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Article

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Abstract: Energy flows in a fertile environment drive societal development and progress. To develop a country sustainably, striking balance between environmental management, natural resource use, and energy generation is a must. However, developing a country with limited access to energy and critical levels of environmental depletion is challenging. This description fits Rwanda, which faces a dual crisis of energy supply shortages and environment depletion. Overpopulation is driving urban and agricultural expansion which in turn unbalance biomass demand to supply the growing energy needs and exacerbate environmental damage. Just when urgent actions must be taken to overcome this current debacle, political aspirations seek to turn Rwanda into a middle- and subsequently high-income country. From our analysis, the available energy resources can only maintain current population in Rwanda as a low-income country. To become an average middle-income country, Rwanda needs an equivalent of 3 Mtoe/yr ($\approx$20 Mbbl/yr) of oil imports, and must install a nominal capacity of 90 GW of solar photovoltaics (PV). For a high-income country, it is necessary to obtain an extra power input of 11.4 Mtoe/yr ($\approx$77 Mbbl/yr) of oil imports and to install a nominal capacity of 400 GW of solar PV. Comparing current power generation capacity in Rwanda against the extra power needed to achieve the middle-income and high-income status indicates a mismatch between available resources and developmental goals.

Keywords: sustainable development; energy; Rwanda

1. Introduction

There is a complex relationship among energy, the environment and development. Since we are mostly energy-blind [1], it is hard to perceive how this relationship pervades all aspects of our life. There is a chasm between the demands of modern globalized urban life and the capacity of local ecosystems to support these demands. The growing gap in comprehending the biophysical underpinnings of modern civilization leads us to underestimate our dependence on mother nature and urban vulnerabilities.

Available energy per unit time and per person has been driving change and "progress" [2] of all societies [3]. This means that sufficient energy resources are critical for all countries that strive to develop and maintain wealth. Traditionally, the wealth of nations is measured through economic indicators such as the gross domestic product (GDP), which measures the monetary value of goods produced, and services provided in a country [4]. Another standard indicator is the human development index (HDI), which evaluates living standards, life expectancy, and access to education [5]. However, both GDP and HDI largely ignore measures of energy consumption as it relates to the wealth of a nation and its resilience [6]. A deeper look shows that energy consumption correlates strongly with the level of development and wealth a nation has. Figure 1 shows the positive correlation of energy consumption and these indicators.

Figure 1a shows the relation between GDP and power consumption. It seems obvious that a higher GDP requires more power consumption to produce goods and provide services. Though less intuitive, Figure 1b also demonstrates how power consumption and

the HDI index are correlated. This correlation clearly shows the proportional relationship between the development of a country and the power that fuels this growth. Developing the underdeveloped countries requires increasing their power supplies. Furthermore, once a certain development level is achieved, a constant power input is needed to maintain the system. In other words, an economy is like a living organism that needs power throughput to stay alive.

Natural energy resources in their primary forms can be found, e.g., in rivers and lakes (hydropower), forests (biomass), or swamps (peat). The color code in Figure 1 represents arable land per capita, which indicates the pressure exerted on the environment to produce food or extract natural resources. The restricted access to land can lead to competition for land use between energy and food. Overpopulated countries that have low HDI have an extra challenge to develop due to limited natural resources. Conversely, overpopulated developed countries are fragile because of their dependence on imports to supply vital needs [6].
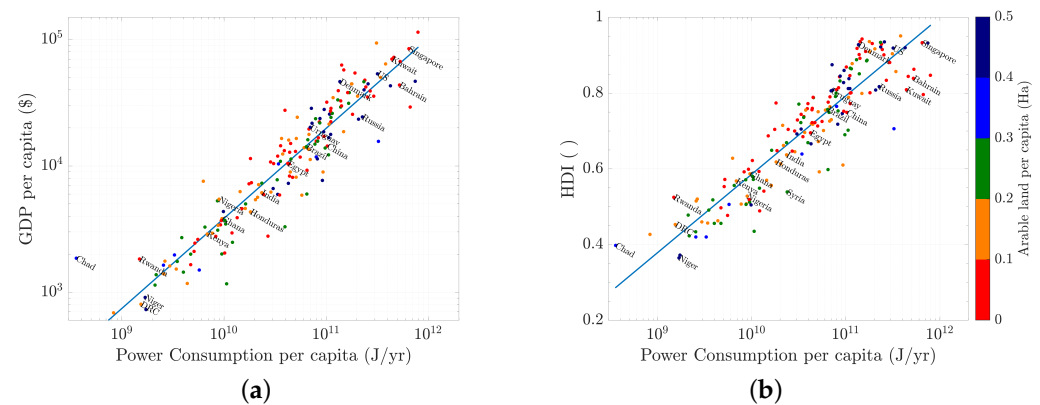

Figure 1. Power consumption indices. (**a**) Power consumption per capita versus GDP; (**b**) Power consumption per capita versus HDI. The color code indicates the arable land per capita. Data from UN [5], EIA [7] and FAO [8].

One of the UN's sustainable development goals is to eliminate extreme poverty [9], which means an increase in energy consumption per capita by this share of the global population. While poverty is always associated with economic status, we must look beyond the traditional indices to achieve this proposed goal. A healthy environment, availability of natural resources, and energy are critical factors for sustainable development. However, the challenges discussed in this paper pertain to a developing a country with a limited access to energy, and in which environmental depletion is already at a dangerous level. Moreover, some underdeveloped countries are already overpopulated and facing exponential population growth that aggravates their biophysical conditions. The question is whether there is hope for development, or if these countries are inevitably destined to collapse [6].

This work is a case study of Rwanda, a country with critical problems, such as over-population, poverty, environmental depletion, and limited energy resources. The current scenario, though not unique to Rwanda, leaves little room for trial and error. A clear understanding of the main barriers to development, local conditions, and limitations is a must. Only with an appropriate set of actions will it be possible to escape poverty and avoid social and environmental breakdowns.

After the review of this paper, France 24 published a 17 min video segment on Rwanda, entitled Rwanda: Tackling the challenge of overpopulation (https://youtu.be/JIpzqT7o N9Q, accessed on 6 May 2022) that illustrates qualitatively all of the major quantitative points we make here.

2. Current Status of Rwanda

The following subsections briefly describe Rwanda's current situation, providing the background information needed to understand the complexity involved in the proposed analysis.

2.1. Economy

Rwanda is a landlocked sub-Saharan country that is developing at a fast rate, with annual GDP growth of 5% over the last decade. This economic growth is echoed in the enhancement of living standards and poverty reduction [10]. Despite the impressive improvements, Rwanda is still classified as a low-income country, evidenced by its per capita GDP of USD 1800 (Purchase Power Parity–Current international, 2016) [11]. The primary sector represents a third of the GDP, and a significant part of the industrial sector processes primary goods [12,13].

2.2. Population

Currently, Rwanda has a population of 12 million people [14]. The current trends indicate that by the year 2100, this number will triple (see Figure S1) [15,16]. A country must account for population projections to have adequate planning and infrastructure management. From an economic perspective, the young population means a considerable workforce for the future that can support the ambitions and plans to develop the country. Despite the advantages of a growing population, any economic plan must carefully consider the strain that an increasing population will put on the country's natural resources regarding sustainable energy production, food production, pollution, ecosystem integrity and biodiversity.

In addition to internal population growth, because of political instability in the region, additional increases in population are likely to result from external sources. Figure 2 shows the countries neighboring Rwanda and their respective Gross National Income (GNI). In 2017, Rwanda received 170,000 refugees, with 53% from Burundi and 46% from the Democratic Republic of Congo (DRC) [17]. Political stability in Rwanda and a fast rate of development could intensify these migration inflows. A regional strategic plan would be needed to avert this situation.
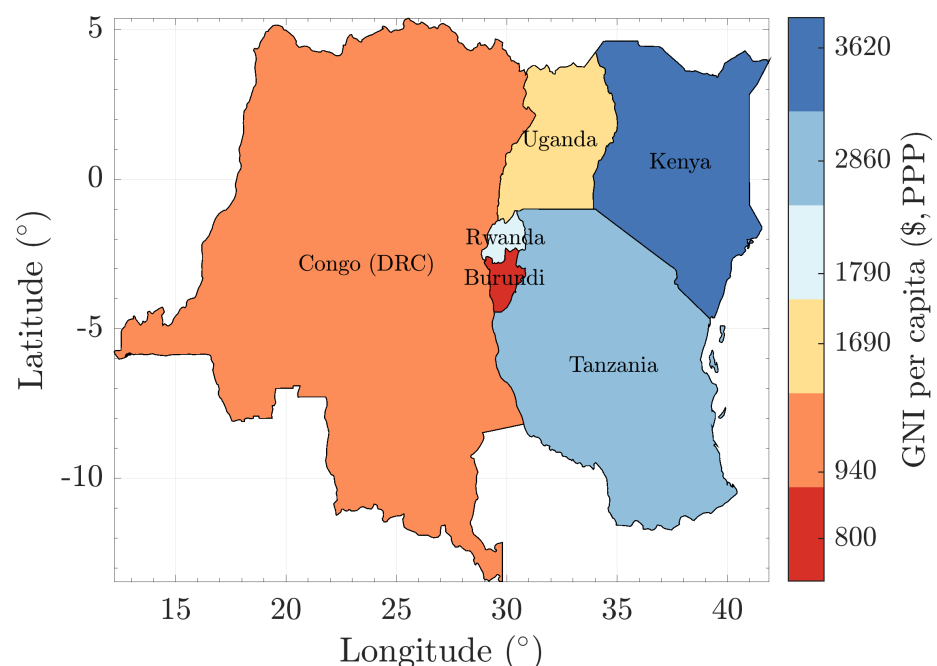

Figure 2. Map with regional GNI per capita. Data from World Bank [18], reference year of 2016. Country borders plotted using Greene et al. [19].

When it comes to population, some limitations of the forecasted values should be mentioned. Current estimations do not include wars or disease outbreaks, which can occur in the future. Furthermore, the sub-Saharan Africa is one of the places that are most vulnerable to climate change; these effects could induce massive migrations [20,21]. Will the migrants move to another region, continent, or a better neighboring country? All of these factors increase the risks of overpopulation, making it critical to effectively plan how to deploy natural resources to meet the growing energy needs.

2.3. Environment

Natural resources have been overexploited in Rwanda. Agriculture uses more than half of the land area [12]. Inadequate farming practices widespread across the sector can result in the systemic environmental depletion. Soil exhaustion and erosion can be observed in vast areas. As a consequence, Rwandans need to find more arable land to supply food in a country with constrained access to land [13,22]. This situation could be described as a socio-ecological trap [23]. An expansion of land use for agricultural purposes limits the resources available for energy development necessary for economic growth [24].

Competition for land use can also be observed through deforestation—another environmental issue in Rwanda. There is little left to be deforested; the only natural forests that remain are national parks, and currently the country is gaining forested area due to governmental initiatives [25–29]. The root cause of deforestation is population growth, which demands an expansion of cultivated and urban areas to provide food and shelter [30]. Inherently, this increases energy consumption demanding more biomass—aggravating deforestation in turn.

2.4. Energy

Rwanda's energy sector is the bottleneck for development. As a typical low-income country, Rwanda has a low energy consumption and little reliance on fossil fuels that result in negligible CO_2 emissions. Rwanda's energy consumption and CO_2 emissions are low even when compared to those of its peers [7].

Figure 3 summarizes Rwanda's power profile. Figure 3a shows power consumption. The principal source is biomass, mainly consumed by households as cooking fuel. Figure 3b shows the electricity generation mix and consumption by sector. Although electricity represents only 2% of total power consumption, it is growing at a fast pace. Both the generation capacity and transmission network are expanding to meet the increasing demand—aiming to reduce costs and increase access and reliability [12,31,32]. The electric power sector faces challenges related to infrastructure maintenance, the struggle to achieve a good mix of power that matches the consumption profile, and the capital required to implement these projects [12].

Another problem associated with electricity generation in Rwanda is that the 218 MW [12] of nominal capacity installed is not reliable and is subject to intermittence. From the electricity produced, the mean capacity factor [33] of only ~0.3 can be estimated [34]. This value is very low for a generation mix that includes reliable resources such as diesel, hydro, and CH_4 as major components—most likely a consequence of hydropower seasonality or dispatch limitations.

Electricity consumption is distributed equally between households and industry; however, high costs and low reliability limit further adoption [35]. Access to electricity is a problem in Rwanda. Despite some progress, in 2019, only 40% of the population had access to electricity, the situation is worse in the rural areas with only 24% [36]. These numbers are below the target proposed by the government, which was 70% in 2017. It is clear that more efforts are required to achieve 100% access to electricity by 2024 [37]. The most cost-effective solution to increase access to electricity in rural areas is through off-grid solutions, which can power lighting and appliances in households and small businesses [37]. Rural electrification has taken off in Rwanda for one simple reason: it reduces costs for the end-users [38], who are spending less money on lighting. The micro-credit system named

"pay as you go" makes it cost-effective to pay for a solar array instead of spending money on kerosene, candles, and batteries [39]. This approach creates a clear win–win situation, with easier access to electricity and more benefits to end-users.
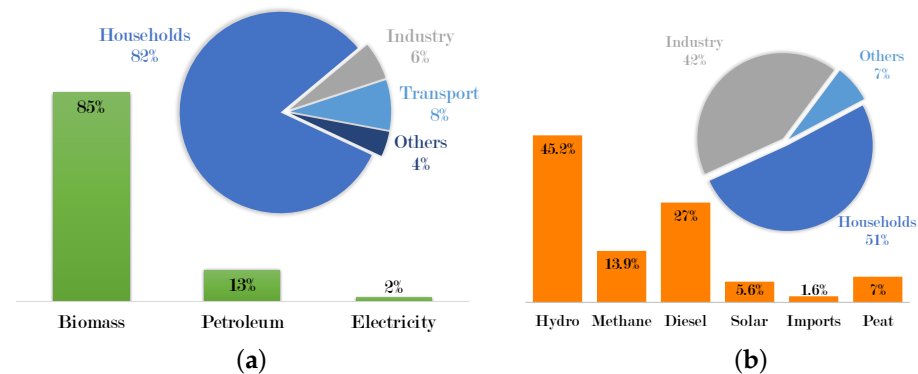

Figure 3. Power and electricity. (**a**) Power consumption; the bar chart shows the consumption by source and the pie chart consumption by sector. (**b**) Electricity; the bar chart shows the nominal capacity installed, which resembles the electricity generation share (51% hydro, 43% thermal, and 5% solar), and the pie chart shows the electricity consumption by sector. Data from the Ministry of Infrastructure (MINIFRA) [12] and Rwanda Energy Group [40].

As a result of underdevelopment, biomass burning, which is usually negligible in a developed country, is Rwanda's most important energy source since it supplies heat for cooking. In Rwanda, biomass is still the most affordable energy source relative to all other substitutes, which are electricity and liquefied petroleum gas (LPG) [30]. Commonly, biomass is collected at no monetary cost, but this task demands on average 6 h/day of labor of a family member [13,41]. While there is no cost to collect biomass, the time spent collecting firewood could be used more productively. This situation is a poverty trap, with consequences for the population's health and the environment [42,43]. However, when properly managed, biomass use can offer energy security, because wood is renewable, not subject to foreign influence, and can contribute to income generation in rural areas [30]. See Supplementary Section 2 for the details on biomass use and clean cooking.

A recent study carried out by MININFRA [41] to elaborate a biomass energy strategy for the period 2019 to 2030 seems to reiterate points from previous reports written a decade earlier [13,30]. Rwanda has an unsustainable demand for biomass, worsened by inefficiencies along the production and consumption chains. Rwanda's government wants to halve the percentage of households using biomass. They want to achieve these goals by spreading more efficient technologies of cooking stoves and fuels [41]. Alternative fuels, such as pellets, briquettes, biogas and electricity, aim for higher conversion efficiency. To strike a balance, Rwandans want to reduce the use of wood biomass and, at the same time, reforest the country.

The oil sector in Rwanda is underdeveloped, and lacks infrastructure and management [12]. The main issues are high price volatility and lack of quality control. The most consumed oil products are diesel fuel to generate electricity, and kerosene, natural gas and LPG [12]. Hydrocarbon price fluctuations have slowed down the replacement of biomass with LPG [44]. Due to an information gap about consumption and usage of these products, it is difficult to elaborate a strategic plan [12].

Figure 4 shows the primary power consumption by source in Rwanda. Because detailed information is missing, the electricity generation mix (except for diesel fuel and heavy oil) is lumped. The estimated losses of petroleum are due to thermodynamic efficiency of power conversion assumed to be 30% [45]. In addition, electricity losses are estimated at approximately 20%, mainly due to theft and technical issues [46]. From the perspective provided by the power flows, we can understand the significant role of biomass as cooking fuel and identify Rwanda's underdevelopment.

A challenge appeared in tracking Rwanda's power flows. Most of the information found was available in MININFRA [12] and Rwanda Energy Group [40]. It is difficult to find more granular information about Rwanda in the commonly used energy databases. In some cases, there were either no data or only petroleum and electricity consumption were accounted for, omitting altogether the biomass energy consumption that in Rwanda's case has a dominant share. When we think about power consumption in underdeveloped countries, this omission could raise questions: Are we underestimating total power consumption? If yes, not accounting for biomass can have severe implications for the future power consumption scenarios that are then misleading.
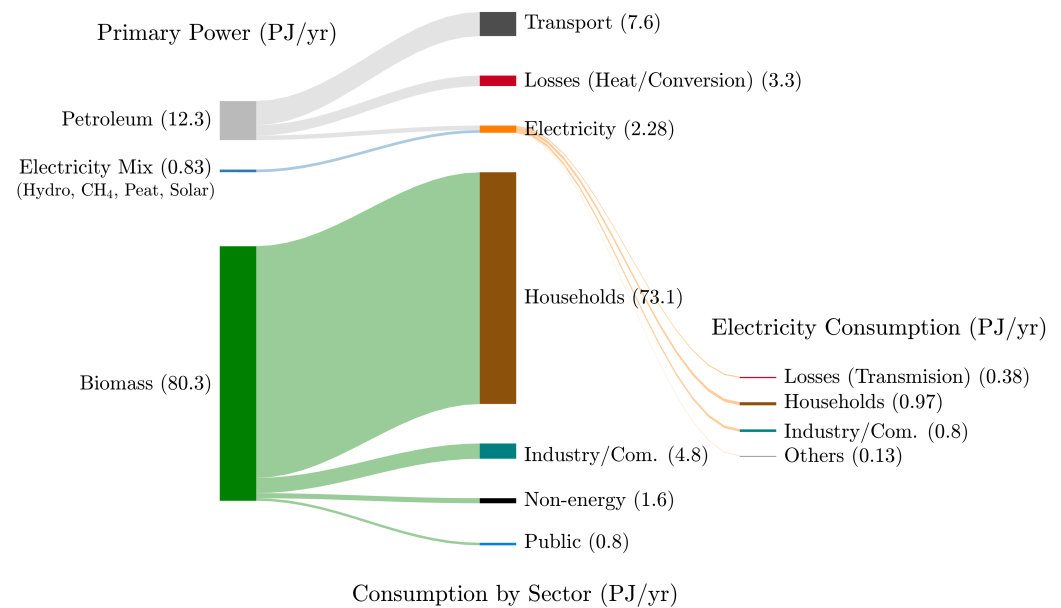

Figure 4. Power flows in Rwanda. Primary power consumption by source and sector and electricity generation by source and its consumption by sectors. This graph was prepared with a modified version of [47].

Beyond the present, it is crucial to verify where the energy for future generations will come from. An evaluation of potential energy resources was reported by MININFRA [12], and Table 1 summarizes the potential resources and currently installed capacity.

A critical remark on evaluating potential resources in Rwanda is that initial assessments usually overestimate the real potential, perhaps to grab attention for further developments or due to uncertainty associated with the early stages. Examples of this situation are the assessment of peat and CH_4 extraction from Lake Kivu, in which initial estimations are nearly five-fold the current estimated potential [12,48].

There are several potential power resources in Rwanda, which are at various stages of research and implementation. Some resources such as hydropower, methane, and peat seem to be well-studied, especially in the areas where exploration projects are planned or implemented. Geothermal resources need to be confirmed and require detailed studies [12]. Solar power appears to be of great interest as an off-grid solution, as it provides access to electricity and does not require grid expansion investment; solar irradiation fluctuates between 4 kWh to 5 kWh per day in all regions [12]. Rwanda has few assessments of wind power potential [12], and they indicate low suitability for conventional generation; nevertheless, low-speed applications could be an alternative. As stated earlier, biomass is currently over-exploited, and its use should be reduced. However, expanding forested areas, adopting agroforestry, and proper management could maintain a certain level of sustainable biomass consumption.

Table 1. Potential power resources. Adapted from MININFRA [12].

Resource	Potential (MW)	Installed (MW)
Hydropower	300–400	98.5
Methane	140–180	30
Peat	120–160	15
Geothermal	47	-
Solar	TBD	12
Biomass	TBD	-
Wind	TBD	-

TBD: To Be Defined, refers to resources that are being evaluated.

2.5. Energy–Environmental Crisis

Rwanda's population is growing fast, heavily taxing the domestic sources of energy, food, and water [13]. Overpopulation is the underlying cause of environmental problems. Degradation of natural resources, in turn, aggravates poverty. Overcoming this challenge requires development and adoption of a sustainable strategy.

The complex relationship between the environment and development is a critical dilemma, and exploitation of natural resources to reach a specific economic goal is a common path of industrialization. However, there is no guarantee that the over-exploitation of natural resources can ensure targeted development. Conversely, irresponsible use of natural resources can lead to issues such as deforestation, creating a poverty trap. Other environmental issues, such as climate-related conditions (e.g., droughts and flooding), limited land access and soil infertility reinforce Rwanda's poverty [13].

The Rwandan energy crisis faces two main challenges. First, there is a lack of energy. Second, demand for biomass is too high. These two conditions are intertwined, and currently there is no viable replacement for biomass; all potential solutions are limited by cost and poverty.

3. Materials and Methods

Rwanda aims to become a middle-income country by 2035 and a high-income one by 2050 [10]. According to the World Bank [18], a middle-income country has a gross national income per capita on average of USD 12,000 (corrected by purchasing power parity (PPP) and current USD value). For a high-income country, gross national income (GNI) per capita is close to USD 30,000. GNI is GDP plus income from abroad, which can be salaries, property income, investments, net taxes, and foreign aid [49,50]. We adopt GNI because it is a better metric to evaluate the welfare of a nation. GNI and GDP usually are similar (see Supplementary Section 3). To estimate the power requirements to achieve the targeted goals, we performed a linear regression of the global data of power consumption per capita versus GNI. The reference data were extracted from the EIA [7] and UNDP [51] databases.

An assessment of Rwanda's currently installed and potential power resources was made from the data reported by MININFRA [12]. Afterward, we explored a scenario of building a power mix mainly driven by solar PV.

4. Results and Discussions

4.1. Developmental Goals and Requirements

The underlying question is whether Rwanda has enough resources to achieve this development target or if it will have to depend mainly on foreign energy inputs. To determine if Rwanda has enough resources, we first must understand the required resources typically used by countries at different levels of development. Figure 5 shows the relation between GNI and power consumption. The blue line is a trend line based on global data, where the gray dots represent individual countries. The red star is Rwanda's current status as a low-income country. The golden stars show the targets to become an average middle-income country or to be considered a high-income country. These goals require 50 GJ/yr and 200 GJ/yr of power per capita.

It is important to mention that Figure 5 is on a log-log scale. To become an average middle-income country, Rwanda's GNI must grow by a factor of 7, and to sustain this income power consumption will increase by a factor of 33. To move from a middle-income to a high-income country, the GNI must increase by a factor of 2.6, and the power consumption must increase by 4. These values are approximations of the required levels of power to sustain a certain economy. Currently, Rwanda is outperforming the global average. However, as a country develops, it becomes more complex to maintain an energy-efficient system.
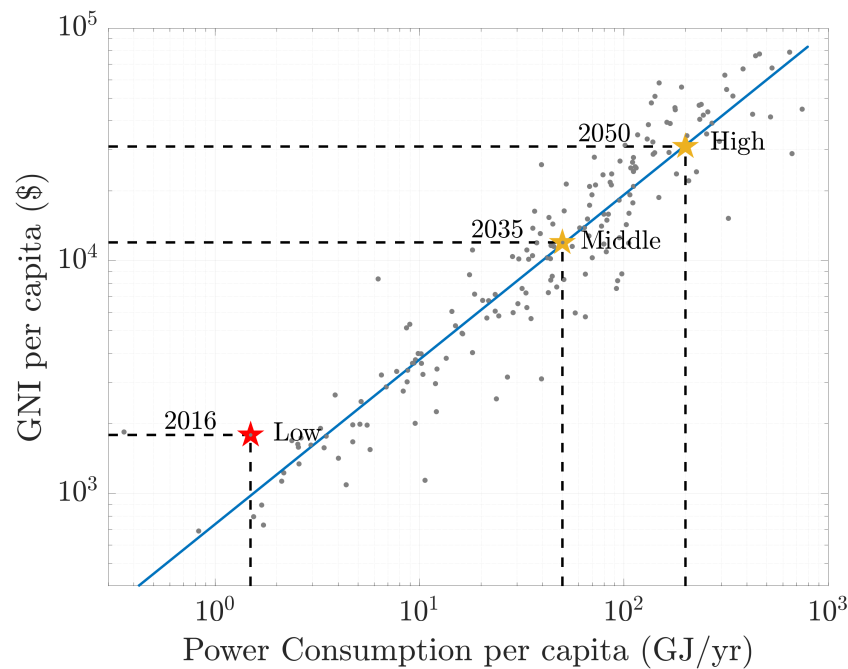

Figure 5. Rwanda's power requirements for development. The red star is the current status of Rwanda; The gold stars show the goals of Rwanda's government to become a middle and high-income country by 2035 and 2050, respectively. It shows the average value of GNI and power consumption per capita based on the global trend. The blue line is the global trend, while the gray dots represent the countries in 2016. The data are from [7,51].

4.2. Available Resources

Figure 6 shows the potential primary power available in Rwanda, based on the data from MININFRA [12,41]. Composed mainly of renewable resources, the primary power potential of Rwanda is from 30 PJ/yr to 85 PJ/yr. For the current population of 12 million people, these power resources are only sufficient to support a low-income economy, i.e., 2.5 GJ/yr to 7 GJ/yr per capita. From a carrying capacity perspective, Rwanda can carry 325,000 people as a high-income country (3% of current population); or 1.3 million people as a middle-income country, which is 10% of the current population (see Figure S3 for details).

As shown in Figure 6, the most abundant resource is biomass, which comprises ~50% of the total potential resources. To achieve the aimed biomass power inputs, the fraction of Rwanda's territory dedicated to agroforestry will be 25% considering the upper limit of the error bar, and 6% at the lower bound; these premises are in alignment with the government goals [41]. CH_4 and peat are non-renewable sources; they will provide power inputs for a limited time. Once exploited, these resources must be replaced with something else. From a long-term perspective, we can question hydropower resources that might be jeopardized by climate change. Another promising resource is solar PV. The estimated values only account for the installed and planned power-generation plants. Solar resources are tricky to evaluate, as we can achieve the desired power supply by covering vast areas with solar

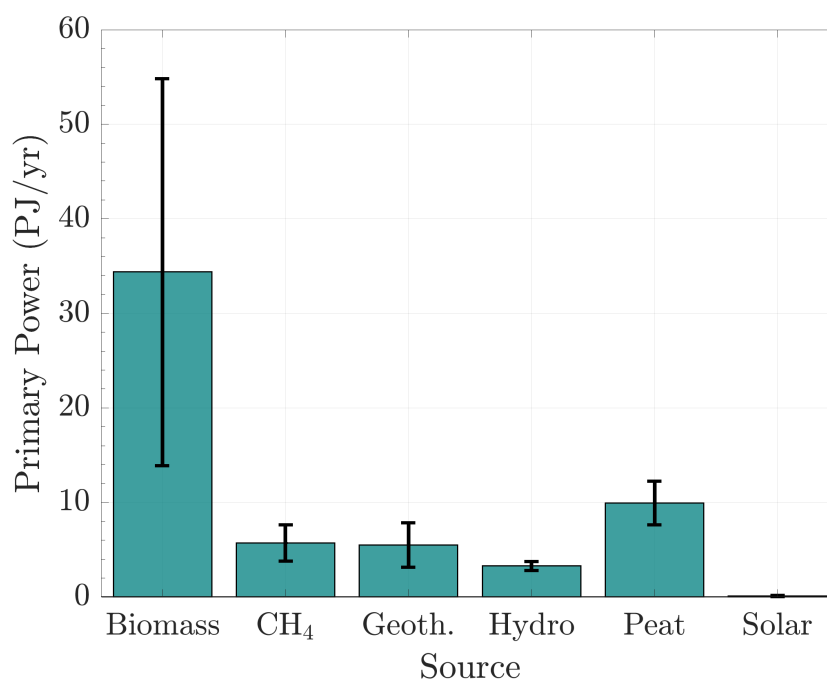panels. Supplementary Section 4 provides detailed assumptions and calculations for the key power resources.

Figure 6. Primary power potentially available in Rwanda. Solar power refers to currently installed and planned installations. Error bars are based on estimation bounds. The data were reported by MININFRA [37,41] and Bolson et al. [48].

Rwanda is a member of the International Atomic Energy Agency (IAEA), and it seems that nuclear energy is on the agenda of Rwanda's government, which is partnering with Russia to obtain the technology [52,53]. From an initial prospect dated back to 1985, the uranium reserves in Rwanda were estimated to be from 500 t to 5000 t [54]. However, no data confirm this potential resource, and there is no other recorded input in the "Red Books" for Rwanda [55]. This uranium reserve could provide an energy input from 0.25 EJ to 12.5 EJ, which could power a high-income Rwanda entirely for up to 5 years. After this period, Rwanda will be relying on foreign resources to run its nuclear power plants. Due to this uncertainty and the required time for developing and implementing a nuclear program, we do not rely on it for our scenario.

4.3. Required Resources

When the power requirements (Figure 5) and the potential resources available in Rwanda (Figure 6) are compared, we find that there is a mismatch. From Figure 6, the high output provides only 0.086 EJ/yr, which is 14% of the power required to become a middle-income country (0.6 EJ/yr), or 3.5% of the required power to be a high-income country (2.4 EJ/yr). Additional power inputs are needed to achieve the required power levels to develop the country based on the current population. There is a range of alternatives to supply Rwanda's power demand, from nuclear to fossil fuels, where a mix of different sources is the most probable. However, sustainable planning must account for a possible constrained supply of fossil fuels in the future. Envisioning a resilient system, we assume that for the extra power required, 80% will come from solar, and the remainder from oil imports.

Figure 7 shows Rwanda's power mix proposed for different income levels. For the current population, the available power resources will maintain Rwanda's status as a low-income country that with a growing population will become even poorer. To satisfy power requirements for a middle-income country, Rwanda needs to import an equivalent of 3 Mtoe/yr ($\approx$20 Mbbl/yr) and install a nominal solar power of 90 GW, which is

approximately 300 million panels. In the case of a high-income country, the oil imports are 11.4 Mtoe/yr ($\approx$77 Mbbl/yr) , and the required solar power is 400 GW, which implies the installation of 1.3 billion panels.
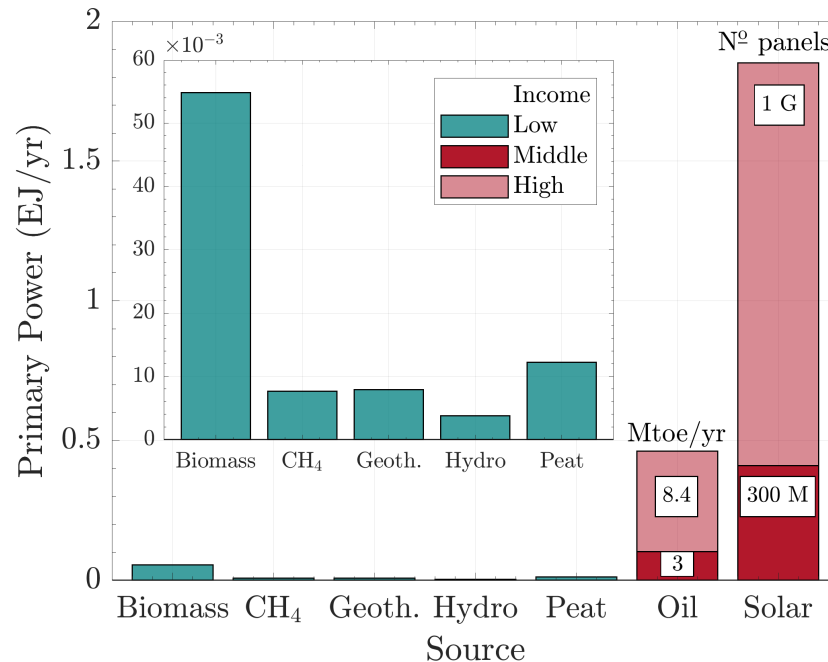

Figure 7. Primary power required for economic development of Rwanda. The inserted figure magnifies the low-income resources from the main figure; units are the same as the main axis. The green areas are the low-income case, which is based on potential resources available in Rwanda. The dark red areas denote the middle income case that requires an extra power input of 3 Mtoe/yr ($\approx$20 Mbbl/yr) and installation of 300 million panels. The area shaded in light red is a high-income case that requires an extra power input of 11.4 Mtoe/yr ($\approx$77 Mbbl/yr) and installation of 1.3 billion panels. The reference values are the population of 12 million people and solar panels with nominal power of 300 W.

4.4. Feasibility of Proposed Scenario

The initial observation is that the low-income scenario compromises all energy resources available in Rwanda. Furthermore, these estimates rely on very efficient systems to sustain the continuous exploration of "renewable" resources. We must emphasize that over-exploitation today probably will result in a shortage tomorrow.

The feasibility analysis of having this magnitude of solar power requires further thought. We can start with the scenario to become a middle-income country. In this case, solar panels will cover an area equivalent to 2% of Rwanda's territory. For the current population (12 M) and assuming the 300 W solar panels, a total of 25 panels per person should be installed. Considering the due date of 2035, starting this massive operation in 2020 requires the installation of 20 million panels per year. According to IRENA [56] the cost of solar photovoltaic in Africa is in a range of 2 USD/W to 4 USD/W for large-scale facilities. Using 2 USD/W as a reference, the total investment will be USD 180 billion or USD 12 billion annually, more than the current GDP of Rwanda of SUD 9 billion.

Moreover, to become a high-income country, that area covered with solar panels will be 8%, installing an equivalent of 110 solar panels per person. Following the proposed timeline, from 2035 to 2050, 73.3 million panels annually should be added. Reaching this target requires an additional 1 billion panels, which will cost USD 660 billion or USD 44 billion annually, based on the time frame. Additionally, there will be the expenses to import oil that will add another USD 3.3 billio per year for the high-income scenario (assuming 40 USD/bbl, which seems quite low in April 2022).

The total investment required in the energy sector for Rwanda to become a high-income country is almost USD one trillion—assuming a low cost for the solar photovoltaic technologies. In addition, we need to recognize that Rwanda's GDP will increase, becoming USD 144 billion by 2035 and USD 372 billion by 2050. We can observe that achieving the proposed solution will require a significant GDP share as energy investments.

With a robust solar power presence, this scenario aims for an energy-independent Rwanda with minimum foreign inputs. The proposed scenario sets Rwanda as a pioneer in solar power, as it will represent more than 70% of the power mix. In comparison, currently, Honduras is a country with a high penetration of solar power, yet it only represents 15% of the power mix [57]. However, the environmental energy crisis does not have a unique solution. Alternatively, the share of oil imports could be more significant than the current scenario, or the adoption of nuclear power could be a possibility [58].

Pioneering as a solar-powered country brings challenges beyond the analysis made here. A resilient energy management program combined with a robust power grid must become reality. The solar power sector will be a combination of on- and off-grid systems. The off-grid systems will rely on batteries to provide electricity continuously. Seasonal variation should not be a problem. To solve daily intermittence, this scenario implies adoption of energy storage systems. The preferred energy carriers, such as H_2 or lithium batteries, lose energy. In practice, their deployment requires a large overproduction by electric systems. For example, H_2, that has a cycle efficiency of 40%, requires the grid system that must be 2.5 times larger than the calculation made in Section 4.3.

The combination of overpopulation and economic growth will require a massive expansion of current energy systems. To cope with this situation, Rwanda's government needs to implement an economy that is very efficient from an energy perspective, and generates a unit of GDP using a small amount of energy. It is likely that development will require an economy that does not rely on the primary sector and heavy industry. However, this brings a challenge for the foundation industries, e.g., cement and steel, and how they will build all the infrastructure required to be a developed country? Or, will they import everything?

Furthermore, calculations made based on power per capita eliminate the complexity of population dynamics. A country with a growing population needs an increase in power demand to remain at the same level of development; to develop further, even more power is required. With the population projected to triple by 2100, Rwanda's power supply must increase at the same proportion for the country to remain at the same development level.

5. Conclusions

Rwanda's power sector has been developing in all aspects—generation, transmission, and accessibility. Rwanda should embrace a long-term vision to ensure the power needs for the targeted levels of development. Most potential resources are renewable, implying a maximum exploitation rate for sustainable development; this could conflict with the development targets. Rwanda will not meet the targeted development goals without a strong presence of solar power or imports to compensate for the gap in natural resources.

The densely populated Rwanda faces the challenges of developing under limited resources. The country must leapfrog its development, as it will not be able to afford the traditional route from an industrial to a service-based economy. Energy efficiency is a fundamental aspect, and they need to wisely spend the energy resources available to build a resilient system, not relying on economic growth or foreign inputs.

The current energy–environmental crisis is a consequence of overpopulation, which exerts pressure on natural resources to provide food, shelter, and energy. Without a proper strategy to contain population growth or reverse it, Rwanda is probably heading to an environmental breakdown that could lead to social unrest.

and clean cooking [59–72]. Section 3 explains the difference between GDP and GNI. Section 4 gives details on the assumptions and calculations for the power available in Rwanda and the requirements depending on the level of development.

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