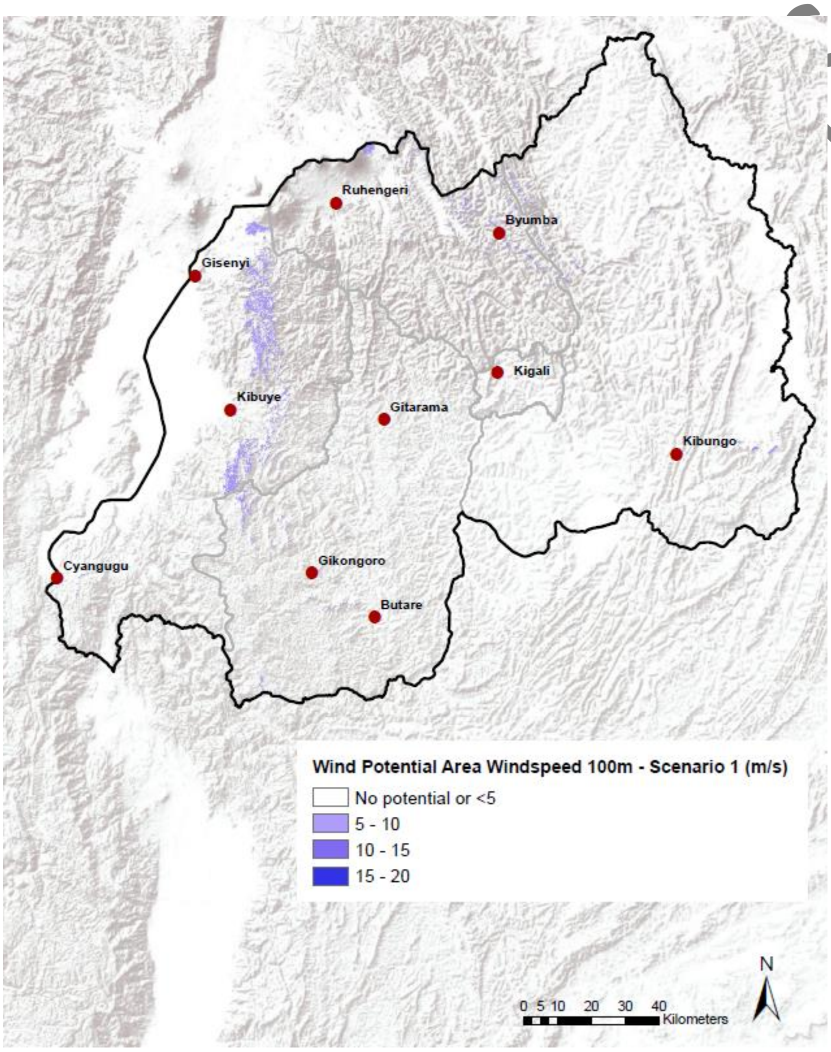

Figure 14: Rwanda— Onshore Wind Potential Areas (Scenario 1: LU + PA + S30

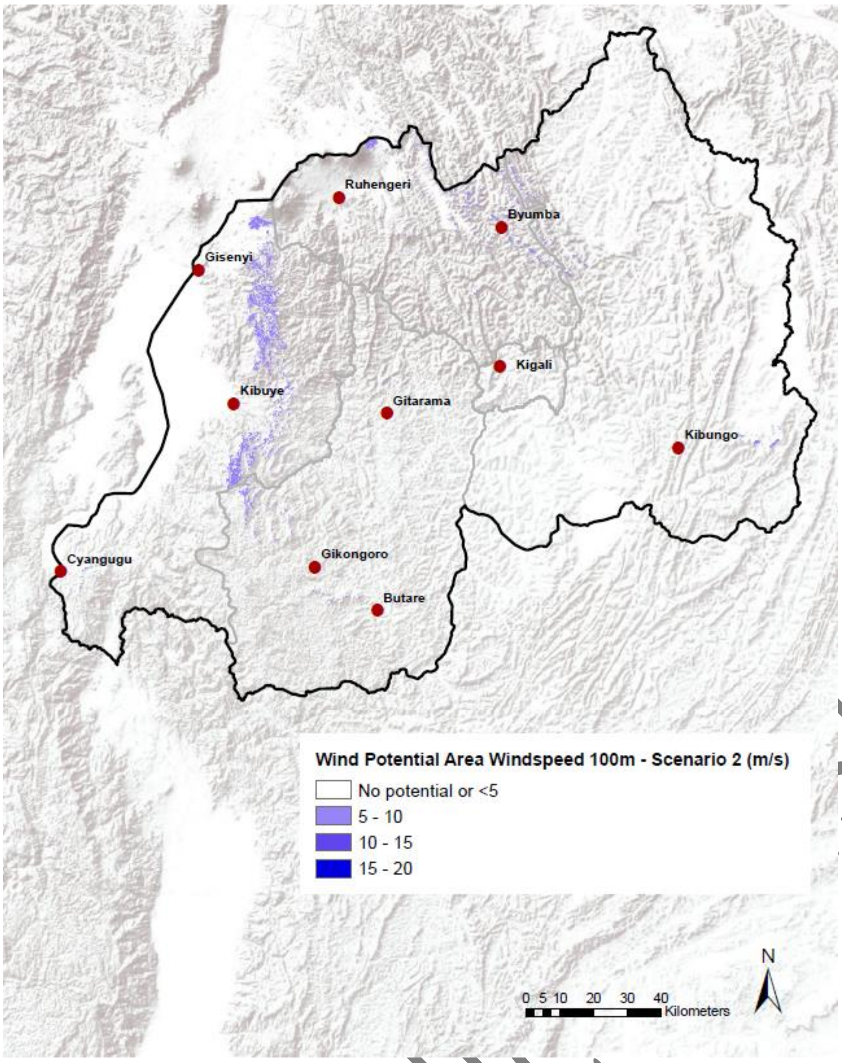

Figure 15: Rwanda—Onshore Wind Potential Areas (Scenario 2: LU + PA + S30 + PT10)

Main challenge for utility-scale solar PV is the availability of land and policy stability

To use Rwanda's utility-scale solar PV potential as efficiently as possible, further research is required, breaking down the utility-scale PV potential further into ground-mounted solar PV, agricultural solar PV, and floating solar PV.

- Utility-scale solar PV: Large-scale solar PV generators require space. Space is limited in Rwanda and energy generation must often compete with other forms of land use. Therefore, space for solar power should be utilized as efficiently as possible, and multiple use options should be considered.
    - Agricultural solar PV is a new development that combines agricultural food production techniques with solar PV equipment. The solar generator is mounted above the field—sometimes several meters high—to leave enough space for harvesting and to ensure light access.
    - R&D is required into floating solar generators on lakes, especially the water storage reservoirs of hydropower stations with dams. Floating solar is a fairly new form of solar PV. In standardized floating devices for utility-scale projects, solar panels designed for ground-mounted systems are usually used.

Furthermore, policy changes regarding licensing and electricity rates for generated solar electricity have undergone changes in the past, which increases the risks to project development and the operation of systems. Higher risks lead to higher capital costs and lower economic advantages. Therefore, policy stability is a key driver of every technology, including utility-scale solar PV power plants.

3.2.3 ASSUMPTIONS FOR HYDROGEN AND SYNFUEL PRODUCTION

In the Rwanda 1.5 °C (R-1.5°C) scenario, hydrogen and sustainable synthetic fuels will be introduced as a substitute for natural gas. Unsustainable biomass will only play a minor role and will be used almost exclusively by industry after 2030. Hydrogen is assumed to be produced by electrolysis, producing an additional electricity demand that will be supplied by extra renewable power production capacity, predominantly solar PV and hydropower. Renewable hydrogen and synthetic fuels are essential for a variety of sectors.

- In the industry sector, hydrogen is an additional renewable fuel option for high-temperature applications, supplementing biomass in industrial processes whenever the direct use of renewable electricity is not applicable.
- The transport sector will also rely increasingly on hydrogen as a renewable fuel, where battery-supported electric vehicles reach their limits and where limited biomass potential restricts the extension of biofuel use. However, future hydrogen applications may be insufficient to replace the whole fossil fuel demand, especially in aviation, heavy-duty vehicles, and navigation. The R-1.5°C scenario introduces synthetic hydrocarbons from renewable hydrogen, electricity, and biogenic/atmospheric CO_2. These synthetic fuels will be introduced after 2030 and provide the remaining fossil fuel demand that cannot meet with biofuels because their potential is limited.

4 Areas of Forest Loss in Rwanda

The Food and Agriculture Organization of the United Nations (FAO) is a specialized agency that leads international efforts to abolish hunger and improve nutrition and food security. The FAO has published extensive food production data and other data related to agriculture and forestry. According to the FAO[42], the forest area in Rwanda in 2020 was 2,760km^2 (including 1,260 km^2 of naturally regenerated forest), which is a 12.9 % decrease from 1990 and a 4.0 % decrease from 2000, respectively [40]. These increases resulted in negative carbon emissions from the forest sector (Table 26).

Table 26: Extent of forest areas and net emissions from forested land in Rwanda (FAO)

	Extent of Forest	
Year	Areas (km^2)	Change from 1990 (%)
1990	3,170	-
2000	2,875	-9.3
2010	2,640	-16.7
2020	2,760	-12.9

Source: FAO Global Forest Resources Assessment Country Reports 2020

Global Forest Change also reported that between 2001 to 2021 Rwanda has lost 430 km^2 of tree cover (equivalent to 8.7% decrease in tree cover since 2000) which generated 27Mt of CO_2e emissions. This includes loss of 4.9 km^2 of humid primary forest between 2002 to 2021, and forest has been cleared mostly with the expansion of agricultural during that period[43]. The loss of forest areas in Rwanda were also visualized with ArcGIS (Table 27 and Figure 16). The spatial dataset by Hansen et al.[44] was used to highlight forest loss (2001–2021) using ArcGIS Areas of forest loss are found across the country, especially in the western province. Table 29 shows the areas of forest loss (km^2), which were also estimated from Hansen et al. (2013) together with the estimated CO_2e emissions since 2000 (the baseline year of this dataset) (Global Forest Watch, 2023)

Table 27: Rwanda—areas of forest loss (km^2) and estimated CO_2e emissions from the forest loss

Years	Area (km^2)	CO_2e emissions (kilotonnes)
2001–2005	54.6	2,172
2006–2010	71.1	3,423
2011–2015	120.4	7,138
2016–2021	184.2	14,504
TOTAL areas of forest loss (2001–2021)	430.4	27,237

Source: Global Forest Change

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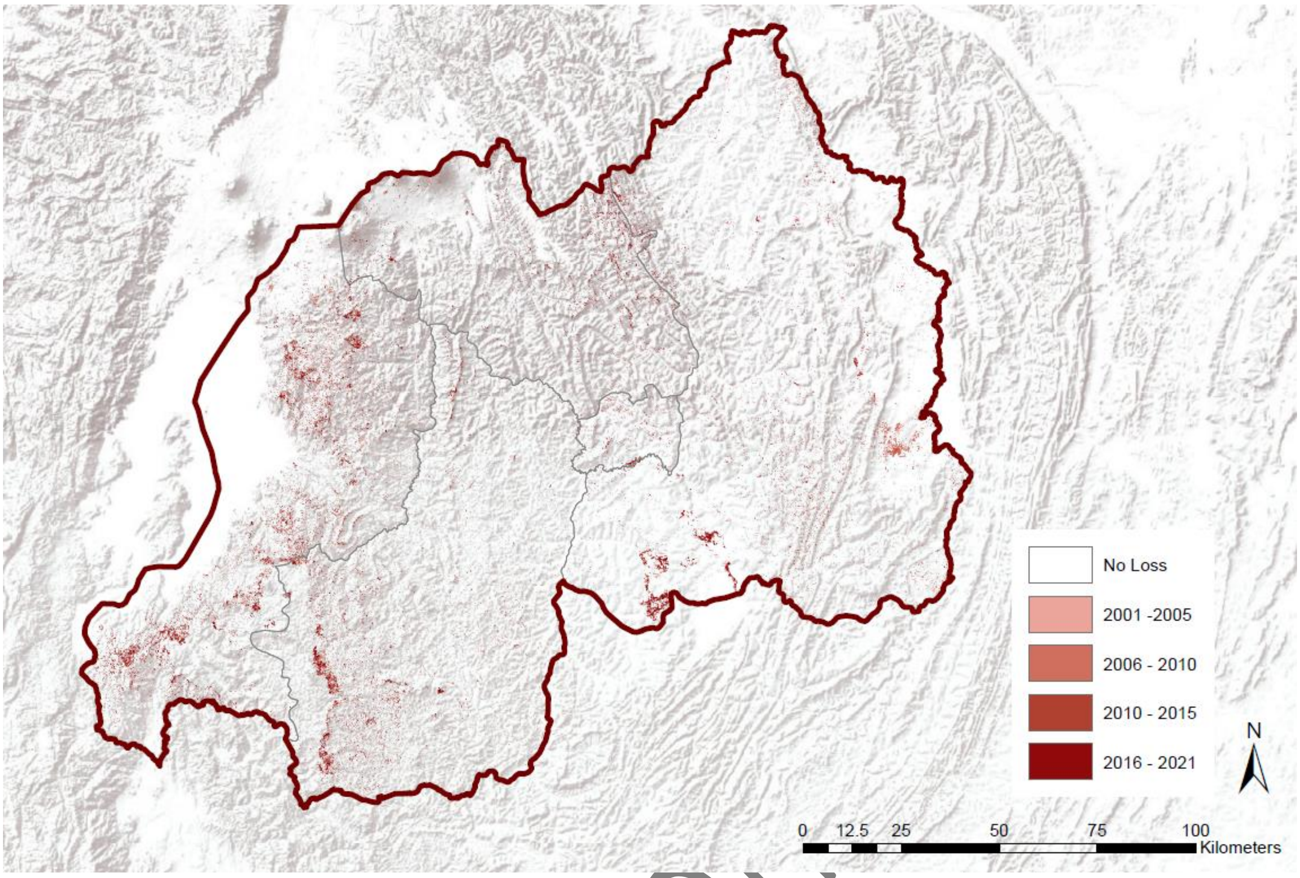
[42] FAO Global Forest Resources Assessment 2020 (Rwanda): https://www.fao.org/3/ca9878fr/ca9878fr.pdf

[43] Global Forest Change (Rwanda): https://www.globalforestwatch.org/dashboards/country/RWA/?map=eyJjYW5Cb3VuZCI6dHJ1ZX0%3D

[44] Hansen, M. C., P. V. Potapov, R. Moore, M. Hancher, S. A. Turubanova, A. Tyukavina, D. Thau, S. V. Stehman, S. J. Goetz, T. R. Loveland, A. Kommareddy, A. Egorov, L. Chini, C. O. Justice, and J. R. G. Townshend. 2013. "High-Resolution Global Maps of 21st-Century Forest Cover Change." Science 342 (15 November): 850-53. Data available on-line at: https://glad.earthengine.app/view/global-forest-change



Source: generated by ISF using Hansen et al. 2013

Figure 16: Areas of forest loss in Rwanda 2001–2021)

5 Key Results—Long-term Scenario

Rwanda must build up and expand its power generation system to increase the energy access rate to 100%. Building new power plants—no matter the technology—will require new infrastructure (including power grids), spatial planning, a stable policy framework, and access to finance.

With lower solar PV and onshore wind prices, renewables have become an economic alternative to building new hydro- and gas power plants. Consequently, renewables achieved a global market share of over 80% of all newly built power plants in 2021[45]. Rwanda has significant solar resources, but only very limited wind potential. The costs of renewable energy generation are generally lower with stronger solar radiation and stronger wind speeds. However, constantly shifting policy frameworks often lead to high investment risks and higher project development and installation costs for solar and wind projects relative to those in countries with more stable policies.

The scenario-building process for all scenarios includes assumptions about policy stability, the role of future energy utilities, centralized fossil-fuel-based power generation, population and GDP, firm capacity, and future costs.

- **Policy stability:** This research assumes that Rwanda will establish a secure and stable framework for deploying renewable power generation. Financing a gas power plant or a wind farm is quite similar. In both cases, a power purchase agreement, which ensures a relatively stable price for a specific quantity of electricity, is required to finance the project. Daily spot market prices for electricity and/or renewable energy or carbon are insufficient for long-term investment decisions for any power plant with a technical lifetime of 20 years or longer.
- **Strengthened energy efficiency policies:** Existing policy settings, namely energy efficiency standards for electrical applications, buildings, and vehicles, must be strengthened to maximize the cost-efficient use of renewable energy and to achieve high energy productivity by 2030.
- **Role of future energy utilities:** With 'grid parity' of rooftop solar PV under most current retail tariffs, this modelling assumes that the energy utilities of the future will take up the challenge of increased local generation and develop new business models that focus on energy services, rather than simply on selling kilowatt-hours.
- **Population and GDP:** Projections of population and GDP are based on historical growth rates. Projections of population growth are taken from the *World Bank Development Indicators*[46]
- **Firm capacity:** The scale of each technology deployed and the combination of technologies in the three scenarios target the firm capacity. Firm capacity is the "proportion of the maximum possible power that can reliably contribute towards meeting the peak power demand when needed."[47] Firm capacity is important to ensure a reliable and secure energy system. Note that variable renewable energy systems still have a firm capacity rating, and the combination of technology options increases the firm capacity of the portfolio of options (see also the 'security of energy supply' point in the REFERENCE scenarios).
- **Cost assumptions:** The cost assumptions are documented in Section 2.

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[45] REN21 – Global Status report 2021.
[46] World Bank, (2023), Reviewed on: https://data.worldbank.org/indicator/SP.POP.TOTL
[47] http://igrid.net.au/resources/downloads/project4/D-CODE_User_Manual.pdf

5.1 THE REFERENCE SCENARIO

There are a few energy and / or electrification plans for Kenya available.

Thus, the One Earth Climate Model builds on existing information. Table 31 provides an overview to the published energy scenarios and / or energy plans including the National Determined Contribution (NDC). In order to compare the One Earth Climate Model for Rwanda, a new reference has been developed as a direct comparison with published energy plans is not possible due to the different sectorial breakdown and technical resolutions.

Table 28: Rwanda – literature review published energy scenarios and parameters

	Rwanda - Parameter	Analysis		
Nr.	Key graphs made from our own modelling results:	One Earth Climate Model	Info IEA, Africa Energy Outlook 2019 1. Stated policy scenario 2. Africa case	Rwanda: National Determined Contribution (NDC)
1.	Final Energy demand until 2050, split by sector (Transport, Industry, Residential)	yes	No IEA scenario available for Rwanda.	
2.	Development Electricity demand until 2050m TWh/a (Transport, Industry, Residential)	yes		
3.	Heat demand final energy [PJ/a] until 2050, (Industry, Residential)	yes		
4.	Development road transport final energy [PJ/a] until 2050 (Road passenger, freight passenger)	yes		
5.	Breakdown of electricity generation capacity [GW] until 2050 (split by source PV, wind, biomass, hydrogen, fossil fuels)	yes		
6.	Energy supply cooking heat supply [PJ/a] until 2050 (split by source of solar collectors, heat pumps, electric direct heating etc.etc)	yes		
7.	Installed capacity renewable heat generation [GW] until 2050 (split by source)	yes		
8.	Transport energy supply by energy source [PJ/a] until 2050 (split by elec., hydrogen, natural gas, synfuels, biofuels, fossil)	yes		
9.	Total primary energy demand by energy source [PJ/a] until 2050 (split by wind , solar , etc)	yes		
10.	Co2 emissions per sector [Mt/a] until 2050 (Industry, Buildings, Transport, Power generation, Other)	yes		CO_2 emission targets for 2015 and 2030.
11.	Investment cost [billion $/a] until 2050	yes		
12.	Shares of cumulative investment in power generation 2020-2050	yes		Total investment projection for 2025-2030.
13.	Cumulative investment heating technologies 2020-2050	yes		
14.	Installed PV capacities up to 2050	yes		

5.1.1 ASSUMPTIONS FOR THE RWANDA 1.5 °C SCENARIO

The Rwanda 1.5 °C (R-1.5°C) scenario is built on a framework of targets and assumptions that strongly influence the development of individual technological and structural pathways for each sector. The main assumptions considered in this scenario-building process are detailed below.

- **Emissions reductions:** The main measures taken to meet the CO_2 emissions reductions in the R-1.5°C scenario include strong improvements in energy efficiency, which will double energy productivity over the next 10–15 years, and the dynamic expansion of renewable energy across all sectors.
- **Growth of renewables industry**: Dynamic growth in new capacities for renewable heat and power generation is assumed based on current knowledge of the potential, costs, and recent trends in renewable energy deployment. Communities will play a significant role in the expanded use of renewables, particularly in terms of project development, the inclusion of the local population, and the operation of regional and/or community-owned renewable power projects.
- **Fossil -fuel phase-out:** The operational lifetime of gas power plants is approximately 30 years. In both scenarios, coal power plants will be phased out early, followed by gas power plants.
- **Future power supply:** The capacity of large hydropower remains flat in Rwanda over the entire scenario period, whereas the quantities of bio-energy will increase within the nation's potential for sustainable biomass (see below). Solar PV is expected to be the main pillar of the future power supply, complemented by the contributions of bio-energy and wind energy. The figures for solar PV combine rooftop and utility-scale PV plants, including floating solar plants.
- **Security of energy supply:** The scenarios limit the share of variable power generation and maintain a sufficient share of controllable, secured capacity. Power generation from biomass and gas-fired backup capacities and storage are considered important for the security of supply in a future energy system, and are related to the output of firm capacity discussed above. Storage technologies will increase after 2030, including battery electric systems, dispatchable hydropower, and hydro pump storage.
- **Sustainable biomass levels:** Rwanda's sustainable level of biomass use is assumed to be limited to 425 PJ—precisely the amount of bio-energy used in 2020. However, low-tech biomass use, such as inefficient household wood burners, is largely replaced in the R-1.5°C scenario by state-of-the-art technologies, primarily highly efficient heat pumps and solar collectors.
- **Electrification of transport**: Efficiency savings in the transport sector will result from fleet penetration by new highly efficient vehicles, such as electric vehicles, but also from assumed changes in mobility patterns and the implementation of efficiency measures for combustion engines. The scenarios assume the limited use of biofuels for transportation, given the limited supply of sustainable biofuels.
- **Hydrogen and synthetic fuels:** Hydrogen and synthetic fuels generated by electrolysis using renewable electricity will be introduced as a third renewable fuel in the transportation sector, complementing biofuels, the direct use of renewable electricity, and battery storage. Hydrogen generation can have high energy losses; but the limited potential of biofuels, and probably battery storage, for electric mobility means it will be necessary to have a third renewable option in the transport sector. Alternatively, this renewable hydrogen could be converted into synthetic methane and liquid fuels, depending on the economic benefits (storage costs versus additional losses) and the technological and market development in the transport sector (combustion engines versus fuel cells). Because Rwanda's hydrogen generation potential is limited, it is assumed that hydrogen and synthetic fuels will be imported. Furthermore, hydrogen utilization will be limited to the industry sector only, and is not expected to contribute more than 5% of industry's energy supply by 2050.

Rwanda's 1.5 °C scenario (R-1.5°C) takes an ambitious approach to transforming Rwanda's entire energy system to an accelerated new renewable energy supply. However, under the R-1.5°C scenario, a much faster introduction of new technologies will lead to the complete decarbonization of energy for stationary energy (electricity), heating (including process heat for industry), and transportation. In the latter, there will be a strong role for storage technologies, such as batteries, synthetic fuels and hydrogen.

The resulting final energy demand for transportation is lower than that under the WEM scenario, based on the assumptions that:

- future vehicles and particularly electric vehicles, will be more efficient; and
- there will be a greater improvement in the public transport system in R-1.5°C.

Under the R-1.5°C scenario, the share of electric and fuel cell vehicles will increase. This scenario also relies on a greater production of synthetic fuels from renewable electricity, for use in the transport and industry sectors. Renewable hydrogen will be converted into synthetic hydrocarbons, which will replace the remaining fossil fuels, particularly in heavy-duty vehicles and air transportation—albeit with low overall efficiency typical of the synthetic fuel system. Because renewable synthetic fuels require a (gas) pipeline infrastructure, this technology is not widely used in Rwanda's energy plan because the costs in the early development stages are relatively high. It is assumed that synthetic fuels and hydrogen will not enter Rwanda's energy system before 2040. Compensating for the high energy losses associated with producing synthetic fuels will require fundamental infrastructure changes, which seem too costly for a developing country. Electricity and hydrogen will play larger roles in the heating sector (mainly heat for industry), replacing fossil fuels. In the power sector, natural gas will also be replaced by hydrogen. Therefore, electricity generation will increase significantly under this scenario, assuming that power from renewable energy sources will be the future's main 'primary energy'.

The R-1.5°C scenario also models a shift in the heating sector towards the increased direct use of electricity because of the enormous and diverse potential for renewable power and the limited availability of renewable fuels for high-temperature process heat in industry. Increased implementation of a district heating infrastructure (interconnections of buildings in central business districts), bio-energy-based heat generation, and solar collectors and heat pumps for office buildings and shopping centres in larger cities are assumed, leading to a growth in electricity demand that partly offsets the efficiency savings in these sectors. A rapid expansion of solar and geothermal heating systems is also assumed.

The increasing shares of variable renewable power generation, principally by solar PV, will require the implementation of smart grids and the fast interconnection of micro- and mini-grids with regional distribution networks, storage technologies such as batteries and pumped hydro, and other load-balancing capacities. Other infrastructure requirements will include an increasing role for on-site renewable process heat generation for industries and mining, and the generation and distribution of synthetic fuels.

5.1.2 ASSUMPTIONS FOR THE RWANDA REFERENCE SCENARIO

The REFERENCE case for Rwanda has been developed on the basis of the Rwanda 1.5˚C scenario but assumed an implementation delay of 15 years. The REFERENCE case is similar – but not identical - to the BAU scenario in Rwanda's National Determined Contribution submission from 2021.

The key differences are:

1. **Heating a sector:** The phase-out of coal, oil and gas is delayed for the residential, service and industry sector by 15 years. Accordingly, electric heat pumps and solar collector systems will remain niche technologies until 2040 but will grow afterwards and increase their shares by 2050.
2. **Transport sector:** Electric mobility will experience significant delays while transport demand will increase as projected in the 1.5C scenario. Vehicles with internal combustion engines (ICE) will remain dominate until 2040. Market shares for electric vehicles will start to grow from 2040 onwards significantly. Furthermore, biofuels are increased in the road transport sector.
3. **Power supply:** The delayed electrification in the heating and transport sector will lead to a slower growth of power demand compared to the 1.5˚C scenario. Additionally, it is assumed that renewable power generation will not fill the gap of increased electricity demand due to delayed implementation and fossil fuel-based power generation will therefore increases.

5.2 RWANDA—ENERGY PATHWAY UNTIL 2050

The following section provides an overview of the key results of three different energy scenarios for Rwanda. The energy scenarios by no means claim to predict the future; instead, they provide useful tools to describe and compare potential development pathways from the broad range of possible ‘futures’. The R-1.5°C scenario was designed to demonstrate the efforts and actions required to achieve the ambitious objective of a 100 percent renewable energy system and to illustrate the options available to change our energy supply system into one that is truly sustainable. The scenarios may serve as a reliable basis for further analyses of possible concepts and actions needed to implement technical pathways to achieve measurable results.

5.2.1 RWANDA—FINAL ENERGY DEMAND

The projections for population development, GDP growth, and energy intensity are combined to project the future development pathways for Rwanda’s final energy demand. These are shown in Figure 17 for the REFERENCE and R-1.5°C scenarios. In the REFERENCE scenario, the total final energy demand will increase by 62% from 107 PJ/a in 2020 to 173 PJ/a in 2050. The R-1.5°C scenario will reduce any additional costs by a higher proportion of electric cars.

As a result of the projected continued annual GDP growth of 7.8% on average until 2025 and 4.5% thereafter until 2050, the overall energy demand is expected to grow under all three scenarios (Figure 17). The residential sector will remain dominant in Rwanda’s energy demand, but the energy demand of the industry sector will increase constantly. By 2050, industry will consume at least four times more energy than in 2020, making this sector the second highest consumer after transport in all three scenarios.

The energy demand of the transport sector will increase 178% by 2050 under the REFERENCE scenario, whereas it will increase 48% under the R-1.5°C scenario. The main reason for the significant difference in growth projections is the high rates of electrification in the latter two pathways.

The large efficiency gains achieved in the R-1.5°C pathway is attributable to the high electrification rates, mainly in the cooking and transport sectors, because combustion processes with high losses are significantly reduced.

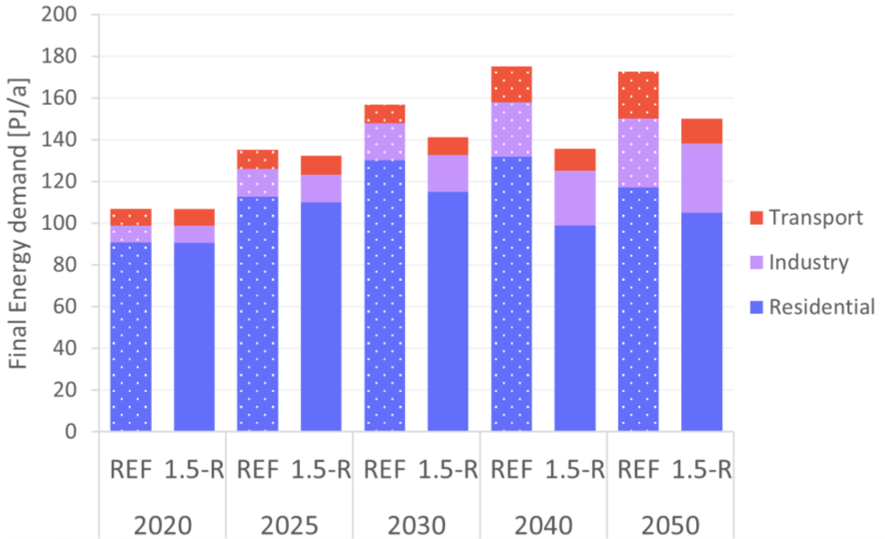


Figure 17: Projection of the total final energy demand by sector (excluding non-energy use and heat from CHP auto producers)

The increased projected electrification of the heating, cooking, and transport sectors, especially under the R-1.5°C scenario, will lead to a significantly increased electricity demand.

The R-1.5°C pathway will accelerate the electrification of the heating, cooking, and transport sectors compared to other pathways, and aims to replace more fossil and biofuels with electricity. By 2050, Rwanda's electricity demand will increase to 31 TWh per year.

Electricity will become the major renewable 'primary' energy, not only for direct use for various purposes, but also for the generation of a limited amount of synthetic fuels to substitute for fossil fuel in providing industrial process heat. Under R-1.5°C, around 0.3 TWh will be used for electric vehicles and rail transport in 2050.

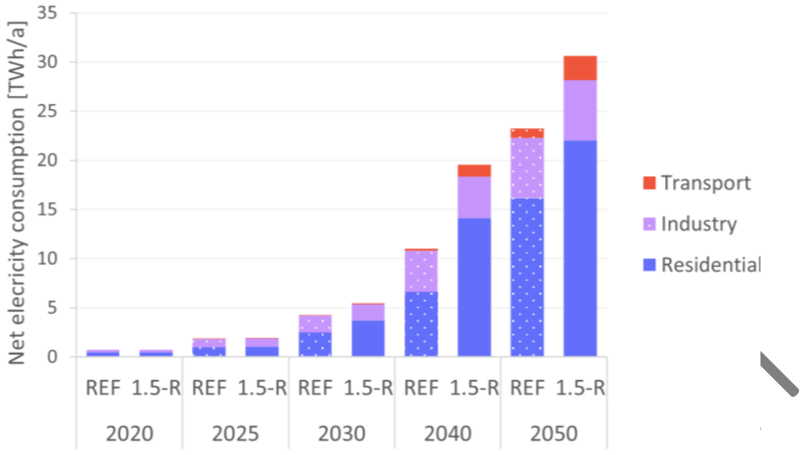


Figure 18: Development of electricity demand by sector

Figure 19: Development of the final energy demand for heat by sector

The energy demand for process heat, space heating of residential and commercial buildings, and cooking will continues to grow in the sustainable pathway. The main driver will be a combination of population growth and the increased role of the industry sector in Rwanda's GDP. The R-1.5°C pathways has an increased role of electrification in the heating supply (with heat pumps) and the implementation of electric cooking.

As a result, the R-1.5°C pathway will lead to an annual heat demand of around 115 PJ/a.

The projected development of the road transport sector (see Figure 20) is very similar between different pathways for Rwanda. More details of the assumptions made for the transport sector projections, broken down into freight and passenger transport, are documented in Section 2.6.

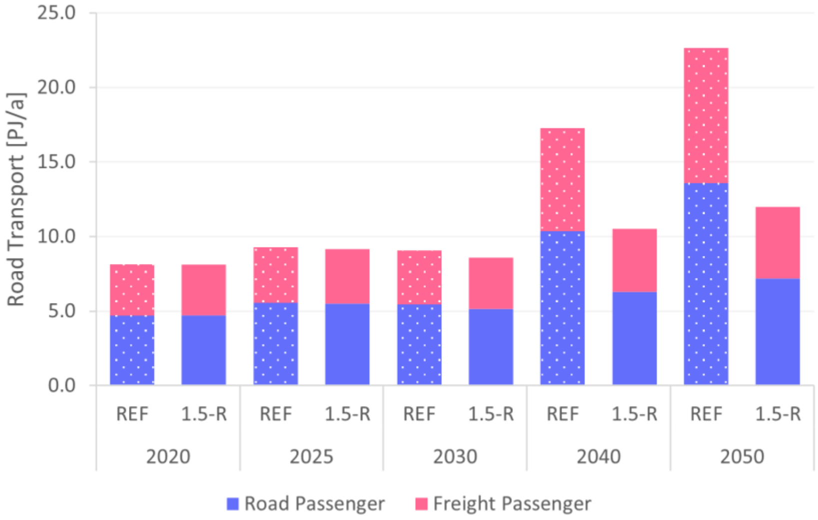


Figure 20: Development of the road transport energy demand for passengers and freight

5.2.2 ELECTRICITY GENERATION

5.2.2.1 Electricity generation, capacity, and breakdown by technology

The development of the electricity supply sector is characterized by a dynamically growing renewable energy market and an increasing share of new renewable electricity, mainly from solar PV. The additional electricity demand caused by accelerated electric cooking and electric vehicles under the R-1.5°C scenario will greatly benefit new renewables, whereas hydropower will continue to generate bulk electricity for industry and export.

By 2025, the share of new renewable electricity production will reach 85% and increase to 100% by 2050 under the R-1.5°C scenario. The installed capacity of new renewables will reach about 8 GW in 2030 and 34 GW in 2050 in the R-1.5°C scenario. In comparison, the REF scenario has 7 GW of renewables in 2030 and 26 GW in 2050. As expected, the R-1.5°C scenarios will lead to higher capacities. Here, the R-1.5°C scenario achieves a 100% electricity supply in 2050, while the REF scenario only reaches 94%.

Table 29 shows the comparative evolution of Rwanda's power generation technologies over time. Solar PV will become the main power source. Around 2025, solar PV will overtake hydropower in installed capacity. The continuing growth of solar PV and additional wind power capacities will lead to a total capacity of 28 GW in 2050, compared with 0.5 GW hydropower under the R-1.5°C scenario. It will lead to a high share of variable power generation and demand-side management, and the management of electric vehicle charging and other storage capacities, such as stationary batteries and pumped hydropower. The development of smart grid management will be required from 2025 onwards to increase the power system's flexibility for grid integration, load balancing, and a secure supply of electricity.

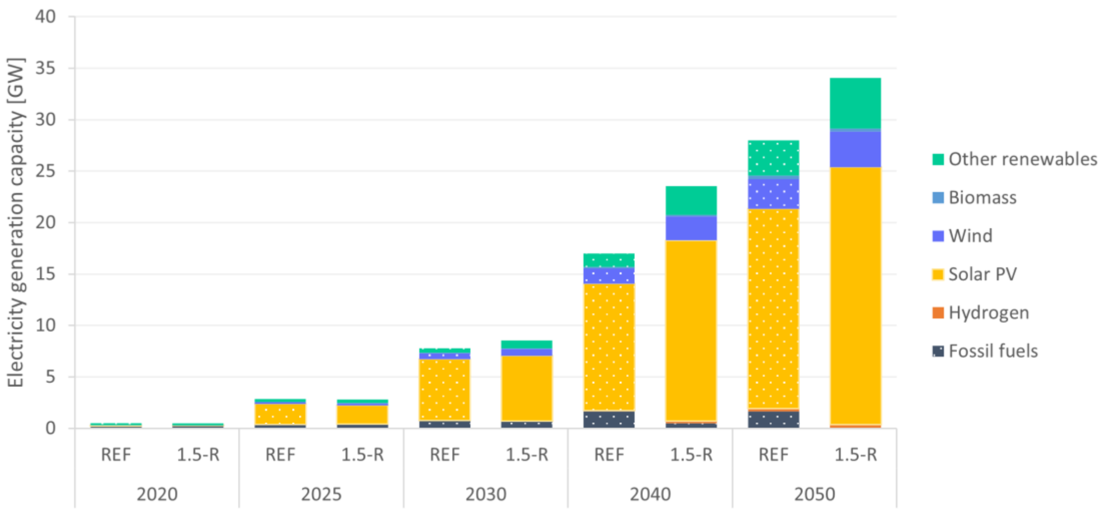


Figure 21: Breakdown of electricity generation by technology

Table 29: Projection of renewable electricity generation capacities

Generation Capacity [GW]			2020	2030	2035	2040	2050
Hydro	REF	GW	0.2	0.3	0.2	0.4	0.9
	R-1.5°C	GW	0.2	0.3	0.3	0.4	0.5
Biomass	REF	GW	0.0	0.0	0.144	0.2	0.3
	R-1.5°C	GW	0.0	0.0	0.110	0.2	0.3
Wind	REF	GW	0	0.6	1	1.5	2.9
	R-1.5°C	GW	0.0	0.7	1	2.3	3.5
PV	REF	GW	0	6.0	9	12.3	19.4
	R-1.5°C	GW	0.0	6.3	6	17.6	25.0
Total	REF	GW	1	8	12	17	28
	R-1.5°C	GW	0	9	16	24	34

5.2.3 ENERGY SUPPLY FOR COOKING AND INDUSTRIAL PROCESS HEAT

Today, bio-energy meets around 90% of Rwanda's energy demand for fuel-based cooking and heating. Dedicated support instruments are required to ensure dynamic development, particularly of electric cooking stoves, renewable heating technologies for buildings, and renewable process heat production. In the R-1.5°C scenario, fuel-based cooking (mainly firewood and LPG) will be replaced by electric cooking stoves. The increased electricity used for e-cooking will increase the electricity demand but will replace a significant amount of bio-energy (firewood) because its efficiency is low. Under R-1.5°C, the use of heat pumps as one of the leading new heating supply technologies will accelerate, and direct electric heating, such as radiators, will be introduced, but only as an interim measure between 2025 and 2030. These will be exchanged for heat pumps at the end of their lifetimes.

- Energy efficiency measures will help to reduce the currently growing energy demand for heating, especially building standards.
- In the industry sector, solar collectors, geothermal energy (including heat pumps), and electricity and hydrogen from renewable sources will increasingly substitute for fossil-fuel- and biofuel-fired systems.

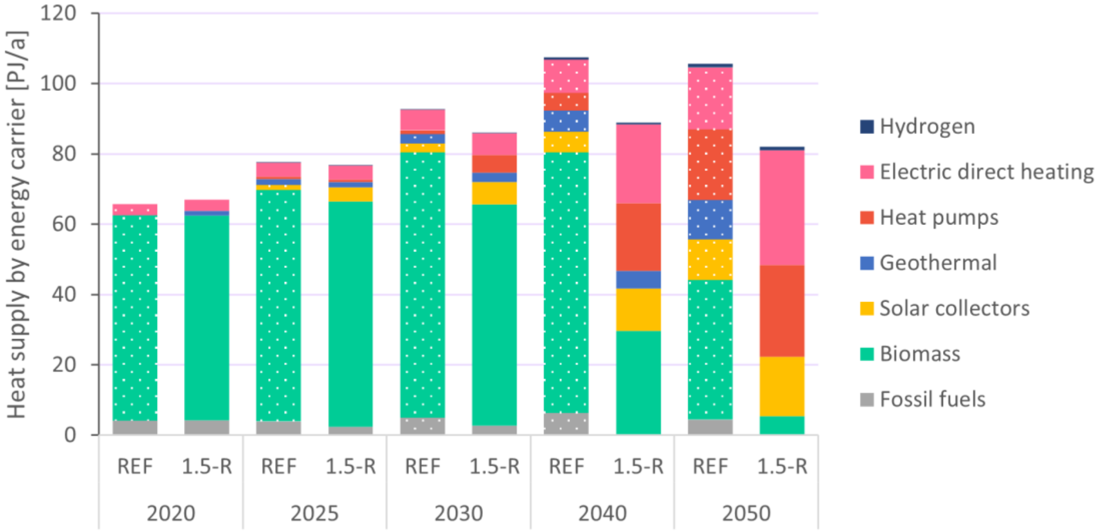


Figure 22: Projection of heat supply by energy carrier (R-1.5°C scenarios)

Table 30: Projection of renewable heat supply (cooking and process heat)

Supply (in PJ/a)		2019	2025	2030	2040	2050
Biomass	REF	58	66	76	74	40
	R-1.5°C	58	64	63	29	5
Solar Heating	REF	0	2	2	6	12
	R-1.5°C	0	4	6	12	17
Heat Pumps (electric & geothermal)	REF	0	1	1	5	20
	R-1.5°C	0	1	5	19	26
Geothermal	REF	0	1	1	3	5
	R-1.5°C	0	2	3	6	11
Direct Electric Heating	REF	3	4	6	10	18
	R-1.5°C	3	4	6	22	33
Total	REF	66	77	91	104	100
	R-1.5°C	66	77	86	90	93

Table 30 shows the development of different renewable technologies for heating in Rwanda over time. Biomass will remain a contributor over the years, with increasing investments in highly efficient modern biomass technology. After 2030, a massive increase in solar collectors and growing proportions of geothermal and environmental heat, as well as electrical heat and some limited renewable hydrogen for industrial process heat, will compensate for the phase-out of fossil fuels. The R-1.5°C scenario includes many efficient heat pumps, which can also be used for demand-side management and load flexibility (see also Section **Error! Reference source not found.**.).

Table 31: Installed capacities for renewable heat generation

Capacities (in GW)		2020	2025	2030	2040	2050
Biomass	REF	10	12	13	14	7
	R-1.5°C	10	11	11	5	1
Geothermal	REF	0	0	0	0	1
	R-1.5°C	0	0	0	1	2
Solar heating	REF	0	0	1	2	4
	R-1.5°C	0	1	2	4	5
Heat pumps (electric and geothermal)	REF	0	0	0	1	7
	R-1.5°C	0	0	2	7	10
Total	REF	13	15	16	19	20
	R-1.5°C	13	15	17	19	21

5.2.4 TRANSPORT

A key target in Rwanda is to introduce incentives for people to support the transition towards electric mobility, especially in urban and semi-urban regions. It is also vital that transport use shifts to efficient public transport modes, such as rail, light rail, and buses, especially in the large expanding metropolitan areas.

Highly efficient propulsion technology, with plug-in hybrid and battery-electric power trains, will bring large efficiency gains. By 2030, electricity will provide 3.8% of the transport under the R-1.5°C scenario. The R-1.5°C scenario will achieve the total decarbonization of the transport sector in Rwanda by 2050. More details about the assumptions made to calculate the transport demand and supply development are documented in Section 2.6.

Table 32: Projection of transport energy demands by mode

Transport mode		Unit	2020	2025	2030	2040	2050
Rail	REF	[PJ/a]	0	0	0	0	0
	R-1.5°C	[PJ/a]	0	0	0	0	0
Road	REF	[PJ/a]	8	9	9	17	23
	R-1.5°C	[PJ/a]	8	9	9	11	12
Domestic Aviation	REF	[PJ/a]	0	0	0	0	0
	R-1.5°C	[PJ/a]	0	0	0	0	0
Total	REF	[PJ/a]	8	9	9	17	23
	R-1.5°C	[PJ/a]	8	9	9	11	12

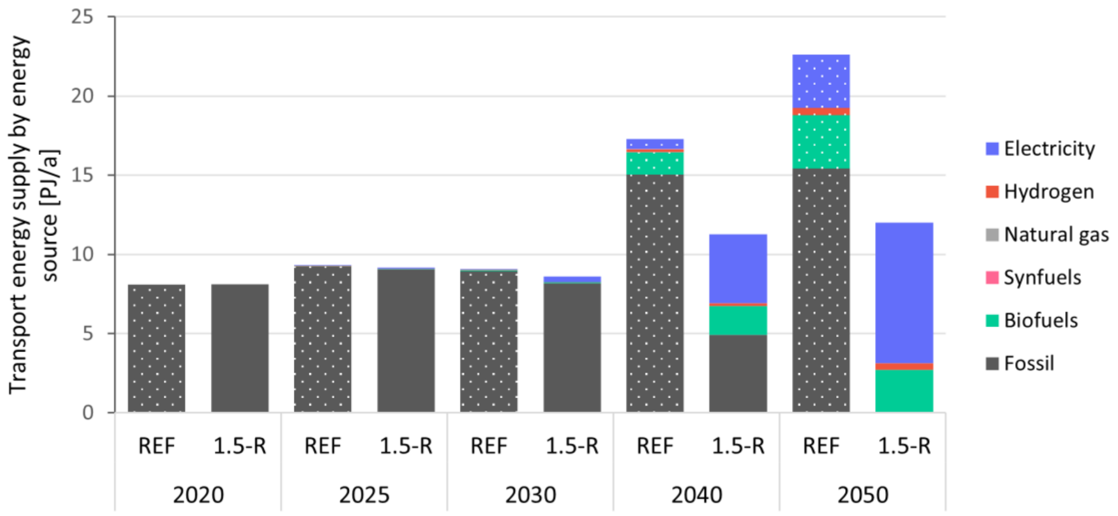


Figure 23: Final energy consumption by transport energy supply

5.2.5 PRIMARY ENERGY CONSUMPTION

Based on the assumptions discussed above, the resulting primary energy consumption from the R-1.5°C is shown in Figure 24. The R-1.5°C scenario will result in primary energy consumption of around 256 PJ in 2050.

The R-1.5°C scenario aims to phase-out oil in the transport sector and oil for industrial use as fast as is technically and economically possible, through the expansion of renewable energies. The fast introduction of very efficient vehicle concepts in the road transport sector will replace oil-based combustion engines. This will lead to an overall renewable primary energy share of more than 92% in 2050 under the R-1.5°C scenario (including non-energy consumption).

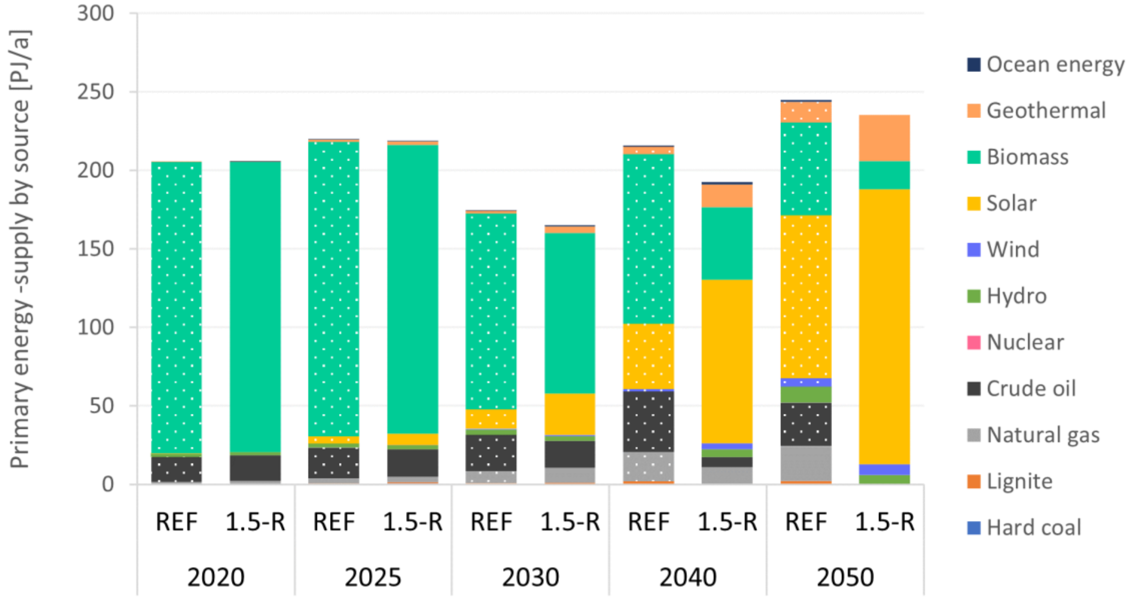


Figure 24: Projection of total primary energy demand by energy carrier (including electricity import balance)

5.2.6 CO_2 EMISSIONS TRAJECTORIES

The R-1.5°C scenario will reverse the trend of increasing energy-related CO_2 emissions after 2025, leading to a reduction of about 40% relative to 2020 by 2030 and of about 23% by 2040. In 2050, full decarbonization of Rwanda's energy sector will be achieved under the R-1.5°C scenario.

In the R-1.5°C scenarios, the cumulative emissions will sum to 31 Mt, respectively.

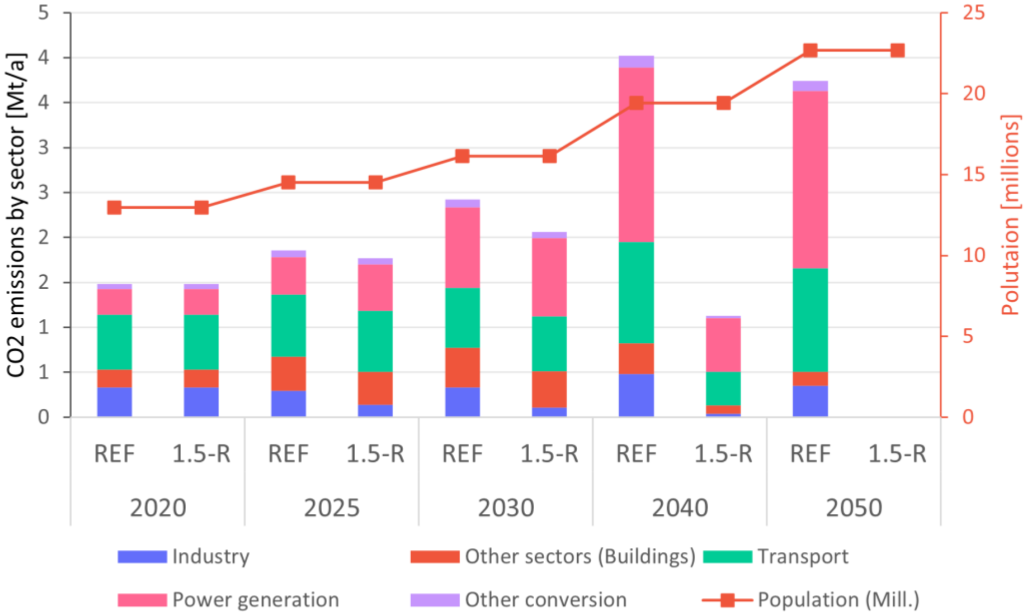


Figure 25: Development of CO_2 emissions by sector

5.2.7 COST ANALYSIS

5.2.7.1 Future costs of electricity generation

Figure 26 shows that introducing new-generation capacities will increase the average electricity generation due to new investments, and consequently, additional capital costs will be required.

The solar PV capacity will increase 128 times in the R-1.5°C scenario from 2020 to 2050. The reason for high generation capacity is the far-reaching electrification strategy to replace fossil fuel with electricity for cooking, heating, and transport.

The R-1.5°C will lead to around higher electricity generation costs for the first 20 years before cost advantages will be reached due to accelerated investment in renewable electricity: full cost of generation is about 35.5 RWF/kWh (0.029$/kWh) under the R-1.5°C scenario in 2030, when no consideration is given to the integration costs for storage or other load-balancing measures (see Figure 26). However, the higher average generation costs under the R-1.5°C scenario will only be temporary and are expected to fall rapidly around 2050, leading to lower generation around 2040 than under both other scenarios. By 2050, the R-1.5°C scenario will lead to average electricity generation costs of 27.9 RWF/kWh (0.023 US$ cent/kWh).

Rwanda's total electricity supply costs will increase with the increasing electricity demand. The R-1.5°C pathway has the highest total electricity costs, but these will directly replace bio-energy and oil fuel costs.

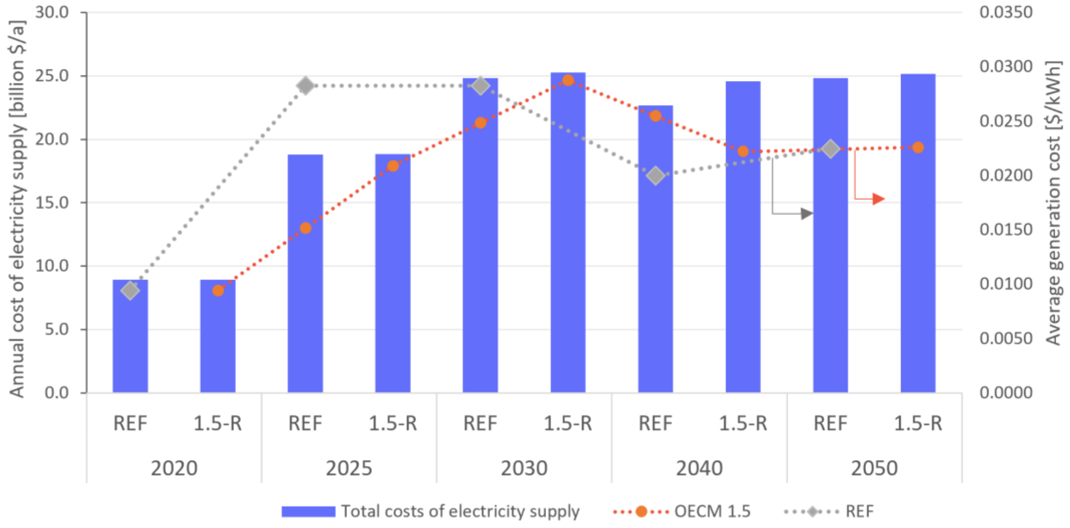


Figure 26: Development of total electricity supply costs and specific electricity generation costs

Investments in power generation

Rwanda will invest in new power generation—mainly solar PV. Here, the main difference between the R-1.5°C scenario and the other scenarios is the investment in other technologies—primarily solar PV. The onshore wind potential of Rwanda is 1,443 MW (Scenario 1) or 1,425 MW (Scenario 2) based on a limited area with annual windspeeds over 5.5 m/s at 100 m height. The electrification of remote villages under the R-1.5°C pathway is mainly based on solar PV power mini-grids with (battery) storage systems. However, wind energy systems can and should play a role in some limited locations. The generation pattern is different from that of solar and will therefore reduce the energy storage requirements because electricity generation is distributed throughout the day and is not limited to daylight hours.

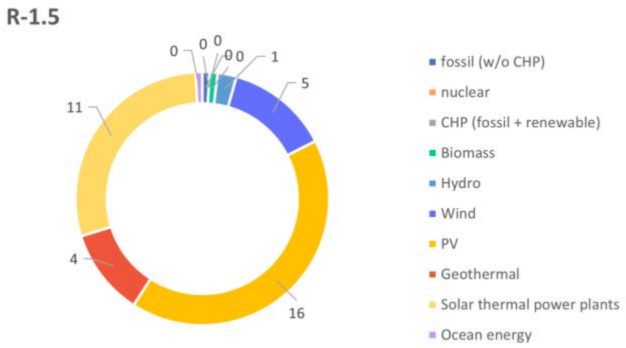


Figure 27: Shares of cumulative investment in power generation, R-1.5°C scenario, 2020 to 2050 [billion $]

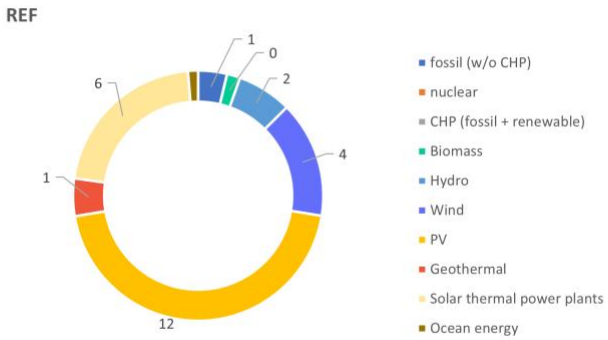


Figure 28: Shares of cumulative investment in power generation, REF scenario, 2020 to 2050 [billion $]

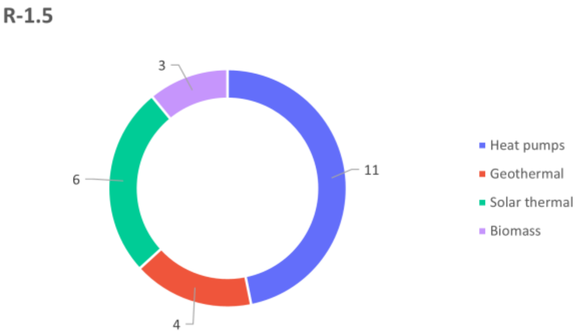
The additional investment in solar PV under the R-1.5°C scenario will amount to around 20 trillion RWF (US$16 billion) over 30 years. This electricity will primarily be used to replace biomass for cooking and heating and to charge various electric vehicles, from two- and three-wheeler vehicles to cars and small delivery trucks.

Table 33: Investment costs in new power generation in the R-1.5°C scenarios (exchange rate: 1 RWF= 0.00081 USD, 29th December 2023)

R-1.5°C	2020-–2050	
	[trillion RWF]	[billion US$]
Hydro	1	1
Biomass	0	0
PV	16	20
Wind	5	6
Fossil & other	16	20
Total	**38**	**47**
REFERENCE	2020-–2050	
	[trillion RWF]	[billion US$]
Hydro	2	2
Biomass	0	1
PV	12	15
Wind	4	5
Fossil & other	9	11
Total	**28**	**34**

5.2.7.2 Future investments in the heating sector

The main difference between the R-1.5°C pathway and other pathways is the significant variety in bio-energy use and the diversification of heating technologies. Electrical heat pumps, geothermal heat pumps, and solar thermal applications for space and water heating and drying will lead to a considerable reduction in the use of biogas and solid biomass, and therefore reduce the fuel costs. Figure 29 shows the shares of cumulative investments in the heating sector between 2020 and 2050.



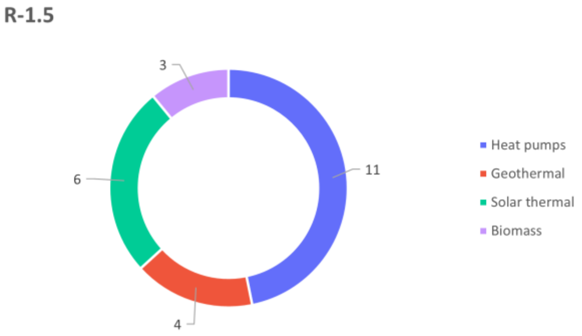


Figure 29: Cumulative investment in the heating technologies (generation) under the R-1.5°C scenario, [billion $] for 2020-2050

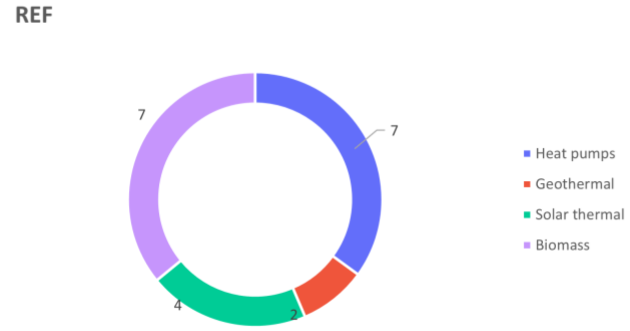


Figure 30: Cumulative investment in the heating technologies (generation) under the REF scenario, [billion $] for 2020-2050

Error! Not a valid bookmark self-reference. shows the cumulative investment and fuel costs in the heating sector for the R-1.5°C scenario and the REF scenario. The overall heat sector costs—investment and fuel costs—over the entire scenario period until 2050 will be 2.8 trillion USD for the R-1.5°C scenario.

Table 34: Rwanda—heating: cumulative investment and fuel costs in 2020–2050

R-1.5°C scenario, cost 2020-2050	[trillion RWF]	[billion US$]
Cumulative heating investment	30	24
Cumulative fuel cost	3341	2,706
Cumulative electricity cost	47	38
Total	3418	2769
REFERENCE scenario	[trillion RWF]	[billion US$]
Cumulative heating investment: 2020–2050	24	19
Cumulative fuel cost	3877	3,141
Cumulative electricity cost	34	28
Total	3935	3188

5.2.8 INVESTMENT AND FUEL COST SAVINGS

Finally, the fuel costs for the power, heating and transport sectors are presented.

All three sectors have very low costs for the power sector because electricity generation is based on solar and wind power—the remaining fuel costs are for the period 2021-2030. Increased electrification will lead to higher investment costs in power generation and higher overall electricity supply costs for Rwanda. Under the most ambitious electrification strategy of the R-1.5°C pathway, total investment will be 3,935 trillion RWF (US$ 3,188 billion).

Fuel cost savings in the heating sector until 2040 alone will be able to re-finance the additional investments in power generation. Table 35 shows all the accumulated fuel costs by sector and scenario and the calculated fuel cost savings in 10-year intervals between 2020 and 2050 in the local currency; **Error! Reference source not found.** presents these n umbers in US dollars.

Additional power generation investments will be compensated by fuel costs savings in the decade that they are made. Across the entire scenario period, fuel cost savings under the R-1.5°C scenario will be 517 trillion RWF (US$ 419 billion), more than 11 times higher than the additional investment in power generation until 2050. Whereas fuel cost predictions are subject to a great deal of uncertainty, the clear result makes the cost-effectiveness of electrification very clear.

Table 35: Accumulated fuel costs for heat generation under the REF and R-1.5°C scenarios in billion USD

REFERENCE		2021–2030		2031–2040		2041–2050		2021–2050		2020–2050 average per year	
		Trillion RWF	Billion USD	Trillion RWF	Billion USD	Trillion RWF	Billion USD	Trillion RWF	Billion USD	Trillion RWF	Billion USD
Power	Total	8	6	11	9	16	13	34	28	1	1
Heat	Total	9	8	4	3	11	9	24	19	1	1
Transport	Total	2906	2354	0	0	0	0	3877	3141	712	577
Summed Fuel Costs		2923	2368	0	0	27	0	3935	3188	714	105
R-1.5°C		2021–2030		2031–2040		2041–2050		2021–2050		2020–2050 average per year	
		Trillion RWF	Billion USD	Trillion RWF	Billion USD	Trillion RWF	Billion USD	Trillion RWF	Billion USD	Trillion RWF	Billion USD
Power	Total	8	6	11	9	16	13	34	28	1	1
Heat	Total	9	8	4	3	11	9	24	19	1	1
Transport	Total	2906	2354	0	0	0	0	3877	3141	554	449
Summed Fuel Costs		2923	2368	14	11	27	22	3935	3188	556	105

6 Rwanda: Power Sector Analysis

In this chapter, we summarize the results of the hourly simulations of the long-term scenarios (Chapter 5). The One Earth Climate Model (OECM) calculates the demand and supply by cluster. This section provides an overview of the possible increase in electrical load under the R-1.5°C scenario, and the consequent increased demand on the power grid transmission capacities, possible new inter-provincial connections, and/or expanded energy storage facilities.

6.1 POWER SECTOR ANALYSIS—METHODOLOGY

After the socio-economic (Section 2) and geographic analyses (Section 3) and the development of the long-term energy pathways for Rwanda (Section 5), the power sector was analysed with the OECM in a third step.

The energy demand projections and resulting load curve calculations are important factors, especially for power supply concepts with high shares of variable renewable power generation. Calculation of the required dispatch and storage capacities is vital for the security of supply. A detailed bottom-up projection of the future power demand, based on the applications used, demand patterns, and household types, will allow a detailed forecast of the demand. Understanding the infrastructure needs, such as power grids combined with storage facilities, requires an in-depth knowledge of the local loads and generation capacities. However, this model cannot simulate frequencies or ancillary services, which would be the next step in a power sector analysis.

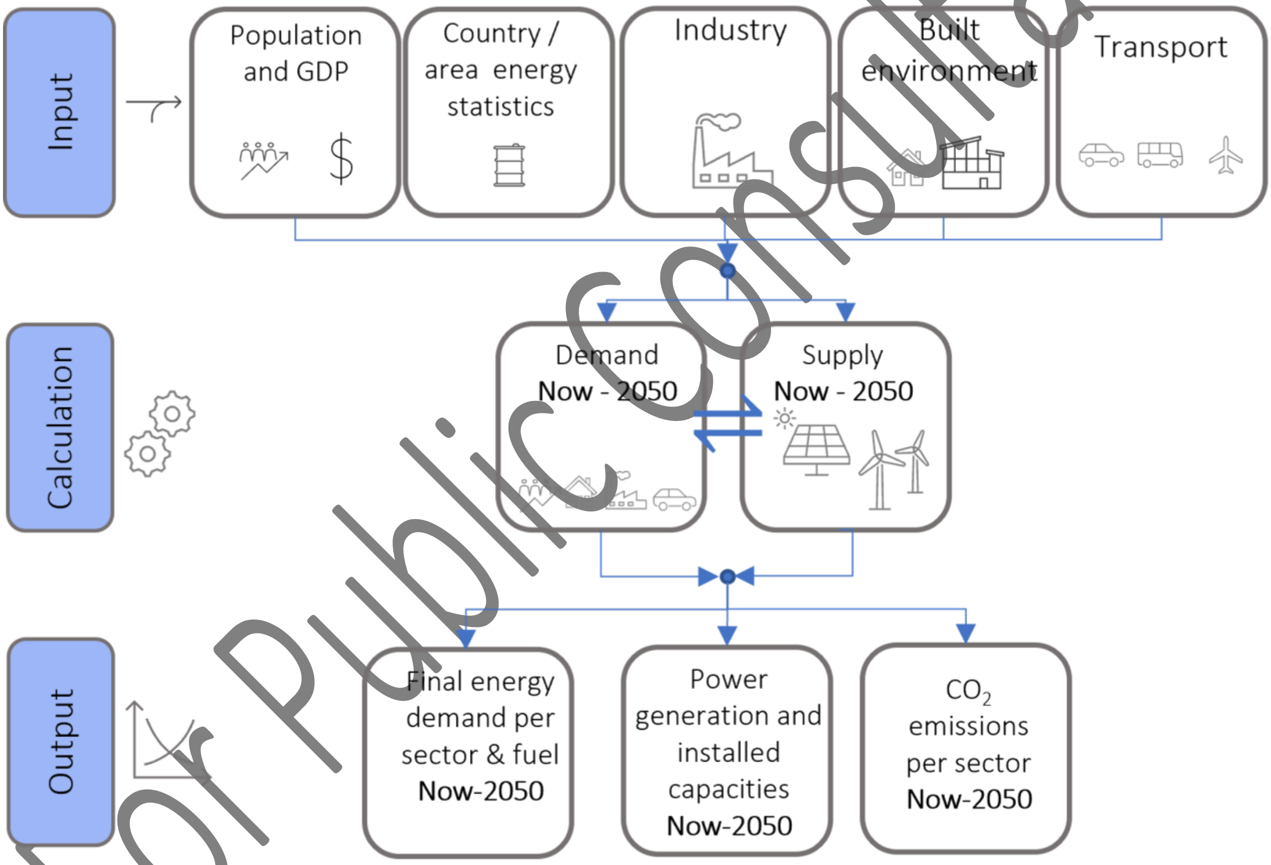


Figure 31: Overview—Energy demand and load curve calculation module

6.1.1 METEOROLOGICAL DATA

Variable power generation technologies are dependent on the local solar radiation and wind regime. Therefore, all the installed capacities in this technology group are connected to cluster-specific time series. The data were derived from the database *renewable.ninja* (RE-N DB 2018)[48], which allows the hourly power output from wind and solar power plants at specific geographic positions throughout the world to be simulated. Weather data, such as temperature, precipitation, and snowfall, for the year 2019 were also available. To utilize climatization technologies for buildings (air-conditioning, electric heating), the demand curves for households and services were connected to the cluster-specific temperature time series. The demand for lighting was connected to the solar time series to accommodate the variability in the lighting demand across the year, especially in northern and southern global regions, which have significantly longer daylight periods in summer and very short daylight periods in winter.

For every region included in the model, hourly output traces are utilized for onshore wind, utility solar, and roof-top solar PV. Given the number of clusters, the geographic extent of the study, and the uncertainty associated with the prediction of the spatial distribution of future-generation systems, a representative site was selected for each of the five generation types.

Once the representative sites were chosen, the hourly output values for typical solar arrays and wind farms were selected from the database of Stefan Pfenninger (at ETH Zurich) and Iain Staffell (renewable.ninja see above). The model methodology used by the renewable.ninja database is described by Pfenninger and Staffell (2016a and 2016b)[49], and is based on weather data from global re-analysis models and satellite observations (Rienecker and Suarez 2011[50]; Müller and Pfeifroth, 2015[51]). It is assumed that the utility-scale solar sites will be optimized, so the tilt angle was selected within a couple of degrees of the latitude of the representative site. For the roof-top solar calculations, this was left at the default of 35° because it is likely that the panels will match the tilt of the roof.

The onshore wind outputs were calculated at an 110m hub height to reflect the potential wind resource available in each cluster which is available to modern turbines with sufficiently high hub heights. It is possible that commercial hub heights will exceed this height before 2050, however, 110m was deemed as appropriate to be indicative of the resource available to both current and future generators. .. A turbine model of Vestas V90 2000 was used.

Limitations: The solar and wind resources can differ within one cluster. Therefore, the potential generation output can vary within a cluster and across the model period (2020–2050).

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[48] RE-N DB (2018) Renewables.ninja, online database of hourly time series of solar and wind data for a specific geographic position, data viewed and downloaded between September and October 2022, https://www.renewables.ninja/

[49] Pfenninger, S, Staffell, I. (2016a), Pfenninger, Stefan and Staffell, Iain (2016). Long-term patterns of European PV output using 30 years of validated hourly reanalysis and satellite data. Energy 114, pp. 1251–1265. doi: 10.1016/j.energy.2016.08.060

Pfenninger, S, Staffell, I. (2016b), Staffell, Iain and Pfenninger, Stefan (2016). Using bias-corrected reanalysis to simulate current and future wind power output. Energy 114, pp. 1224–1239. doi: 10.1016/j.energy.2016.08.068

[50] Rienecker, M, Suarez MJ, (2011) Rienecker MM, Suarez MJ, Gelaro R, Todling R, et al. (2011). MERRA: NASA’s modern-era retrospective analysis for research and applications. Journal of Climate, 24(14): 3624–3648. doi: 10.1175/JCLI-D-11-00015.1

[51] Müller, R., Pfeifroth, U (2015), Müller, R., Pfeifroth, U., Träger-Chatterjee, C., Trentmann, J., Cremer, R. (2015). Digging the METEOSAT treasure—3 decades of solar surface radiation. Remote Sensing 7, 8067–8101. doi: 10.3390/rs70608067

6.1.2 POWER DEMAND PROJECTION AND LOAD CURVE CALCULATION

The OECM power analysis model calculates the development of the future power demand and the resulting possible load curves. The model generates annual load curves with hourly resolution and the resulting annual power demands for three different consumer sectors:

- households;
- industry and business; and
- transport.

Although each sector has its specific consumer groups and applications, the same set of parameters was used to calculate the load curves:

- electrical applications in use;
- demand pattern (24 h);
- meteorological data
  - sunrise and sunset, associated with the use of lighting appliances;
  - temperature and rainfall, associated with climatization requirements;
- efficiency progress (base year 2018 for 2020 until 2050, in 5-year steps;
  - possibility that the electricity intensity data for each set of appliances will change, e.g., change from compact fluorescent lamp (CFL) light bulbs to light-emitting diodes (LEDs) as the main technology for lighting.

6.1.3 THE OECM 24/7 DISPATCH MODULE

The OECM 24/7 dispatch module simulates the physical electricity supply with an interchangeable cascade of different power generation technologies. The cascade starts with the calculated load in megawatts for a specific hour.

The first-generation technology in the exogenous dispatch order provides all the available generation, and the remaining load is supplied by the second technology until the required load is entirely met.

In the case of oversupply, the surplus variable renewable electricity can either be moved to storage, moved to other regions (including export to other countries if specified in modelling assumptions), or—if neither option is available—curtailed. Non-variable renewable sources will reduce output.

In the case of undersupply, electricity will be supplied either from available storage capacities, from neighbouring clusters, or from dispatch power plants.

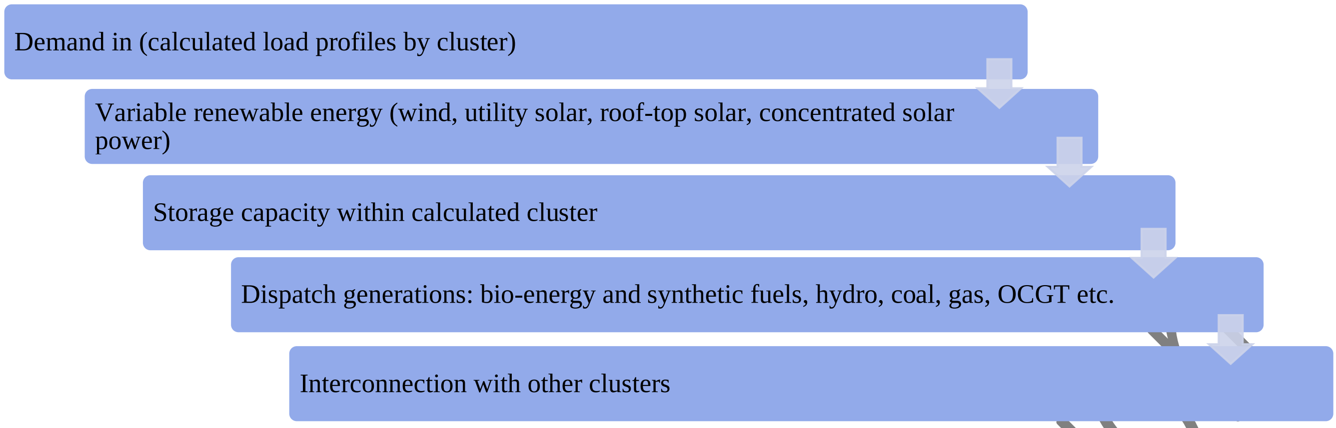
The key objective of the modelling is to calculate the load development by region, modifying the residual load (load minus generation), theoretical storage, and interconnection requirements for each cluster and for the whole survey region. The theoretical storage requirement is provided as the “storage requirement to avoid curtailment”. The economic battery capacity is a function of the storage and curtailment costs, as well as the availability of dispatch power plants and their costs. This analysis focuses on the technical storage requirements.

Figure 32 provides an overview of the dispatch calculation process. The dispatch order can be changed in terms of the order of renewables and the dispatch power plant, as well as in terms of the order of the generation categories: variable, dispatch generation, or storage.

The following key parameters are used as input: generation capacity by type, the demand projection and load curve for each cluster, interconnections with other clusters, and meteorological data, from which solar and wind power generation are calculated with hourly resolution.

The installed capacities are derived from the long-term projections described in Section 5 and the resulting annual generation in megawatt hours is calculated on the basis of meteorological data (in the cases of solar and wind power) or dispatch requirements.

Figure 32: Dispatch order within one cluster



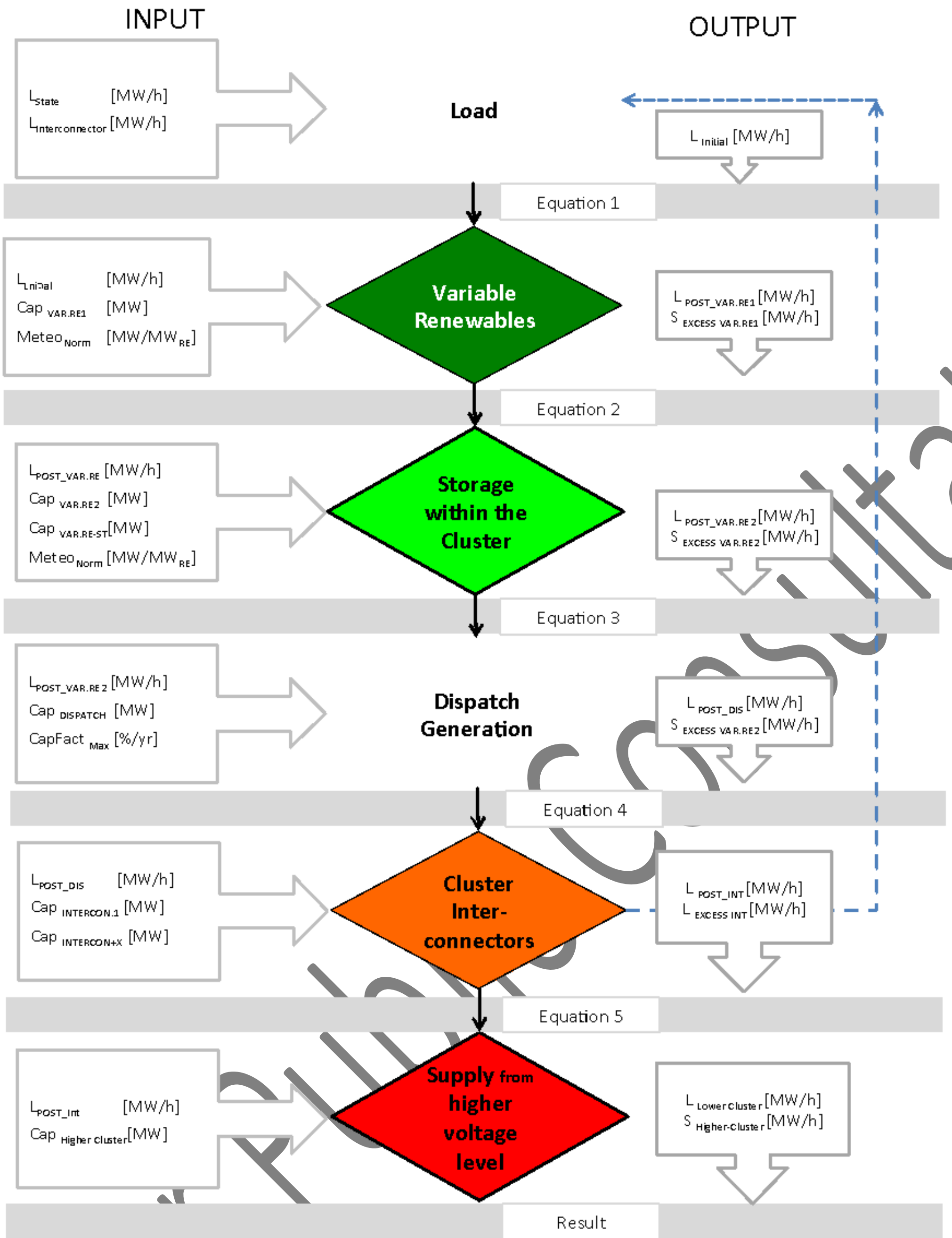
Overview: input and output— OECM 24/7 energy dispatch model

Figure 33 gives an overview of the input and output parameters and the dispatch order. Although the model allows changes in the dispatch order, a 100% renewable energy analysis always follows the same dispatch logic. The model identifies excess renewable production, which is defined as the potential wind or solar PV generation that exceeds the actual hourly demand in MW during a specific hour. To avoid curtailment, the surplus renewable electricity must be stored with some form of electrical storage technology or exported to a different cluster. Within the model, excess renewable production accumulates through the dispatch order. If storage is present, it will charge the storage within the limits of the input capacity. If no storage is included, this potential excess renewable production is reported as 'potential curtailment' (pre-storage). It is assumed that a certain number of behind-the-meter consumer batteries will be installed, independently of the system requirements.

Limitations

The calculated loads are not optimized with regard to local storage, the self-consumption of decentralized producers of solar PV electricity, or demand-side management. Therefore, the calculated loads may be well below the calculated values.

Figure 33: Overview—Input, output, and dispatch order



6.2 RWANDA: DEVELOPMENT OF POWER PLANT CAPACITIES

Rwanda has substantial untapped renewable energy potential, as described in Section 3. Currently Gas and hydropower plants provide the bulk of the grid-connected electricity generation, followed by diesel generators. Whereas solar PV generators still have a small share. However, solar PV generators will expand rapidly and provide increasing electricity, both grid-connected and off-grid in micro-grids, especially in remote areas of the country, where the national power grid will not reach villages in the coming years. In this analysis, we contribute to the debate on the role that decentralized renewable electricity generation—mainly solar PV and onshore wind but also mini-hydro and biomass energy-based generators—can play in the future.

In terms of Rwanda's renewable electricity potential, the vast majority of future generation will be solar PV and onshore wind. Hydropower plants have already been one of the major contributors of the power sector for decades and will continue to maintain its role with a potential to increase generation slightly. Whereas sustainable biomass resources are limited.

Therefore, the capacity for solar PV installations will increase substantially under the R-1.5°C pathway. The average solar photovoltaic market will range around 1,200 MW per year between 2021 and 2035 and remain on a stable 1,000 MW per year market volume between 2036 and 2005. Rwanda's wind power market is projected to increase its annual market volume to around 1,000 MW by 2030 and 1,500 MW between 2035 and 2045 making it an important local industry. Rwanda's hydropower plant capacity will grow by a factor of 3 from around 300 MW in 2021 to 3,000 MW in 2050.

Rwanda's renewable potential is exceptionally diverse and not only limited to solar and wind power. Therefore, under the R-1.5°C pathway, the full range of renewable technology will be utilized (Table 38).

Table 36:Rwanda—average annual changes in installed power plant capacity (main technologies)

Power Generation: average annual changes in installed capacity [MW/a]							Average annual	
	2021–2025	2026–2030	2031–2035	2036–2040	2041–2045	2046–2050	2021-2035	2021-2050
biomass	0	0	0	0	0	0	0	0
hard coal	0	0	0	0	0	0	0	0
lignite	0	0	0	0	0	0	0	0
fuel cell	0	0	0	0	0	0	0	0
natural gas	0	0	200	0	-200	0	67	0
oil	0	0	0	0	0	0	0	0
diesel	0	0	0	0	0	0	0	0
hydro	0	0	0	100	200	100	0	90
wind onshore	0	0	0	50	50	50	0	50
wind offshore	0	0	0	0	0	0	0	0
PV	500	800	1,400	1,000	1,000	600	900	883
geothermal	0	0	0	0	200	0	0	33
Total CHP plants	0	0	0	0	0	0	0	0
biomass & waste	0	0	0	0	0	0	0	0
hard coal	0	0	0	0	0	0	0	0
lignite	0	0	0	0	0	0	0	0
fuel cell	0	0	0	0	0	0	0	0
gas	0	0	0	0	0	0	0	0
geothermal	0	0	0	0	0	0	0	0
oil	0	0	0	0	0	0	0	0

However, there will be a rapid increase in the electricity demand with the high electrification rates in the transport and heating sectors. After 2035, a significant share of Rwanda's solar market will provide electricity for households and electric mobility. By 2030, solar PV will generate around 26 TWh— close to 80% of Rwanda's projected electricity demand. By 2050, wind power and solar PV will provide over 90 % of the country's electricity demand, which is projected to increase by a factor of 45 relative to 2021.

6.3 RWANDA: UTILIZATION OF POWER GENERATION CAPACITIES

Table 37 shows the installed capacities for roof-top and utility -scale solar PV under the R-1.5°C scenario in 2020, 2030 and 2050. The distributions are based on the regional solar potentials and the regional electricity demands, with the aim of generating electricity where the demand is located. Whereas roof-top solar PV power generation is modular and can be installed close to the consumer or even integrated into buildings, utility-scale solar PV is usually further away from settlements and close to medium- or high-voltage power lines. Furthermore, solar power plants (= utility-scale PV) have double-digit megawatt capacities, on average. The best solar resources are in the south of the country along the border with India.

Table 37: Rwanda R-1.5°C pathway—Installed photovoltaic capacities 2020, 2030 and 2050

R-1.5C pathway	2020	2030	2050
	[MW]	[MW]	[MW]
Photovoltaic (roof-top & solar home systems	12	4,500	19,500
Photovoltaic (utility-scale & stand-alone grid	8	1,500	6,500

The R-1.5°C scenario aims for an even distribution of variable power plant capacities across all regions by distributing roof-top and utility-scale solar PV power-generation facilities accordingly. In this analysis, we have assumed that 75% of the solar PV installations are roof-top / solar home systems and 25% are utility-scale power plants / stand-alone grids ('off grid'). The distribution is based on the population in each of the sub-regions. Compared with the vast solar potential, wind generation will be very limited and will not compensate for differences in seasonal generation. However, to diversify the generation mix to reduce the seasonal storage requirements, the wind resources of Rwanda should be used to the highest possible degree.

The projections for 2030 and 2050 show an increase of variable renewables in regions with higher dispatchable capacities, while dispatchable increase in regions where there are currently no capacities. On average, Rwanda will have around 85% variable renewables with the rest of dispatchable power plants, mainly hydro. Therefore an interconnection with neighbouring countries and a intelligent electricity storage concept is vital.

Table 38: Rwanda—power system shares by technology group

Power Generation Structure in Percentage of Annual Supply [%/a]		R-1.5C		
		Variable Renewable	Dispatch Renewable	Dispatch Fossil
Rwanda	2020	5%	42%	53%
	2030	84%	13%	3%
	2050	85%	15%	0%

The significant regional differences in the power system shares—the ratio between dispatchable and non-dispatchable variable power generation—will require a combination of increased interchange, storage facilities, and demand-side management incentives.

Table 39 shows the system-relevant technical characteristics of the various generation types. Future power systems must be structured according to the generation characteristics of each technology to maximize their synergy. Power utilities can encourage sector coupling—between industry, transport, and heating—to utilize various demand-side management possibilities and to maximize the cross-benefits. The integration of large shares of variable power generation will require a more flexible market framework. Those power plants requiring high-capacity factors because of their technical limitations regarding flexibility ("base-load power plants") might not be desirable to future power system operators. Therefore, capacity factors will become more a technical characteristic than an economic necessity. Flexibility is a commodity that increases in value over time.

Table 39: System-relevant generation types

Generation Type	Fuel	Technology
Limited Dispatchable	Fossil, uranium	Coal, brown coal/lignite, (including co-generation)
	Renewable	Hydropower, bioenergy, and synthetic fuels, geothermal, concentrated solar power (including co-generation)
Dispatchable	Fossil	Gas, oil, diesel (including co-generation)
		Storage systems: batteries, pumped hydropower plants, hydrogen- and synthetic-fuelled power and co-generation plants
	Renewable	Bioenergy, hydro, hydrogen- and synthetic-fuelled power, and co-generation plants
Variable	Renewable	Solar photovoltaic, onshore wind

6.4 RWANDA: DEVELOPMENT OF LOAD, GENERATION, AND RESIDUAL LOAD

Table 40 shows the calculated annual demand, maximum and minimum loads, and the calculated average load Rwanda's for 2021. The results are based on the R-1.5°C pathway projections. To validate the data, we compared our results with the real-time data published by the local grid operator. The statistical data for each province for 2021 were not available at the time of writing, so the values are estimates and may vary by ±10% for each data point. However, the published online data for Rwanda's power sector is within the same order of magnitude. The calculation of the maximum, minimum, and average loads for the base year (2020/21) are important to calibrate the OECM and to compare the values with future projections.

Table 40: Rwanda—calculated load, generation, and residual load in 2020/21

Real Load (rounded)—measured by grid operators in 2018	Electricity Generation [TWh/a]	Maximum Load (Domestic) [MW]	Maximum Generation [MW]	Minimum Load [MW]	Average Load [MW]
Rwanda Total	0.190	0.22	0.22	0.11	0.16

Table 41 shows that according to calculation, the average load will increase by a factor of approximately 8 over the next decade. By 2050, the overall electricity load of Rwanda will increases from under 1 GW in 2021 to around 10 GW in 2050. The increase in load is attributable to the increase in the overall electricity demand with the electrification of cooking, heating, and cooling, which constitutes an increase of the living standards of all Rwanda's households as they acquire more residential appliances. The calculated load depends on various factors, including the local industrial and commercial activities. A detailed analysis of the planned expansion of economic activity for each province was beyond the scope of this research and the results are therefore estimates. The residual load is the difference between the power generation and the demand—a negative residual load indicates an oversupply, whereas a positive value implies an undersupply.

Table 41: Rwanda—projection of load, generation, and residual load until 2050

Development of Load and Generation		K-1.5C			
		Maximum Load	Maximum Generation	Maximum Residual Load	Peak Load Increase
		[MW]	[MW]	[MW]	[%]
Rwanda	2020	0.22	0.22	0.00	100%
	2030	1.66	3.74	-2.08	755%
	2050	9.02	19.43	-10.41	4100%

Furthermore, the growth of the commercial and industrial sectors of Rwanda and the electrification of transport will lead to a sharp increase in the electricity demand and therefore the overall power load. This increased load will require an expansion of Rwanda's power distribution and transmission grid, both within Rwanda and as interconnections with neighbouring countries—especially Tanzania.

The development of power generation is assumed to grow proportionally to the growth in demand in each province. A more detailed assessment of the exact locations of power generation is required to optimize the required expansion of transmission grids. To reduce the residual load to avoid an over- and/or undersupply for each province, either increased grid capacity or more storage systems will be required.

Increased electric mobility will require additional capacity in the power grid to accommodate the higher charging loads for vehicles. Our analysis shows that with the smart distribution and management of electric vehicle charging stations, additional transmission lines will be required. The high share of solar PV will lead to high generation peaks during summer months and low generation capacities during winter. To manage the generation peaks of solar PV generators, utility-scale installations will require on-site storage capacity, whereas roof-top PV will require increased ‘behind-the-meter’ storage facilities (see Section 6.5).

A detailed local assessment is required of whether a new power grid interconnection can be built, or if regional micro-grids with increased storage capacity are a better solution. Stand-alone micro-grids are the preferred option because the construction of transmission grids will be impractical, especially in region Rwanda’s with a low population density in the northern and north coast region.

Limitations

The calculated loads are not optimized regarding local storage, self-consumption by decentralized producers of solar PV electricity, or demand-side management. Therefore, the calculated loads may differ from the actual values. Furthermore, the calculated export/import loads to neighbouring countries are simplified and combined into a single value. Peak load and peak generation events do not occur at the same time, so their values cannot be simply summed. Moreover, peak loads can vary across all regions and appear at different times. Therefore, to sum all the regional peak loads will only provide an indication of the peak load for the whole country. The maximum residual load[52] shows the maximum undersupply in a region and indicates the maximum load that will be imported into that region. This event can only be several hours long, so the interconnection capacity might not be as high as the maximum residual load indicates. Optimizing the interconnections for all regions was beyond the scope of this analysis. To guarantee the security of supply, the residual load of a region must be supplied by one or more of the following options:

- imports from other regions through interconnections.
- battery storage facilities on-site at solar PV installations and for electric vehicles.
- available back-up capacities, such as gas peaking plants.
- load and demand-side management.

In practice, security of supply will be achieved with a combination of several measures and will require the in-depth analysis of regional technical possibilities.

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[52] Residual load is the load remaining after the local generation within the analysed region is exhausted. There could be a shortage of load supply due to the operation and maintenance of a coal power plant or reduced output from wind and/or solar power plants.

6.4.1 ANNUAL VARIATIONS OF RENEWABLE ENERGY GENERATION

Solar and wind power generation has different annual variation pattern which are dependent on the climate zone and geographical location. This section provides a high-level analysis about the electricity import and/or export needs under the R-1.5°C scenario with high shares of variable power generation. Electricity demand ('load') and generation ('supply') must be balanced at all times. If local generation cannot meet demand, electricity must either be imported from other regions or taken from existing storage facilities. If the generation is higher than the load, the surplus electricity can either be exported to other regions, stored, the load increased or production reduced. The term 'curtailment' is defined as the forced reduction of electricity generation (see also 6.4). In order to determine the annual distribution -of Rwanda's solar and wind power generation, generation and expected load are simulated in a one -hourly resolution (8760 h/a).

Figure 34 and Figure 35 show the analyse results in weekly values for 2030 and 2050 respectively. During times of high generation, generation exceeds the demand (green line), the red line shows when demand exceeds generation. State of the art power system operation of renewable power generation dominated grid, utilize a combination of demand and generation side management, export and import from neighbouring regions and a cascade of different storage technologies such as batteries, hydro pump storage storage and hydrogen/synthetic fuel production later used for e.g. industrial processes heat or feedstock for the chemical industry.

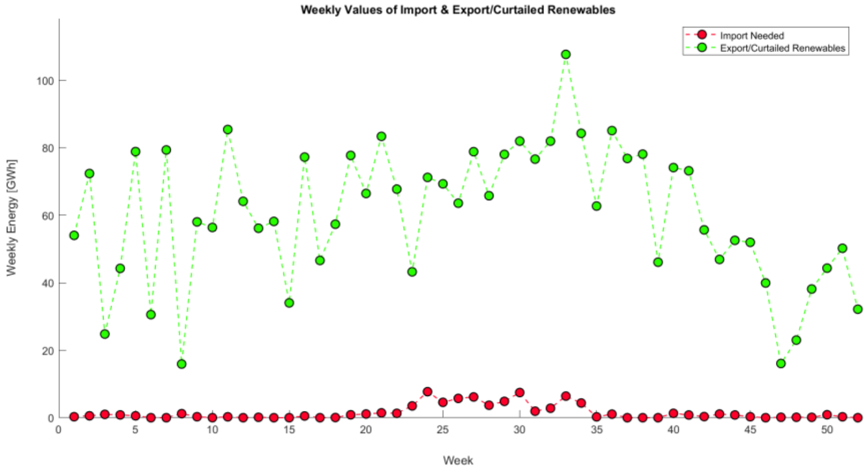

Figure 34: Rwanda: Weekly values of electricity import & export – 2030

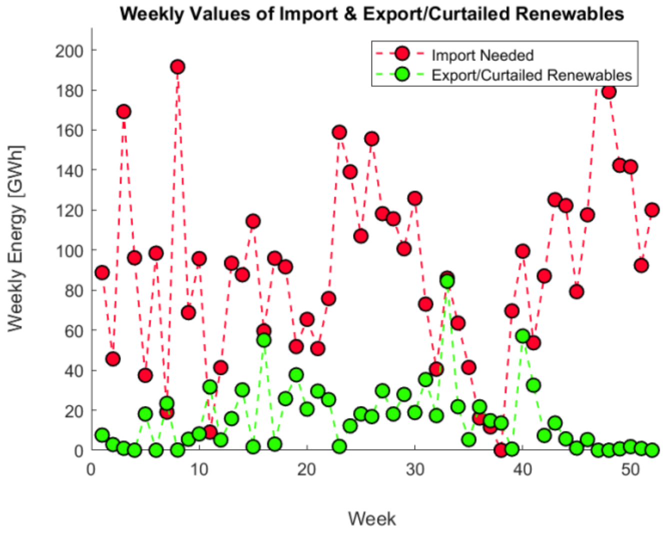

Figure 35: Rwanda: Weekly values of electricity import & export – 2050

The analysis shows that between 8th June and 16th June – based on historical meteorological data (6.1.1) – power generation from both wind and solar is on the lowest level within the entire year. This coincides with Rwanda's beginning of the dry season. The other extreme – a period with very high-power generation rates – has been determined around early February, a very sunny season. The purple area (Figure 36and Figure 37) shows charging (negative values) and discharging (positive values) of storage systems. Brown areas specify times with dispatch needs (import or export of electricity) and green areas are renewable power generation. Finally, the white areas which indicate periods of unmet demand are further investigated. Thus, the analysis of local annual solar and wind power generation variation serves as the first step in determining the technical storage requirements.

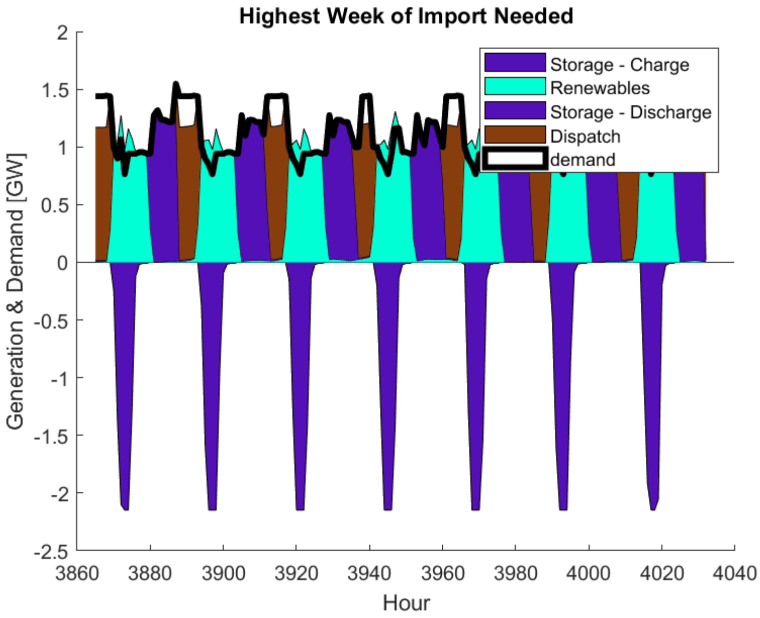

Figure 36: Rwanda - lowest renewable electricity production under the R-1.5°C scenario in 2050

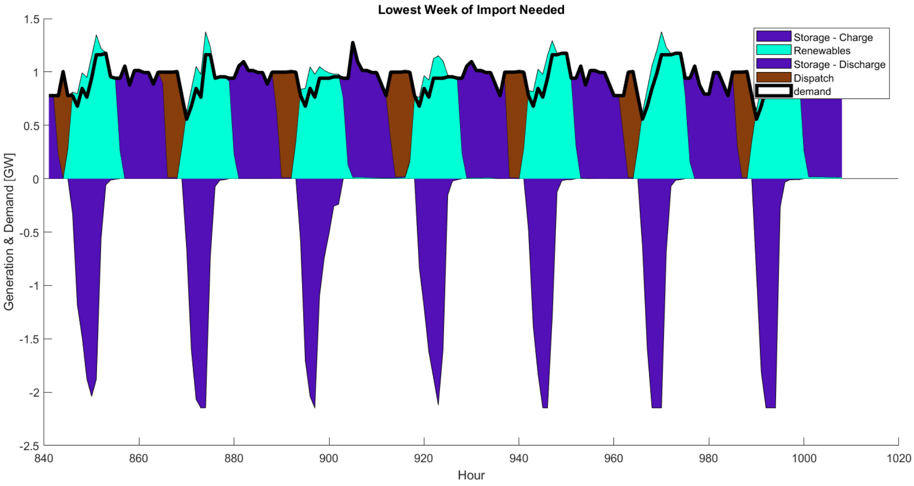

Figure 37: Rwanda - highest renewable electricity production under the R-1.5°C scenario in 2050

6.5 STORAGE REQUIREMENTS

6.5.1 INTRODUCTION

The quantity of storage required will be largely dependent upon the storage costs, grid expansion possibilities, and the generation mix itself. In terms of grid expansion, the geographic situation greatly influences the construction costs; crossing mountains, rivers, or swamps is significantly more expensive than crossing flat lands (Wendong 2016)[53]. Furthermore, the length of the permission process and whether people will be displaced by grid expansions may make storage economically preferable to grid expansion, even though the current transmission costs are lower per megawatt-hour than the storage costs. Cebulla et al. (2018)[54] reported that "in general terms, photovoltaic-dominated grids directly correlate to high storage requirements, in both power capacity and energy capacity. Conversely, wind-dominated scenarios require significantly lower storage power and energy capacities, if grid expansion is unlimited or cheap". In an analysis of 400 scenarios for Europe and the USA, they also found that once the share of variable renewables exceeds 40% of the total generation, the increase in electrical energy storage power capacity is about 1–2 GW for each percentage of variable renewable power generation in wind-dominated scenarios and 4–9 GW in solar-PV-dominated scenarios.

When variable power generation shares exceed 30%, storage requirements increase. The share of variable generation will exceed 30% between 2025 and 2030 under both Energy [R]evolution scenarios in all regions. Therefore, a smart grid integration strategy that includes demand-side management and the installation of additional decentralized and centralized storage capacities must be established. Over the past decade, the cost of batteries, especially lithium batteries, has declined significantly. However, solar PV costs have also declined significantly. Storage is economic when the cost per kilowatt-hour is equal to or lower than the cost of generation. Therefore, if storage costs are high, curtailment could be economic. However, there are several reasons for curtailment, including transmission constraints, system balancing, and economic reasons (NREL 2014)[55]. The California Independent System Operator (CISO)[56] defines economic curtailment during times of oversupply as a market-based decision. "During times of oversupply, the bulk energy market first competitively selects the lowest cost power resources. Renewable resources can 'bid' into the market in a way to reduce production when prices begin to fall. This is a normal and healthy market outcome. Then, self-scheduled cuts are triggered and prioritized using operational and tariff considerations. Economic curtailments and self-scheduled cuts are considered 'market-based'".

6.5.2 DETERMINATION OF STORAGE DEMANDS

Rwanda currently operates around 40 small and medium sized run-of-river hydropower plants, some of which are with dams and therefore a possible pump storage capacity potential. However, according to the Global Pumped Hydro Atlas (ANU 2022)[57], Rwanda has good storage sites with a potential of at least 1 GWh per million people. The utilization of this potential by implementing additional water reservoir storage capacities and pumped hydro storage (PHS) facilities will put Rwanda in a comfortable position to integrate large amounts of variable solar PV and wind power generation. There are three types of hydropower plants:

I. Run-of-river power plants, which use the available volumes of passing river water and have limited possibilities to regulate the output; winter is usually the time with the lowest production volumes.
II. Storage power plants, which are 'run-of-river' power stations with a water storage reservoir on the intake side. Power generation can be increased and reduced within the water reservoir capacity to complement the variable demand and/or solar generation.
III. Pumped hydro storage (PHS) power plants, which have a water storage reservoir on both sides (in-take and out-flow) and can pump water after electricity generation back into the in-take reservoir. PHS plants can operate as a short-, medium-, or long-term electricity storage technology. Historically, PHS systems have been used to balance inflexible nuclear power plants, which must operate in base-load mode, and to hedge against price fluctuations on power markets.

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[53] Wendong (2016), Wei, Wendong et al. Regional study on investment for transmission infrastructure in China based on the State Grid data,10.1007/s11707-016-0581-4, Frontiers of Earth Science, June 2016.

[54] Cebulla et al. (2018), How much electrical energy storage do we need? A synthesis for the U.S., Europe, and Germany, Journal of Cleaner Production, February 2018, https://www.researchgate.net/publication/322911171_How_much_electrical_energy_storage_do_we_need_A_synthesis_for_the_US_Europe_and_Germany/link/5a782bb50f7e9b41dbd26c20/download

[55] Wind and Solar Energy Curtailment: Experience and Practices in the United States; Lori Bird, Jaquelin Cochran, and Xi Wang, National Renewable Energy Laboratory (NREL), March 2014, https://www.nrel.gov/docs/fy14osti/60983.pdf

[56] Impacts of renewable energy on grid operations, factsheet, https://www.caiso.com/Documents/CurtailmentFastFacts.pdf

[57] ANU (2022), Australian National University, 100% Renewable Energy Group, Global Pumped Hydro Energy Storage Atlas, https://re100.eng.anu.edu.au/global/

In this analysis, we assume that 'peak-shaving' is used to avoid peak generation events. The term 'peak-shaving' refers to the reduction in the solar or hydro generation capacity in times of high production. Peak-shaving involves pro-actively managing solar generation by reducing the output, e.g., from utility-scale PV, to eliminate short-term spikes. These spikes only appear for a limited time—from minutes to hours—and significantly increase the actual grid or storage capacity because the capacity must cope with the highest peak.

With peak-shaving, this peak can be reduced with only a minor effect on the overall annual generation because peak events are relatively infrequent. The assumed "economic curtailment rate" for the N-1.5°C pathway will increase to 5% relative to the annual generation (in GWh/a) for solar PV for the years until 2030, and to 10% between 2031 and 2050. However, economic curtailment rates are dependent upon the available grid capacities and can vary significantly, even within Rwanda. Curtailment will be economic when the power generated by a PV power plant exceeds the demand for only a few hours a day and this event occurs rarely across the year. Therefore, the expansion of storage capacities will not be economically justifiable.

To build up the additional required storage capacity, we assume that a percentage of the solar PV capacity will be installed with battery storage. The suggested solar battery system must be able to store the entire peak capacity for 4 full load hours. The N-1.5°C scenario requires that all utility-scale solar PV and 75% of all roof-top PV systems built after 2030 must be equipped with a battery or other storage technology systems.

The estimates provided for storage requirements also presuppose that variable renewables such as solar PV and wind will be first in the dispatch order, ahead all other types of power generation. Priority dispatch is the economic basis for investment in utility-scale solar PV and wind projects. The curtailment rates or storage rates will be significantly higher when priority dispatch is given to, for example, hydro power plants in 'baseload' generation mode.

This case has not been calculated because it would involve a lack of investment in solar in the first place. With decreasing storage costs, as projected by Bloomberg (2019)[58], interconnections may become less economically favourable than batteries. The storage estimates provided are technology neutral and do not favour any specific battery technology.

Table 42 shows the storage required to avoid curtailment above 10% of the annual generation for Rwanda under the K-1.5°C scenario without peak-shaving. With a share of around 33% of dispatchable power generation in 2050, and an increasing share of stand-alone grids storage, capacities need to grow according the solar photovoltaic shares.

Battery storage is mainly used in distribution grids and stand-alone-grids, while the expansion of hydro pump storage is entirely grid connected for seasonable storage on the medium and high voltage transmission grid and to provide power system relevant support such as ancillary services.

The storage demand for micro-grids and off-grid systems must be calculated individually and is not part of this assessment. However, micro-grids always require either a storage system with a capacity large enough (in terms of both the electricity supply in kilowatt-hours and the required load in kilowatts) to bridge the gap in times of low or no generation possibilities.

Table 42: Rwanda - Calculated electricity storage capacities by technology and year

Storage Capacity	Units	2020	2025	2030	2035	2040	2045	2050
Battery	[MW]	10	20	2,350	4,700	7,050	9,400	11,750
Hydro Pump storage	[MW]	0	0	10	60	110	160	210
H2	[MW]	0	0	0	0	10	10	20
Total	[MW]	10	20	2,360	4,760	7,170	9,570	11,980

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[58] Bloomberg (2019), A Behind the Scenes Take on Lithium-ion Battery Prices, Logan Goldi-Scot, Bloomberg NEF, March 5 2019, https://about.bnef.com/blog/behind-scenes-take-lithium-ion-battery-prices/

6.5.3 COST DEVELOPMENT—BATTERY STORAGE TECHNOLOGIES

Battery technologies have developed significantly over the past decade, and the global annual market increased from 700 MW in 2015 to close to 16,000 MW in 2021 (IEA-BAT 2020)[59]. The market is split roughly equally between grid-scale storage and 'behind-the-meter' storage for solar PV projects. The rapidly growing demand for electric vehicles has significantly accelerated the development of battery technologies, and manufacturing capacities have grown by double digits, with costs decreasing accordingly. The battery costs per kilowatt-hour storage capacity decreased from US$668 (RWF 801,600) in 2013 to US$137 (RWF 164,400) in 2020—a reduction of 79% over the past 7 years. Bloomberg New Energy Finance estimates that battery costs will decline further to around US$58 (RWF 69,600) by 2030.

6.5.4 FURTHER RESEARCH REQUIRED

A calculation of the required investment costs in storage technologies that will be needed after 2030 and by 2050 would entail such high uncertainty that such estimates seem meaningless. Furthermore, a more-detailed storage technology assessment for the R-1.5°C scenario based on the specific situation of Rwanda—with its unique potential for stand-alone grid that get interconnected with the expanding national grid over time between 2030 and 2050 is required.

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[59] IEA-BAT (2020) IEA Energy Storage – website viewed October 2022, https://www.iea.org/reports/grid-scale-storage

7 Rwanda: Data Annex

Tanzania 1.5˚C

Electricity generation [TWh/a]	2020	2025	2030	2035	2040	2045	2050
Power plants	8	15	41	93	155	229	345
- Hard coal (& non-renewable waste)	0	0	0	0	0	0	0
- Lignite	0	0	0	0	0	0	0
- Gas	3	3	3	2	2	2	0
of which from H2	0	0	0	0	0	0	0
- Oil	1	1	1	1	2	0	0
- Diesel	0	0	0	0	0	0	0
- Nuclear	0	0	0	0	0	0	0
- Biomass (& renewable waste)	0	0	0	1	2	4	6
- Hydro	3	3	3	3	5	6	9
- Wind	0	2	6	15	33	71	167
of which wind offshore	0	1	2	4	6	8	9
- PV	0	6	26	66	105	135	145
- Geothermal	0	0	0	3	6	10	16
- Solar thermal power plants	0	0	0	0	1	1	2
- Ocean energy	0	0	0	0	0	0	0
Combined heat and power plants	0	0	0	0	0	0	0
- Hard coal (& non-renewable waste)	0	0	0	0	0	0	0
- Lignite	0	0	0	0	0	0	0
- Gas	0	0	0	0	0	0	0
of which from H2	0	0	0	0	0	0	0
- Oil	0	0	0	0	0	0	0
- Biomass (& renewable waste)	0	0	0	0	0	0	0
- Geothermal	0	0	0	0	0	0	0
- Hydrogen	0	0	0	0	0	0	0
CHP by producer							
- Main activity producers	0	0	0	0	0	0	0
- Autoproducers	0	0	0	0	0	0	0
Total generation	7.524	15.347	40.971	92.772	155.124	229.261	344.578
- Fossil	4.482	4.692	4.392	3.645	3.615	2.004	0.000
- Hard coal (& non-renewable waste)	0.000	0.000	0.000	0.000	0.000	0.000	0.000
- Lignite	0.000	0.000	0.000	0.000	0.000	0.000	0.000
- Gas	3.104	3.258	3.040	2.430	2.066	2.004	0.000
- Oil	1.378	1.434	1.351	1.215	1.549	0.000	0.000
- Diesel	0.000	0.000	0.000	0.000	0.000	0.000	0.000
- Nuclear	0.000	0.000	0.000	0.000	0.000	0.000	0.000
- Hydrogen	0.000	0.000	0.000	0.000	0.000	0.000	0.000
- of which renewable H2	0.000	0.000	0.000	0.000	0.000	0.000	0.000
- Renewables (w/o renewable hydrogen)	3.042	10.655	36.579	89.126	151.509	227.256	344.578
- Hydro	2.782	2.607	3.040	3.240	5.454	6.167	9.414
- Wind	0.004	1.788	6.433	14.854	32.574	70.718	166.863
- PV	0.188	5.961	25.922	66.380	104.635	135.265	144.682
- Biomass (& renewable waste)	0.068	0.136	0.406	1.121	2.191	3.761	5.799
- Geothermal	0.000	0.130	0.676	3.240	6.060	10.279	15.848
- Solar thermal power plants	0.000	0.033	0.101	0.292	0.595	1.066	1.972
- Ocean energy	0.000	0.000	0.000	0.000	0.000	0.000	0.000
Distribution losses	0.947	0.624	1.617	3.875	6.587	9.834	15.162
Own consumption electricity	0.204	0.385	0.997	2.390	4.063	6.065	9.351
Electricity for hydrogen production	0.006	2.314	7.188	11.766	17.402	23.680	27.610
Electricity for synfuel production	0.000	0.000	0.000	0.025	0.070	0.097	0.144
Final energy consumption (electricity)	6.473	12.224	31.685	75.952	129.106	192.725	297.153
Variable RES (PV, Wind, Ocean)	0	8	32	81	137	206	312
Share of variable RES	3%	50%	79%	88%	88%	90%	90%
RES share (domestic generation)	40%	69%	89%	96%	98%	99%	100%

Transport - Final Energy [PJ/a]	2020	2025	2030	2035	2040	2045	2050
road	91	104	89	79	96	117	140
- fossil fuels	91	104	87	59	61	56	54
- biofuels	0	0	0	0	0	0	0
- synfuels	0	0	0	0	0	0	0
- natural gas	0	0	0	0	0	0	0
- hydrogen	0	0	0	1	1	1	1
- electricity	0	0	2	20	34	60	85
rail	0	0	0	0	0	0	0
- fossil fuels	0	0	0	0	0	0	0
- biofuels	0	0	0	0	0	0	0
- synfuels	0	0	0	0	0	0	0
- electricity	0	0	0	0	0	0	0
navigation	0	0	0	0	0	0	0
- fossil fuels	0	0	0	0	0	0	0
- biofuels	0	0	0	0	0	0	0
- synfuels	0	0	0	0	0	0	0
aviation	1	1	1	1	1	1	2
- fossil fuels	1	1	1	1	1	0	0
- biofuels	0	0	0	0	1	1	1
- synfuels	0	0	0	0	0	0	1
total (incl. pipelines)	92	105	90	80	97	118	142
- fossil fuels	92	105	88	59	61	56	54
- biofuels (incl. biogas)	0	0	0	0	1	1	1
- synfuels	0	0	0	0	0	0	1
- natural gas	0	0	0	0	0	0	0
- hydrogen	0	0	0	1	1	1	1
- electricity	0	0	2	20	34	60	85
total RES	0	0	2	20	35	61	88
RES share	0%	0%	2%	25%	36%	52%	62%

Heat supply and air conditioning [PJ/a]	2020	2025	2030	2035	2040	2045	2050
District heating plants	0	0	0	0	0	0	0
- Fossil fuels	0	0	0	0	0	0	0
- Biomass	0	0	0	0	0	0	0
- Solar collectors	0	0	0	0	0	0	0
- Geothermal	0	0	0	0	0	0	0
Heat from CHP 1)	0	0	0	0	0	0	0
- Fossil fuels	0	0	0	0	0	0	0
- Biomass	0	0	0	0	0	0	0
- Geothermal	0	0	0	0	0	0	0
- Hydrogen	0	0	0	0	0	0	0
Direct heating	614	717	878	991	1,123	1,242	1,289
- Fossil fuels	29	36	26	18	3	0	0
- Biomass	556	588	665	628	577	483	137
- Solar collectors	0	38	63	101	138	168	228
- Geothermal	0	15	26	41	70	103	154
- Heat pumps 2)	0	2	35	77	129	186	350
- Electric direct heating	29	33	42	87	144	206	277
- Hydrogen	0	0	1	2	6	12	16
Total heat supply3)	614	717	878	991	1,123	1,242	1,289
- Fossil fuels	29	36	26	18	3	0	0
- Biomass	556	588	665	628	577	483	137
- Solar collectors	0	38	63	101	138	168	228
- Geothermal	0	15	26	41	70	103	154
- Heat pumps 2)	0	2	35	77	129	186	350
- Electric direct heating (incl. process heat)	29	37	62	124	200	289	404
- Hydrogen	0	0	1	2	6	12	16
RES share (including RES electricity)	92%	93%	96%	97%	99%	100%	100%
electricity consumption heat pumps (TWh/a)	0.0	0.0	0.0	0.0	0.0	0.0	0.0

Installed Capacity [GW]	2020	2025	2030	2035	2040	2045	2050
Total generation	4	9	29	69	112	152	196
- Fossil	2	2	2	2	2	1	0
- Hard coal (& non-renewable waste)	0	0	0	0	0	0	0
- Lignite	0	0	0	0	0	0	0
- Gas (w/o H2)	1	1	1	1	1	1	0
- Oil & Diesel	1	1	1	1	1	0	0
- Diesel	0	0	0	0	0	0	0
- Nuclear	0	0	0	0	0	0	0
- Hydrogen (fuel cells, gas power plants, ga	0	0	0	0	0	0	0
- Renewables	1	7	27	67	110	152	196
- Hydro	1	1	1	1	2	2	3
- Wind	0	1	2	5	11	24	58
of which wind offshore	0	0	1	1	1	2	2
- PV	0.1983	5.4195	24	60	95	123	132
- Biomass (& renewable waste)	0.016	0.031	0.093	0.256	0.500	0.9	1.3
- Geothermal	0	0	0	0	1	1	2
- Solar thermal power plants	0	0	0	0	0	0	1
- Ocean energy	0	0	0	0	0	0	0
Variable RES (PV, Wind, Ocean)	0	6	26	65	106	147	189
Share of variable RES	6%	65%	88%	95%	95%	97%	96%
RES share (domestic generation)	35%	74%	92%	97%	98%	100%	100%

Final Energy Demand [PJ/a]	2020	2025	2030	2035	2040	2045	2050
Total (incl. non-Energy use)	843	963	1,109	1,234	1,418	1,601	1,687
Total Energy use 1)	841	960	1,107	1,231	1,415	1,597	1,682
Transport	98	105	90	80	97	118	142
- Oil products	98	105	88	59	61	56	54
- Natural gas	0	0	0	0	0	0	0
- Biofuels	0	0	0	0	1	1	1
- Synfuels	0	0	0	0	0	0	1
- Electricity	0	0	2	20	34	60	85
RES electricity	0	0	2	19	34	59	85
- Hydrogen	0	0	0	1	1	1	1
RES share Transport	0%	0%	2%	25%	36%	52%	62%
Industry	95	121	166	226	307	414	416
- Electricity	6	11	30	50	74	107	257
RES electricity	2	8	27	48	72	106	257
- Public district heat	0	0	0	0	0	0	0
RES district heat	0	0	0	0	0	0	0
- Hard coal & lignite	20	16	11	7	0	0	0
- Oil products	1	1	2	2	0	0	0
- Gas	6	8	5	2	0	0	0
- Solar	0	4	9	13	18	27	40
- Biomass	61	80	106	143	194	240	64
- Geothermal	0	1	3	6	10	16	24
- Hydrogen	0	0	1	4	12	24	32
RES share Industry	67%	77%	88%	94%	99%	100%	100%
Other Sectors	649	735	850	925	1,010	1,065	1,125
- Electricity	17	32	81	199	349	515	710
RES electricity	7	22	72	191	341	511	710
- Public district heat	0	0	0	0	0	0	0
RES district heat	0	0	0	0	0	0	0
- Hard coal & lignite	0	0	0	0	0	0	0
- Oil products	8	18	13	10	3	0	0
- Gas	0	0	0	0	0	0	0
- Solar	0	34	54	88	120	141	189
- Biomass	623	636	679	592	478	321	96
- Geothermal	0	14	23	35	60	87	130
- Hydrogen	0	0	0	0	0	0	0
RES share Other Sectors	97%	96%	97%	98%	99%	100%	100%
Total RES	694	799	976	1,141	1,339	1,534	1,628
RES share	82%	83%	88%	93%	95%	96%	97%
Non energy use	2	2	3	3	4	4	5
- Oil	2	2	3	3	4	4	5
- Gas	0	0	0	0	0	0	0
- Coal	0	0	0	0	0	0	0

Energy-Releated CO2 Emissions [Million tons/a]	2020	2025	2030	2035	2040	2045	2050
Condensation power plants	3	3	3	2	2	1	0
- Hard coal (& non-renewable waste)	0	0	0	0	0	0	0
- Lignite	0	0	0	0	0	0	0
- Gas	2	2	1	1	1	1	0
- Oil + Diesel	1	2	1	1	2	0	0
Combined heat and power plants	0	0	0	0	0	0	0
- Hard coal (& non-renewable waste)	0	0	0	0	0	0	0
- Lignite	0	0	0	0	0	0	0
- Gas	0	0	0	0	0	0	0
- Oil	0	0	0	0	0	0	0
CO2 emissions power and CHP plants	3	3	3	2	2	1	0
- Hard coal (& non-renewable waste)	0	0	0	0	0	0	0
- Lignite	0	0	0	0	0	0	0
- Gas	2	2	1	1	1	1	0
- Oil + Diesel	1	2	1	1	2	0	0
CO2 intensity (g/kWh)	0	0	0	0	0	0	0
without credit for CHP heat	0	0	0	0	0	0	0
- CO2 intensity fossil electr. generation	684	657	633	625	657	404	0
- CO2 intensity total electr. generation	407	201	68	25	15	4	0
CO2 emissions by sector	14	16	14	10	9	5	4
0	0%	0%	0%	0%	0%	0%	0%
- Industry 1)	3	3	2	1	1	0	0
- Other sectors 1)	1	3	2	2	1	0	0
- Transport	7	8	7	4	5	4	4
- Power generation 2)	3	3	3	2	2	1	0
- Other conversion 3) - part of industry & tr	0	1	1	0	0	0	0
Population (Mill.)	60	69	79	90	102	114	126
CO2 emissions per capita (t/capita)	0	0	0	0	0	0	0

Primary Energy Demand [PJ/a]	2020	2025	2030	2035	2040	2045	2050
Total (incl. non-energy-use)	1,070	1,265	1,171	1,306	1,496	1,667	1,780
- Fossil (excluding on-energy use)	183	217	184	137	114	72	54
- Hard coal	20	16	11	7	0	0	0
- Lignite	0	0	0	0	0	0	0
- Natural gas	35	37	31	21	16	15	0
- Crude oil	128	165	143	108	98	57	54
- Nuclear	0	0	0	0	0	0	0
- Renewables	884	1,045	985	1,166	1,379	1,590	1,721
- Hydro	10	9	11	12	20	22	34
- Wind	0	1	6	26	76	198	535
- Solar	1	57	149	329	500	639	738
- Biomass	873	962	790	747	692	592	203
- Geothermal	0	16	29	53	91	140	211
- Ocean energy	0	0	0	0	0	0	0
Total RES	884	1,045	983	1,162	1,371	1,579	1,703
RES share	83%	83%	84%	89%	92%	96%	97%

Tanzania

REFERENCE

Electricity generation [TWh/a]	2020	2025	2030	2035	2040	2045	2050
Power plants	8	15	41	87	146	214	324
- Hard coal (& non-renewable waste)	0	0	0	0	0	0	0
- Lignite	0	0	0	0	0	0	0
- Gas	3	5	13	29	49	57	74
of which from H2	0	0	0	0	0	0	0
- Oil	1	1	3	6	8	6	0
- Diesel	0	0	0	0	0	0	0
- Nuclear	0	0	0	0	0	0	0
- Biomass (& renewable waste)	0	0	0	1	2	3	5
- Hydro	3	3	3	3	5	6	9
- Wind	0	2	6	14	31	50	78
of which wind offshore	0	1	2	4	6	8	9
- PV	0	4	14	31	45	82	142
- Geothermal	0	0	0	3	6	10	15
- Solar thermal power plants	0	0	0	0	1	1	2
- Ocean energy	0	0	0	0	0	0	0
Combined heat and power plants	0	0	0	0	0	0	0
- Hard coal (& non-renewable waste)	0	0	0	0	0	0	0
- Lignite	0	0	0	0	0	0	0
- Gas	0	0	0	0	0	0	0
of which from H2	0	0	0	0	0	0	0
- Oil	0	0	0	0	0	0	0
- Biomass (& renewable waste)	0	0	0	0	0	0	0
- Geothermal	0	0	0	0	0	0	0
- Hydrogen	0	0	0	0	0	0	0
CHP by producer							
- Main activity producers	0	0	0	0	0	0	0
- Autoproducers	0	0	0	0	0	0	0
Total generation	8	15	41	87	146	214	324
- Fossil	4	6	16	35	57	63	74
- Hard coal (& non-renewable waste)	0	0	0	0	0	0	0
- Lignite	0	0	0	0	0	0	0
- Gas	3	5	13	29	49	57	74
- Oil	1	1	3	6	8	6	0
- Diesel	0	0	0	0	0	0	0
- Nuclear	0	0	0	0	0	0	0
- Hydrogen	0	0	0	0	0	0	0
- of which renewable H2	0	0	0	0	0	0	0
- Renewables (w/o renewable hydrogen)	3	9	25	53	89	151	250
- Hydro	3	3	3	3	5	6	9
- Wind	0	2	6	14	31	50	78
- PV	0	4	14	31	45	82	142
- Biomass (& renewable waste)	0	0	0	1	2	3	5
- Geothermal	0	0	1	3	6	10	15
- Solar thermal power plants	0	0	0	0	1	1	2
- Ocean energy	0	0	0	0	0	0	0
Distribution losses	1	1	2	4	6	9	14
Own consumption electricity	0	0	1	2	4	6	9
Electricity for hydrogen production	0	2	7	12	17	24	28
Electricity for synfuel production	0	0	0	0	0	0	0
Final energy consumption (electricity)	6	12	31	71	121	179	278
Variable RES (PV, Wind, Ocean)	0	6	21	45	76	132	219
Share of variable RES	3%	39%	51%	52%	52%	61%	68%
RES share (domestic generation)	40%	58%	61%	60%	61%	71%	77%

Transport - Final Energy [PJ/a]	2020	2025	2030	2035	2040	2045	2050
road	91	104	91	123	172	244	305
- fossil fuels	91	104	89	117	162	224	263
- biofuels	0	0	1	3	5	9	24
- synfuels	0	0	0	0	0	0	0
- natural gas	0	0	0	0	0	0	0
- hydrogen	0	0	0	1	1	1	1
- electricity	0	0	1	2	4	10	18
rail	0	0	0	0	0	0	0
- fossil fuels	0	0	0	0	0	0	0
- biofuels	0	0	0	0	0	0	0
- synfuels	0	0	0	0	0	0	0
- electricity	0	0	0	0	0	0	0
navigation	0	0	0	0	0	0	0
- fossil fuels	0	0	0	0	0	0	0
- biofuels	0	0	0	0	0	0	0
- synfuels	0	0	0	0	0	0	0
aviation	1	1	1	1	1	1	2
- fossil fuels	1	1	1	1	1	0	0
- biofuels	0	0	0	0	1	1	1
- synfuels	0	0	0	0	0	0	1
total (incl. pipelines)	92	105	93	124	173	245	307
- fossil fuels	92	104	90	118	162	224	263
- biofuels (incl. biogas)	0	0	2	3	6	10	25
- synfuels	0	0	0	0	0	0	1
- natural gas	0	0	0	0	0	0	0
- hydrogen	0	0	0	1	1	1	1
- electricity	0	0	1	2	4	10	18
total RES	0	0	2	5	9	18	40
RES share	0%	0%	2%	4%	5%	7%	13%

Heat supply and air conditioning [PJ/a]	2020	2025	2030	2035	2040	2045	2050
District heating plants	0	0	0	0	0	0	0
- Fossil fuels	0	0	0	0	0	0	0
- Biomass	0	0	0	0	0	0	0
- Solar collectors	0	0	0	0	0	0	0
- Geothermal	0	0	0	0	0	0	0
Heat from CHP 1)	0	0	0	0	0	0	0
- Fossil fuels	0	0	0	0	0	0	0
- Biomass	0	0	0	0	0	0	0
- Geothermal	0	0	0	0	0	0	0
- Hydrogen	0	0	0	0	0	0	0
Direct heating	614	717	878	991	1,123	1,242	1,289
- Fossil fuels	29	39	44	51	56	42	36
- Biomass	556	585	647	594	524	441	102
- Solar collectors	0	38	63	101	138	168	228
- Geothermal	0	15	26	41	70	103	154
- Heat pumps 2)	0	2	35	77	129	186	350
- Electric direct heating	29	33	42	87	144	206	277
- Hydrogen	0	0	1	2	6	12	16
Total heat supply3)	614	717	878	991	1,123	1,242	1,289
- Fossil fuels	29	39	44	51	56	42	36
- Biomass	556	585	647	594	524	441	102
- Solar collectors	0	38	63	101	138	168	228
- Geothermal	0	15	26	41	70	103	154
- Heat pumps 2)	0	2	35	77	129	186	350
- Electric direct heating (incl. process heat)	29	37	62	124	200	289	404
- Hydrogen	0	0	1	2	6	12	16
RES share (including RES electricity)	92%	92%	91%	87%	84%	85%	84%
electricity consumption heat pumps (TWh/a)	0.0	0.0	0.0	0.0	0.0	0.0	0.0

Installed Capacity [GW]	2020	2025	2030	2035	2040	2045	2050
Total generation	4	8	23	50	78	120	187
- Fossil	2	3	7	15	24	25	26
- Hard coal (& non-renewable waste)	0	0	0	0	0	0	0
- Lignite	0	0	0	0	0	0	0
- Gas (w/o H2)	1	2	4	10	17	20	26
- Oil & Diesel	1	1	3	5	7	5	0
- Diesel	0	0	0	0	0	0	0
- Nuclear	0	0	0	0	0	0	0
- Hydrogen (fuel cells, gas power plants, ga	0	0	0	0	0	0	0
- Renewables	1	5	16	35	55	95	162
- Hydro	1	1	1	1	2	2	3
- Wind	0	1	2	5	11	17	26
of which wind offshore	0	0	1	1	1	2	2
- PV	0	4	13	28	41	74	129
- Biomass (& renewable waste)	0.016	0.031	0.092	0.239	0.467	0.8	1.2
- Geothermal	0	0	0	0	1	1	2
- Solar thermal power plants	0	0	0	0	0	0	1
- Ocean energy	0	0	0	0	0	0	0
Variable RES (PV, Wind, Ocean)	0	4	15	33	51	91	155
Share of variable RES	6%	54%	65%	66%	66%	76%	83%
RES share (domestic generation)	35%	64%	70%	69%	70%	79%	86%

Final Energy Demand [PJ/a]	2020	2025	2030	2035	2040	2045	2050
Total (incl. non-Energy use)	843	962	1,111	1,277	1,493	1,727	1,852
Total Energy use 1)	841	960	1,108	1,274	1,489	1,722	1,847
Transport	98	105	93	124	173	245	307
- Oil products	98	104	90	118	162	224	263
- Natural gas	0	0	0	0	0	0	0
- Biofuels	0	0	2	3	6	10	25
- Synfuels	0	0	0	0	0	0	1
- Electricity	0	0	1	2	4	10	18
RES electricity	0	0	0	1	3	7	14
- Hydrogen	0	0	0	1	1	1	1
RES share Transport	0%	0%	2%	4%	5%	7%	13%
Industry	95	121	166	225	305	412	415
- Electricity	6	11	30	50	74	107	257
RES electricity	2	6	18	30	45	76	198
- Public district heat	0	0	0	0	0	0	0
RES district heat	0	0	0	0	0	0	0
- Hard coal & lignite	20	19	23	24	27	26	23
- Oil products	1	1	2	2	3	0	0
- Gas	6	8	10	13	15	10	4
- Solar	0	4	9	13	18	27	40
- Biomass	61	76	89	113	148	203	35
- Geothermal	0	1	3	6	10	16	24
- Hydrogen	0	0	1	4	12	24	32
RES share Industry	67%	73%	72%	74%	76%	84%	79%
Other Sectors	649	735	850	925	1,010	1,065	1,125
- Electricity	17	32	81	199	349	515	710
RES electricity	7	19	49	120	214	364	548
- Public district heat	0	0	0	0	0	0	0
RES district heat	0	0	0	0	0	0	0
- Hard coal & lignite	0	0	0	0	0	0	0
- Oil products	8	18	18	20	20	13	14
- Gas	0	0	0	0	0	0	0
- Solar	0	34	54	88	120	141	189
- Biomass	623	636	674	582	461	309	83
- Geothermal	0	14	23	35	60	87	130
- Hydrogen	0	0	0	0	0	0	0
RES share Other Sectors	97%	96%	94%	89%	85%	85%	84%
Total RES	694	791	923	996	1,097	1,264	1,317
RES share	82%	82%	83%	78%	74%	73%	71%
Non energy use	2	2	3	3	4	4	5
- Oil	2	2	3	3	4	4	5
- Gas	0	0	0	0	0	0	0
- Coal	0	0	0	0	0	0	0

Energy-Releated CO2 Emissions [Million tons/a]	2020	2025	2030	2035	2040	2045	2050
Condensation power plants	3	4	9	19	28	28	29
- Hard coal (& non-renewable waste)	0	0	0	0	0	0	0
- Lignite	0	0	0	0	0	0	0
- Gas	2	2	6	13	21	23	29
- Oil + Diesel	1	2	3	6	7	5	0
Combined heat and power plants	0	0	0	0	0	0	0
- Hard coal (& non-renewable waste)	0	0	0	0	0	0	0
- Lignite	0	0	0	0	0	0	0
- Gas	0	0	0	0	0	0	0
- Oil	0	0	0	0	0	0	0
CO2 emissions power and CHP plants	3	4	9	19	28	28	29
- Hard coal (& non-renewable waste)	0	0	0	0	0	0	0
- Lignite	0	0	0	0	0	0	0
- Gas	2	2	6	13	21	23	29
- Oil + Diesel	1	2	3	6	7	5	0
CO2 intensity (g/kWh)	0	0	0	0	0	0	0
without credit for CHP heat	0	0	0	0	0	0	0
- CO2 intensity fossil electr. generation	684	610	568	537	496	453	388
- CO2 intensity total electr. generation	407	254	220	214	192	133	89
CO2 emissions by sector	14	18	22	35	47	51	53
0	0%	0%	0%	0%	0%	0%	0%
- Industry 1)	3	3	4	4	5	4	3
- Other sectors 1)	1	3	3	3	2	1	1
- Transport	7	8	7	9	12	17	20
- Power generation 2)	3	4	9	19	28	28	29
- Other conversion 3) - part of industry & tr	0	1	1	1	1	1	1
Population (Mill.)	60	69	79	90	102	114	126
CO2 emissions per capita (t/capita)	0	0	0	0	0	0	0

Primary Energy Demand [PJ/a]	2020	2025	2030	2035	2040	2045	2050
Total (incl. non-energy-use)	1,070	1,273	1,235	1,510	1,816	2,045	2,194
- Fossil (excluding on-energy use)	183	235	311	510	715	766	828
- Hard coal	20	19	23	24	27	26	23
- Lignite	0	0	0	0	0	0	0
- Natural gas	35	51	117	244	390	430	528
- Crude oil	128	164	171	242	299	310	277
- Nuclear	0	0	0	0	0	0	0
- Renewables	884	1,036	922	997	1,097	1,275	1,360
- Hydro	10	9	11	11	18	21	32
- Wind	0	1	6	24	71	123	214
- Solar	1	51	107	201	285	445	726
- Biomass	873	959	769	709	633	549	182
- Geothermal	0	16	29	52	90	137	207
- Ocean energy	0	0	0	0	0	0	0
Total RES	884	1,035	921	994	1,092	1,267	1,347
RES share	83%	81%	75%	66%	60%	62%	62%

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