J. Res. Technol. Eng. 4 (2), 2023, 111-124

Journal Of Research Technology & Engineering

www.jrte.org

Potential Renewable Energy Sources in Sri Lanka

*R.G.S.A. Ranathunga

Faculty of Technology, University of Sri Jayewardenepura, Sri Lanka
*sandeepa.anjaleer@gmail.com
Received:22 March 2023; Revised: 26 March 2023; Accepted: 28 March 2023; Available online: 10 April 2023

Abstract: The primary energy source of Sri Lanka is fossil fuels such as diesel and coal. Sri Lanka used 12.8 million tons of oil equivalent energy in 2020, consisting of 43% of crude oil and finished products, 37% of biomass, 11% of coal, 6% of hydro and 3% of other renewable energy. In the future goal of Sri Lankan energy, it is pledged to follow only renewable energy electricity generation by 2050. Sri Lanka is fortunate with a number of renewable energy resources because of the geographic and climatic settings of the country. The primary renewable resources available in Sri Lanka are Biomass, Hydro, Solar, and Wind power. Of these resources, some of them, such as hydro power, are widely used and already developed to supply the country's energy demand, while others have the capacity for improvement when the relevant technologies become mature and economically viable for use. Although Sri Lanka is devoted to 100% renewable energy electricity generation, it is a challenge to overcome several technical problems, such as renewable energy mixing difficulties and financial problems for Sri Lanka's power sector. Hence, the relevant authorities need to look for positive approaches, solid strategies, new policies and regulations to invest in new renewable energy projects and special incentives to promote it among society and draw consumers toward new renewable energy.

Index Terms: Biomass, Hydropower, Renewable energy, Solar energy, Wind energy

1 Introduction

Nowadays, industrialization and the fast-growing population, resulted in high energy demand worldwide. In 2021, the main energy demand in the world increased by 5.8%, equal to 595.15 EJ. The energy consumption growth was 4.5% in 2020, 1.3% in 2019, and 2.9% in 2018, while from 2008 to 2018, the average growth rate per year was 1.5% [1]. The world energy consumption by source for the year 2021 is shown in Fig. 1. Fossil fuels such as coal, natural gas, and oil are the primary energy source in the present world [2]. For 2021, total energy consumption from oil is 184.21 EJ, coal is 160.1 EJ, and natural gas is 145.35 EJ. In 2021 the global share of energy from fossil fuels accounted for 82% of the total primary energy consumption. Figure 01 shows the world energy consumption by source in 2021[1].

Since there is a universal dependency on fossil fuels, it is causing energy-related problems, as well as ecological issues, energy supply security and cost affordability. Even though fossil fuel is the primary source, it is predicted to be depleted within the next 40-50 years [3]. Therefore, it could be expected a decrement in fossil fuel reserves and an escalation of prices in the future [4]. Also, using fossil fuels in power generation has drawbacks of rising global warming potential, climate change, destroying ecosystems and biodiversity and rising sea level [5]. Hence, most nations worldwide are trying to reduce their fossil fuel energy consumption by replacing it with renewable energy resources [6].

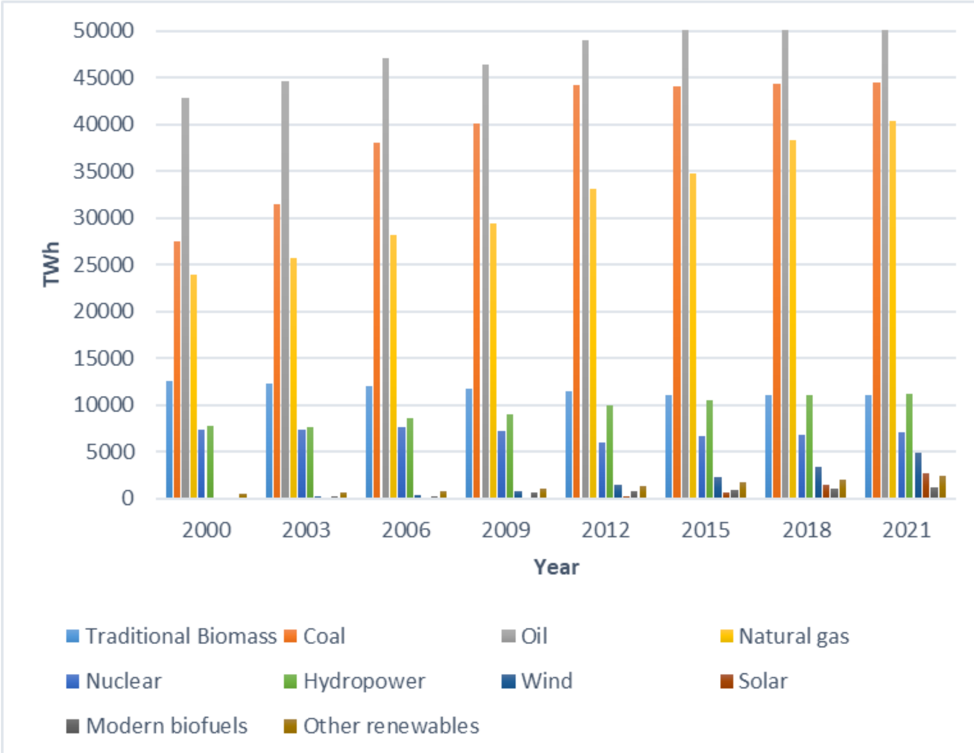

Fig. 1. World energy consumption by source in 2021

Renewable energy is based on continuing, repetitive, and self-renewing energy sources, which have a wide range of resources, like sunlight, hydropower, wind, geothermal energy, tidal energy and biomass such as energy crops, agricultural, industrial and municipal residues. These resources can be utilized in electricity production, transportation fuels, and providing heat for industrial processes [7]. Table 1 shows these major renewable energy sources and their energy conversion and usage forms.

Table 1. Major renewable energy sources and their usage form [8]

Energy source	**Usage and conversion method**
Hydropower	Power generation by turbines
Modern biomass	Heat and power generation by pyrolysis, gasification, and digestion
Solar	Photovoltaic and thermal power generation by water heaters, Solar home systems, solar dryers, solar cookers
Wind	Power generation by wind generators, windmills, water pumps
Wave and Tidal	Power generation by Barrage, tidal stream
Geothermal	Urban heating, power generation, hydrothermal, hot dry rock

Table 2 shows the global renewable energy setting by 2040. According to the European Renewable Energy Council in 2006, almost 50% of the world's energy demand will achieve from renewable energy sources in 2040 [9].

Table 2. Global renewable energy scenario by 2040

	2001	2010	2020	2030	2040
Biomass (mtoe)	1080	1313	1791	2483	3271
Large hydro (mtoe)	22.7	266	309	341	358
Geothermal (mtoe)	43.2	86	186	333	493
Small hydro (mtoe)	9.5	19	49	106	189
Wind (mtoe)	4.7	44	266	542	688
Solar thermal (mtoe)	4.1	15	66	244	480
Photovoltaic (mtoe)	0.1	2	24	221	784
Solar thermal electricity (mtoe)	0.1	0.4	3	16	68
Tidal/wave/ocean (mtoe)	0.05	0.1	0.4	3	20
Total Renewable energy sources (mtoe)	1365.5	1745.5	2964.4	4289	6351
Total consumption (mtoe)	10038	10549	11425	12352	13310
Renewable energy sources (%)	13.6	16.6	23.6	34.7	47.7

Sri Lanka used 12.8 million tons of oil equivalent energy in 2020, consisting of 43% of crude oil and finished products, 37% of biomass, 11% of coal, 6% of hydro and 3% of other renewable energy. Fig. 2 shows the primary energy supply by source, 2020 [10].

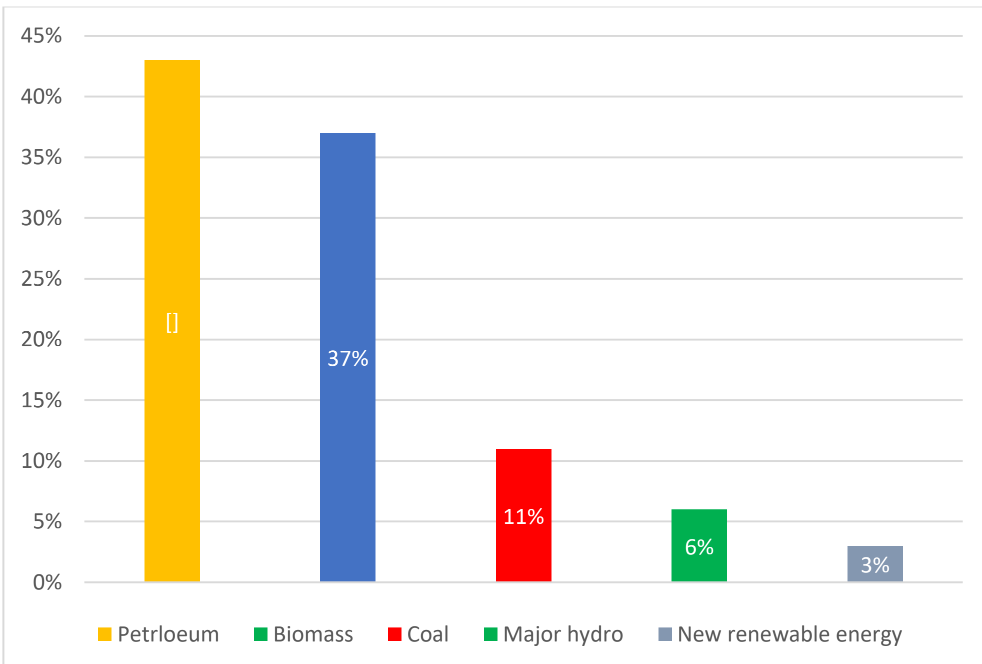

Fig. 2. The primary energy supply by source, 2020

In the future goal of Sri Lankan energy, in the Climate Vulnerable Forum at the 22nd UNFCCC Conference in Marrakesh, Morocco, in November 2016, Sri Lanka pledged to follow only renewable energy electricity generation by 2050. Sri Lanka is fortunate with a number of renewable energy resources because of the geographic and climatic settings. The primary renewable resources available in Sri Lanka are Biomass, Hydro, Solar, and Wind power. Some of these resources, like hydropower, are widely used and already developed to supply the energy demand of the country, while others have the capacity for improvement when the relevant technologies become mature and economically viable for use [11].

Although Sri Lanka is devoted to 100% renewable energy electricity generation, it is a challenge to overcome several technical problems, such as renewable energy mixing difficulties and financial issues for Sri Lanka's power sector [12].

2 RENEWABLE ENERGY SOURCES: STATUS AND PERSPECTIVES

2.1 Hydropower

Hydropower has accounted for up to 71% of renewable energy sources worldwide, being the leading source of this supply as of 2016 [13]. In most countries, hydropower is the only local energy source. Therefore, hydropower ranked at the top in electricity generation among other renewable energy technologies [14]. At the end of 2021, the total global hydroelectricity consumption was 40.26EJ [1]. Table 3 shows the world hydropower consumption in EJ from 2011 to 2021, according to the region.

Table 3. World hydroelectricity consumption from 2011 to 2021

Region	2011	2012	2013	2014	2015	2016	2017	2018	2019	2020	2021
North America	7.23	6.77	6.73	6.60	6.39	6.55	6.93	6.74	6.58	6.56	6.34
Central and South America	7.30	7.13	6.87	6.62	6.43	6.55	6.72	6.76	6.57	6.54	6.22
Europe	5.66	6.18	6.49	6.28	6.17	6.28	5.60	6.16	5.97	6.22	6.12
CIS	2.11	2.10	2.25	2.16	2.09	2.27	2.30	2.33	2.36	2.49	2.51
Middle East	0.18	0.21	0.23	0.19	0.16	0.19	0.20	0.12	0.38	0.27	0.18
Africa	1.10	1.10	1.15	1.21	1.17	1.13	1.21	1.28	1.32	1.38	1.45
Asia Pacific	11.10	12.46	13.44	14.86	15.19	15.70	16.04	16.45	17.00	17.61	17.44

In Sri Lanka, hydropower is one of the main energy sources used in power generation. A substantial portion of the main hydro capacity in the country has already been utilized and provides electricity at an affordable cost to the national grid. At present, hydropower plants deliver both peak and base electricity requirements. By the end of 2019, there were five types of typical user groups as follows,

- Large multipurpose systems consist of major power plants for sale to utility
- Commercial grid-connected - 205 power plants
- Off-grid electricity at the village level
- Off-grid electricity in industries - A few power plants in the tea industry
- Mechanical drives in industries

The topography of Sri Lanka gives an outstanding opportunity to utilize energy. The energy in rivers flowing from the country's central hills to the surrounding ocean could be harnessed. Sri Lanka has nearly utilized the hydropower potential in the river system because hydroelectricity generation had an early start.

The Laxapana and Mahaweli complexes are two major hydropower complexes in Sri Lanka. These two complexes have a number of power plants. The Laxapana hydropower complex is established on the Kelani River, and the Mahaweli hydropower complex is established on the Mahaweli River. Besides these main complexes, Samanalawewa and Kukule Ganga are two other independent large-scale hydropower stations. Smaller power plants like Iginiyagala and Uda Walawa also produce hydropower using their corresponding reservoir storage. Table 4 lists major hydropower plants and their corresponding generation capacities.

Table 4. Hydropower generation by plant

Hydropower plant	**Plant capacity (MW)**	**Generation in 2019 (GWh)**	**Generation percentage (%)**
Laxapana Complex			
Wimalasurenda	50	114.2	3.0
Canyon	60	132.2	3.5
Laxapana	53.5	260.3	6.8
Samanala	75	375.7	9.9
New Laxapana	116	448.8	11.8
Mahaweli Complex			
Kotmale	201	378.3	10.0
Nilambe	3.2	7.4	0.2
Ukuwela	40	161.7	4.3
Bowatenna	40	57.3	1.5
Victoria	210	464.5	12.2
Randenigala	122	236.9	6.2
Rantembe	49	125.5	3.3
Upper Kotmale	150	380.5	10.0
Other complex			
Iginiyagala	11.25	12.4	0.3
Uda Walawa	6	9.4	0.2
Samanalawewa	120	312.0	8.2
Kukule Ganga	70	323.6	8.5
Total	1377	3800.9	100.0

The main challenge faced by hydropower generation in Sri Lanka is that the output is highly unpredictable because the production of power plants mainly depends on climate and weather factors. The water cycle, temperature increment, and rainfall frequency, which are the consequences of global warming, disrupt the operation of hydropower plants. The temperature in Sri Lanka is increasing at the rate of 0.0164°C/year while inducing increases in evaporation [15]. Also, the rainfall patterns in mountainous areas of Sri Lanka are very dynamic and rapidly fluctuating. This affects hydropower generation as most plants are located in central hill areas [16].

To avoid most of the challenges with hydropower plants, it is suitable to establish small-scale hydropower plants. Small-scale hydropower plants are classified as which have a capacity of less than 10MW [17]. Small hydropower plants, as opposed to large hydropower plants, usually divert a small part of a river. The main benefit of these plants is that they can establish with relatively less capital. Exploring the potential of small hydropower in Sri Lanka is important because of the absence of possible land and sites for large-scale hydropower plant establishment, inflation, high labour cost, and harmful environmental effects[18].

The issues that need to be addressed in the small-scale hydropower sector are the lack of a proper transmission solution for acceptance of power from small hydropower plants, limits in adding more small hydropower to the grid at the local grid and the national power system level, and public opposition arising with conflicting use of water resources [19].

2.2 Solar Energy

Solar thermal energy from the sun is the world's most abundant and most available form of energy. The sun provides 1.7 x 1022 J of energy in one and half days, equivalent to the energy created by three trillion oil barrel resources found on Earth. Humans use 4.6 x 1020 J of energy per year, which is equal to the energy provided by the sun in 60 minutes. Therefore, it is evident that the energy from the sun is able to achieve the whole energy requirements of the world solely [5].

Utilizing energy from sunlight is done using a photovoltaic system which converts solar energy into electrical energy. Other than these conventional photovoltaic systems, there are thermo-photovoltaics systems which use infrared radiation to generate electricity. Photovoltaic systems use semiconductor materials to transform sunlight into electricity. The mechanism of solar cells is that When sunlight strikes the surface of a solar cell, electrons become excited and move to the N-Type layer; similarly, holes move to the P-Type layer. The external load drives the current by transferring electrons from the N-Type to the P-Type [20]. Since these solar cells are made from semiconductor materials, they don't have any mechanical parts, and there's no emission while operating. These photovoltaic systems need minimum maintenance and have a long lifetime [21].

Many developed and developing countries worldwide have pursued power generation by solar energy over time. For example, by the end of 2015, solar power established a share of 7.9%, 7.6%, and 7.0% in Italy, Greece and Germany from total power generation [22]. The solar power generation in Europe increased by 8 GW, and in the United Kingdom, Germany, and France increased by only 5.3 GW, while China achieved a total solar power capacity of 43 GW. [23]. India also installed grid-connected solar power plants with a capacity of 18.5GW in 2015, and they are planning to expand it up to 100GW by 2022 [24]. Tables 5 and 6 represent the global solar power generation from 2000 to 2019 and solar power generation by continent, respectively.

Table 5. Global solar power generation from 2000 to 2019 [25]

	2000	**2005**	**2010**	**2015**	**2016**	**2017**	**2018**	**2019**
Power generation (TWh)	1.33	4.33	33.7	254	331	442	567	694

Table 6. Global solar power generation by continent [25]

	Africa	**America**	**Asia**	**Europe**	**Oceania**
Power generation (TWh)	10.17	127	396	146	14.98

As Sri Lanka is positioned within the equatorial belt, there is a massive potential for solar radiation to be received throughout the year. The expected annual solar radiation across the country varies from 4.2 to 5.6 kWh/m^2 per day, whereas central hills receive lower radiation of 2 to 3.5 kWh/m2 per day [26].

Sri Lankan society utilized this solar resource from ancient times for drying things, such as crops and clothes, and for heating purposes, and it has mainly remained a non-commercial energy resource [27]. In the present day, existing solar energy is applied for thermal applications, for example, cooking purposes, heating water, and drying crops. Solar-drying technology is an alternative to processing vegetables and fruits in clean and hygienic conditions with no energy cost [8]. By the end of 2019; there were four types of typical solar energy user groups as follows,

- Solar photovoltaic for rooftop systems and household lighting
- Grid-connected PV by 14 power plants for sale to utility
- Solar thermal usage in both industrial and domestic sectors
- Informal use in domestic and agriculture sectors

Eight small-scale solar power plants with a total capacity of 51.36MW were established by mid-2017. The potential for using solar energy for power production is estimated at 6 GW. By the end of 2019, fourteen power plants had been developed. Table 07 shows the list of solar power producers and their performance in Sri Lanka [10]

Table 7. The performance of the Solar power plants in the country in 2019

Power Plant	**Installed Capacity (MW)**	**Power Generation (GWh)**
Gannoruwa 1	0.50	0.5
Gannoruwa 2	0.12	-
Thiruppane	0.74	0.4
Saga	10	2.6
Solar One Ceylon Power	10	-
Iris	10	18.6
Anorchi Lanka	10	18.5
Nedunkulam	10	21.1
Vavuniya 2	3	1.7
Vavuniya 3	1	1.7
Beliaththa 1	1	0.6
Embilipitiya 2	1	0.2
Embilipitiya 3	1	0.2
Pallekelle 1	1	0.1

Sri Lanka sustainable authority introduced the rooftop solar net metering system in 2010, and it became increasingly popular among the community. The consumers connected to the grid through net metering are identified as micropower producers [28]. After that, in 2016, two other options were introduced, net accounting and net plus, by initiating the "Battle for Solar Energy" program. At the end of 2017, there were over 8000 consumers and 93.7 MW of rooftop solar systems connected to the national grid [10]

Solar power is capable of replacing the power plants running on petroleum and coal that serve the daytime peak. Since solar power is generated through the peak demand time, its development is more feasible than wind power because wind power produces during off-peak hours [29].

Even if solar technology is highly reliable than other renewable technologies, there are a number of limitations related to it. The elevated costs and minimal efficiency of solar power technologies are the main considerable challenge in energy utilization [30]. Another barrier to developing solar energy technologies in developing countries like Sri Lanka is the shortage of applicable policies and regulations to promote solar energy production. For the development of solar power generation, policy frameworks should be designed well to decrease the implementation cost [31]. Another familiar problem is the shortage of skilled workers and qualified engineers [32]. Community acceptance of renewable energy technologies and the lack of social awareness are other challenges for solar energy development. Also, large-scale solar power plants require significantly enormous amounts of land, which can be an issue [33].

To overcome the above challenges and improve the development of solar energy system applications in Sri Lanka, the government needs certain approaches and solid political strategies.

Feed-in tariffs (FIT) are one of the major policies followed by industrialized countries to support utilizing solar energy technology development. FIT means promising small-scale solar energy producers a price higher than the market price for what they deliver to the grid. Germany, Spain, Italy, France, Japan, China, and the USA followed this mechanism and have significantly promoted solar energy technologies within their countries [34].

Promoting small-scale solar power generation among residents and industries is a solution for additional land requirements. To motivate households in solar power generation, it is essential to introduce financial interventions like providing loan facilities with low-interest rates to adopt the rooftop solar system and can provide tax benefits to households investing in rooftop solar. A lot of households in the USA and Malaysia have brought their solar power systems with low-interest loans (4–5%), and each user can borrow more than 20,000 USD for ten years. In the EU countries, they have an extensive range of tax incentives to promote renewable energies usage [35]

The USA established financing solutions through third-party financing. It primarily followed by two models, power purchase agreements (PPA) and solar leases. In PPA, a third-party installer installs a solar system on a customer's rooftop free of charge and sells the power generated by the system to the customer at a fixed rate which offsets the customer's power bill. At the end of the contract, the customer can buy the solar system or extend the contract. In a solar lease, the customer pays for the solar system over a period instead of paying for the power generated [36].

2.3 Biomass

Biomass is a renewable resource derived from plants and vegetation that naturally regrows [37]. Biomass is an alternative solution to reduce fossil fuel dependence in energy production. Biomass is more popular worldwide as an energy source because it has significant environmental benefits and the capacity for the affordable supply [38]. Also, using biomass in power generation has other benefits to society and the economy since it provides employment opportunities, carbon trading benefits, and mitigates greenhouse gas emissions [39]

Energy crops and biomass residues are the two types of biomasses. Energy crops are grown primarily for energy generation. These energy crops can be categorized as fast-growing trees with an 8 to 20 years lifespan, used as wood fuel, annual crops harvested with traditional farming machinery, and energy crops for liquid biofuel [40]. Biomass residues are used as fuel for the generation of heat and power. These biomass residues can be grouped into several categories: forest residues, agricultural, wood wastes, waste vegetable oil, municipal solid waste, industrial waste, sewage sludge, and seaweed [41]. Several technologies are used to convert biomass into fuel for several applications like heat, power generation and biofuels. The leading technologies used in the present world are Biochemical processes like hydrolysis, fermentation and anaerobic digestion, chemical processes like hydrogenation, transesterification and catalysis and thermochemical processes like direct combustion, torrefaction, hydrothermal liquefaction, pyrolysis and gasification [42]

In the global context, biomass has become the fourth-largest energy source in the world, next to coal, oil, and natural gas, as it provides about 14% of the global energy demand. In most rural areas in developing countries, 90% of total energy requirements are fulfilled by biomass [43]. The world biomass energy potential is about 100 EJ annually, about 30% of global energy consumption today. However, only 40 EJ per year of available biomass is used in energy production [44]. Figure 03 shows the bioenergy capacity worldwide in 2021. Energy from biomass can be used in different sectors, such as electricity production, heat production and transportation. Table 08 shows the global biomass energy generation from 2000 to 2019 [25].

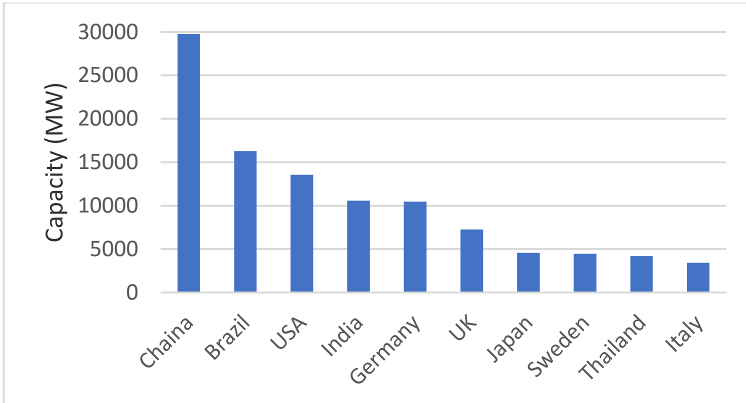

Fig. 3. The bioenergy capacity worldwide in 2021 [45]

Table 8. Global biomass energy generation from 2000 to 2019

	2000	2005	2010	2015	2016	2017	2018	2019
Electricity generation (TWh)	214	298	458	620	663	701	737	768
Heat production (EJ)	0.60	0.76	1.09	1.35	1.45	1.50	1.53	1.61
Transportation (EJ)	0.42	0.81	2.37	3.28	3.40	3.52	3.75	3.99

In Sri Lanka, nearly 80% of the population depends on biomass to fulfil domestic energy needs, mainly for cooking. It is also used in the industrial sector for thermal energy requirements. Biomass has minimal usage in electricity generation in the country, even though it has the largest part of the primary energy supply. Biomass is highly demanded in commercial and non-commercial applications since it is the country's most significant primary energy source [46]. By the end of 2019, there were four types of typical biomass energy user groups as follows,

- Households – mainly for cooking
- Commercial – Hotels and bakeries
- Industrial – Steam generation, tea drying, Brick and tile
- Private power plants – 13 plants for sale to utility and small plants in rural and suburban areas and factories for their own consumption

Table 9. The biomass energy supply and the share of the total energy supply from 2010 to 2019

	2010	2015	2016	2017	2018	2019
Biomass supply (PJ)	180.5	174.6	168.6	165.3	165.5	169.0
Share from total energy supply (%)	42.8	36.6	33.4	34.2	32.6	33.2

Mostly available biomass types in Sri Lanka are unprocessed logs, processed chips, municipal waste, industrial waste and agricultural waste [47]. When considering the ongoing biomass conversions in the country, firewood is used in boilers to generate steam and electricity in industries. Sugar cane bagasse is used to receive thermal energy to generate steam for boiler-turbine units used for electricity generation, and wood is mainly used as charcoal for hotels and household markets [11]. Apart from these, Dendro power generation, a biomass energy harvesting method using an energy crop named Gliricidia, is another kind of biomass technology being used in the country.

There were ten small biomass power producers by the end of 2017. The total installed capacity was 26.1 MW, and the total power generated from biomass was 16 GWh. "Sri Lanka Renewable Energy Master Plan" estimates the country's potential for biomass-based generation capacity is 2,400 MW [10]. Table 10 shows the performance of biomass power plants in the country in 2018.

Table 10. The performance of the biomass power plants of the country in 2018 [48].

Powerplant	Commissioned year	Installed capacity (MW)	Power generation (GWh)	Average unit price (LKR / kWh)
Dendro				
Kottamurichchana	2011	0.50	0.000	-
Embilipitiya	2013	1.50	0.592	20.703
Batalayaya	2014	5.00	38.370	20.704
Batugammana	2015	0.02	0.000	-
Loluwagoda	2016	4.00	25.821	24.346
Loggaloya	2017	2.00	7.673	23.837
Panamure	2018	0.99	1.170	23.448
Kalawa Aragama	2018	10.0	0.000	-
Total		**24.01**	**73.626**	**22.35**
Biomass				
Badalgama	2005	1.00	0.813	13.472
Tokyo	2008	10.00	10.858	8.573
Ninthawur	2014	2.00	1.830	14.254
Dikkanda	2015	0.08	0.000	-
Total		**13.08**	**13.501**	**9.63**

The country has an annual technical biomass potential of 8000 MW, but considering social and environmental limitations, the utilizable potential is 1000 MW [12].

Large-scale biomass consumption is affected by critical environmental issues, such as deforestation, climate change, land degradation, biodiversity loss, and harmful health impacts by air pollution [49]. Therefore, there is a need to look forward to developing biomass production to create a sustainable fuelwood supply in the future. However, in Sri Lanka, large-scale biomass production has barriers as follows.

- Low experience in new biomass conversion technologies
- High initial costs of some plantations
- Low biomass yield
- Land availability and rights
- Lack of comprehensive national biomass policy and regulation
- Inefficiencies in government

2.4 Wind Energy

Wind generation depends on several factors, such as uneven solar heating, the Coriolis effect, and geographical conditions. The wind is created by the air motion due to the atmospheric pressure gradient and flows from high-pressure to low-pressure regions. When a high atmospheric pressure gradient is present, it results in a higher wind speed. Therefore, large wind power can be created [50]. Wind energy is the second-best source in terms of installed capacity and rapid growth among all the other renewable energy technologies in power generation, where the top is hydropower.

In the present day, wind energy in power production is widely used worldwide as it is now a mature and competitive sector. It is a sustainable source of electricity, which can be installed and transmitted very rapidly, even in distant, remote, and mountainous areas. The electricity formed by wind power systems could save several billion barrels of oil and avoid many million tons of carbon and other emissions [51]

The kinetic energy created by flowing air is used to produce power from wind. The energy conversion of wind is done using wind turbines. The turbine converts the kinetic energy of the wind into electrical energy. The turbine starts to operate when the wind strikes the turbine blades and rotates. Hence, the wind's kinetic energy converts into rotational energy by rotating a shaft attached to the generator and producing electricity through electromagnetism. The turbine's size and the blades' length affect the amount of power that can be gathered from the wind. [52]. Two types of turbines are used in wind power generation, horizontal-axis wind turbines and vertical-axis wind turbines [53]. The maximum power of the wind turbine is reached when the wind speed is approximately 12 to 14 m/s. The latest wind turbines in the market have capacities varying from 0.5 MW to 10 MW, with rotor diameters from 15m to 190m [54]

In 2021, 93.6 GW of wind power potential was installed globally. The total installed wind capacity is 837 GW. Compared to 2020, it is a growth of 12.4%. By the end of 2021, the total onshore wind capacity was 780 GW, and the offshore wind capacity was 57.2 GW. China, the US, Germany, India and Spain are the world's top five largest wind power markets. These five countries together are accountable for 72% of the total wind power generation worldwide [55]. Tables 11 and 12 represent the global wind power generation from 2000 to 2019 and solar power generation by continent, respectively.

Table 11. Global wind power generation from 2000 to 2019 [25]

	2000	**2005**	**2010**	**2015**	**2016**	**2017**	**2018**	**2019**
Power generation (TWh)	31	104	342	834	963	1135	1277	1427

Table 12. Global wind power generation by continents [25]

	Africa	**America**	**Asia**	**Europe**	**Oceania**
Power generation (TWh)	17.5	426	522	442	20.0

The location of Sri Lanka is fortunate in wind energy production as it is surrounded by the ocean, which causes in providing strong wind energy capacity. The country's two main wind climates are the South-Western monsoon and the North-Eastern monsoon. [56]

The South-Western monsoon passes the west coast and certain hilly areas of the country. The wind coming across the mountain areas is turbulent. Therefore, the South-Western monsoon is the most energetic one. However, both monsoons bring stable and solid winds over southeastern and northwestern coastal belts [57]. By the end of 2019, the typical user groups of wind energy are as follows,

- Grid-connected wind from 15 power plants for retail to customers
- Off-grid power plants for domestic use
- Water pumping in agriculture

It is estimated that Sri Lanka has plentiful potential wind resources of 5,653 MW[29]. The country had an overall installed generation capacity of 131 MW by the end of 2017 [57]. The Ceylon Electricity Board and National Renewable Energy Laboratory carried out wind resources studies and proposed that the coastal zone from Hambanthota to Kirinda has a wind capacity of 200 MW, and the coastal region from Puttalam to Jaffna and from Jaffna to Trincomalee has significant wind resources ("Dep. Meteorol. Sri Lanka," 2020) The first wind project was established in Hambantota with a capacity of 3MW in 1999, which was unsuccessful. After the government launched an energy policy to boost electricity generation by renewable energy in 2015, wind power generation achieved productive development. By 2016, Sri Lanka had 131.45 MW of installed wind capacity. Now, the cost of electricity produced from wind power plants is less than that generated from fossil fuels [57].

By maximizing wind energy generation, Sri Lanka aims to expand renewable energy capacity by 32%. In 2019, there were 15 wind power plants with an installed capacity of 128.5 MW. Total power generation was 348.2 GWh. Table 13 shows the performance of the Wind power plants in the country in 2019.

Table 13. The performance of the Wind power plants in the country in 2019 [11]

Name of Power Plant	Capacity (MW)	Generation (GWh)
Mampury 1	10	21.2
Seguwanthivu	10	25
Vidatamunai	10	25.7
Willpita	0.85	0.4
Nirmalapura	10	29.2
Ambewala	3	3
Madurankuliya	10	37.4
Uppudaluwa	10	20
Kalpitiya	9	22.2
Erumbukkudal	4	11.7
Mampury 2	10	27.6
Mampury 3	10	27.1
Puloppalai	10	34.6
Vallimunai	10	35.3
Musalpetti	10	27.7

3 Conclusion

There is a very high potential for developing renewable power generation in Sri Lanka because of the vast availability of solar, biomass, wind and hydro resources. The location of Sri Lanka gives an outstanding opportunity to utilize energy. However, the lack of new technologies, the lack of establishing new projects, and financial instability are the main challenges in this sector. Also, the country's recent and continuous electrical power cuts are affecting the economy. Therefore, the relevant authorities need to look for positive approaches, solid strategies, new policies and regulations to invest in new renewable energy projects and special incentives to promote it among society and draw consumers toward new renewable energy.

References

[1] BP, "BP Statistical Review of World Energy 2022,(71st edition)," *[online] London BP Stat. Rev. World Energy.*, pp. 1–60, 2022, [Online]. Available: https://www.bp.com/content/dam/bp/business-sites/en/global/corporate/pdfs/energy-economics/statistical-review/bp-stats-review-2022-full-report.pdf

[2] A. K. Karmaker, M. M. Rahman, M. A. Hossain, and M. R. Ahmed, "Exploration and corrective measures of greenhouse gas emission from fossil fuel power stations for Bangladesh," *J. Clean. Prod.*, vol. 244, no. September, 2020, doi: 10.1016/j.jclepro.2019.118645.

[3] S. Proskurina, M. Junginger, J. Heinimö, B. Tekinel, and E. Vakkilainen, "Global biomass trade for energy— Part 2: Production and trade streams of wood pellets, liquid biofuels, charcoal, industrial roundwood and emerging energy biomass," *Biofuels, Bioprod. Biorefining*, vol. 13, no. 2, pp. 371–387, 2019, doi: 10.1002/bbb.1858.

[4] J. Ratnasiri, "Alternative energy-prospects for Sri Lanka," 2008.

[5] M. E. Karim, R. Karim, M. T. Islam, F. Muhammad-Sukki, N. A. Bani, and M. N. Muhtazaruddin, "Renewable energy for sustainable growth and development: An evaluation of law and policy of Bangladesh," *Sustain.*, vol. 11, no. 20, 2019, doi: 10.3390/su11205774.

[6] P. K. Ozili, "Global energy crisis : impact on the global economy," *Proc. IAC Budapest*, no. December, pp. 85–89, 2021.

[7] S. R. Bull, "Renewable energy today and tomorrow," *Proc. IEEE*, vol. 89, no. 8, pp. 1216–1226, 2001, doi: 10.1109/5.940290.

[8] N. L. Panwar, S. C. Kaushik, and S. Kothari, "Role of renewable energy sources in environmental protection: A review," *Renew. Sustain. Energy Rev.*, vol. 15, no. 3, pp. 1513–1524, 2011, doi: 10.1016/j.rser.2010.11.037.

[9] I. Kralova and J. Sjöblom, "Biofuels-renewable energy sources: A review," *J. Dispers. Sci. Technol.*, vol. 31, no. 3, pp. 409–425, 2010, doi: 10.1080/01932690903119674.

[10] Asian Development Bank, *Sri Lanka: Energy Sector Assessment, Strategy, and Road Map*, no. December. 2020. [Online]. Available: https://www.adb.org/sites/default/files/institutional-document/547381/sri-lanka-energy-assessment-strategy-road-map.pdf

[11] Sri Lanka Sustainable Energy Authority, "Sri Lanka Energy Balance 2019," p. 136, 2019, [Online]. Available: http://www.energy.gov.lk/images/energy-balance/energy-balance-2019-lq.pdf

[12] Sri Lanka Sustainable Energy Authority, "Sri Lanka Energy Balance 2015-An analysis of the energy sector performance," 2015.

[13] E. F. Moran, M. Claudia, N. Moore, N. Müller, and D. W. Hyndman, "Sustainable hydropower in the 21st century," vol. 115, no. 47, 2018, doi: 10.1073/pnas.1809426115.

[14] P. Taylor and I. Yüksel, "Energy Sources , Part B : Economics , Planning , and Policy Hydroelectric Power in Developing Countries Hydroelectric Power in Developing Countries," no. December 2014, pp. 37–41, 2009, doi: 10.1080/15567240701756897.

[15] G. Naveendrakumar, M. Vithanage, H. Kwon, M. C. M. Iqbal, S. Pathmarajah, and J. Obeysekera, "Five Decadal Trends in Averages and Extremes of Rainfall and Temperature in Sri Lanka," vol. 2018, 2018.

[16] C. S. De Silva and S. Lanka, "Impacts of Climate Change on Water Resources in Sri Lanka Impacts of Climate Change on Water Resources in Sri Lanka," no. July, 2016.

[17] A. Y. Hatata and S. Saad, "A feasibility study of small hydro power for selected locations in Egypt," *Energy Strateg. Rev.*, vol. 24, no. April, pp. 300–313, 2019, doi: 10.1016/j.esr.2019.04.013.

[18] E. I. L. Silva and E. N. S. Silva, *Hand ook on : Small Hydropower Development and Environment : A Case Study on Sri Lanka*. Water Resources Science and Technology, 2016.

[19] N. Fernando, H. Wickramasinghe, N. Wimal, and S. E. Authority, "World Small Hydropower Development Report 2013," *United Nations Ind. Dev. Organ. Int. Cent. Small Hydro Power*, pp. 267–269, 2013.

[20] M. B. Hayat, D. Ali, K. C. Monyake, L. Alagha, and N. Ahmed, "Solar energy—A look into power generation, challenges, and a solar-powered future," *Int. J. Energy Res.*, vol. 43, no. 3, pp. 1049–1067, 2019, doi: 10.1002/er.4252.

[21] J. Chen, "Recent Developments on Silicon Based Solar Cell Technologies and their Industrial Applications.," *Energy Effic. Improv. Smart Grid Components. IntechOpen*, 2015.

[22] E. Kabir, P. Kumar, S. Kumar, A. A. Adelodun, and K. H. Kim, "Solar energy: Potential and future prospects," *Renew. Sustain. Energy Rev.*, vol. 82, no. September 2016, pp. 894–900, 2018, doi: 10.1016/j.rser.2017.09.094.

[23] W. Johnston, "Australian solar PV installations hit the 5 gigawatt mark," 2016.

[24] K. Partner, "State Renewable Energy Capacity Addition Roadmap".

[25] "Global Bioenergy Statistics 2021," 2021, [Online]. Available: https://www.worldbioenergy.org/news/640/47/Global-Bioenergy-Statistics-2021/

[26] D. Renné, R. George, B. Marion, and D. H. Nrel, "Solar Resource Assessment for Sri Lanka and Maldives Prepared by :," no. January, 2003, doi: 10.2172/15004299.

[27] S. Sayanthan and N. Kannan, "Renewable energy resource of Sri Lanka ! A review," *Int. J. Environ. Agric. Res.*, vol. 3, no. 4, pp. 80–85, 2017.

[28] W. Fernando, N. Gupta, C. Suheyl Ozveren, and G. Kamyab, "Renewable energy resources and technologies applicable to Sri Lanka towards a 100% RE future," *IET Conf. Publ.*, vol. 2019, no. CP764, pp. 1–8, 2019, doi: 10.1049/cp.2019.0628.

[29] H. Chen, Y. Yu, X. Shi, and F. Wen, "Development of variable renewable energy policy in developing countries: a case study of Sri Lanka," *Int. J. Public Pol.*, vol. 14, no. 1/2, p. 10, 2018, doi: 10.1504/ijpp.2018.10011843.

[30] E. Karakaya and P. Sriwannawit, "Barriers to the adoption of photovoltaic systems: The state of the art," *Renew. Sustain. Energy Rev.*, vol. 49, pp. 60–66, 2015, doi: 10.1016/j.rser.2015.04.058.

[31] C. A. Gabriel, "What is challenging renewable energy entrepreneurs in developing countries?," *Renew. Sustain. Energy Rev.*, vol. 64, pp. 362–371, 2016, doi: 10.1016/j.rser.2016.06.025.

[32] K. Yenneti, "The grid-connected solar energy in India: Structures and challenges," *Energy Strateg. Rev.*, vol. 11–12, pp. 41–51, 2016, doi: 10.1016/j.esr.2016.06.002.

[33] J. Khoury, R. Mbayed, G. Salloum, E. Monmasson, and J. Guerrero, "Review on the integration of photovoltaic renewable energy in developing countries - Special attention to the Lebanese case," *Renew. Sustain. Energy Rev.*, vol. 57, pp. 562–575, 2016, doi: 10.1016/j.rser.2015.12.062.

[34] V. Kihlström and J. Elbe, "Constructing markets for solar energy—a review of literature about market barriers and government responses," *Sustain.*, vol. 13, no. 6, 2021, doi: 10.3390/su13063273.

[35] A. Chaianong and C. Pharino, "Outlook and challenges for promoting solar photovoltaic rooftops in Thailand," *Renew. Sustain. Energy Rev.*, vol. 48, pp. 356–372, 2015, doi: 10.1016/j.rser.2015.04.042.

[36] M. Singh *et al.*, "100% percent Electricity Generation through Renewable Energy by 2050: Assessment of Sri Lanka's Power Sector," p. 116, 2017.

[37] M. Casau, D. C. M. Cancela, J. C. O. Matias, M. F. Dias, and L. J. R. Nunes, "Coal to biomass conversion as a path to

sustainability: A hypothetical scenario at pego power plant (Abrantes, Portugal)," *Resources*, vol. 10, no. 8, 2021, doi: 10.3390/resources10080084.
[38] I. Ahmed *et al.*, "Socio-economic and environmental impacts of biomass valorization: A strategic drive for sustainable bioeconomy," *Sustain.*, vol. 13, no. 8, pp. 1–32, 2021, doi: 10.3390/su13084200.
[39] M. Hoogwijk, A. Faaij, R. Van Den Broek, G. Berndes, D. Gielen, and W. Turkenburg, "Exploration of the ranges of the global potential of biomass for energy," *Biomass and Bioenergy*, vol. 25, no. 2, pp. 119–133, 2003, doi: 10.1016/S0961-9534(02)00191-5.
[40] G. Berndes, M. Hoogwijk, and R. Van Den Broek, "The contribution of biomass in the future global energy supply: A review of 17 studies," *Biomass and Bioenergy*, vol. 25, no. 1, pp. 1–28, 2003, doi: 10.1016/S0961-9534(02)00185-X.
[41] H. Unal and K. Alibas, "Agricultural residues as biomass energy," *Energy Sources, Part B Econ. Plan. Policy*, vol. 2, no. 2, pp. 123–140, 2007, doi: 10.1080/15567240600629401.
[42] A. I. Osman, N. Mehta, A. M. Elgarahy, A. Al-Hinai, A. H. Al-Muhtaseb, and D. W. Rooney, *Conversion of biomass to biofuels and life cycle assessment: a review*, vol. 19, no. 6. Springer International Publishing, 2021. doi: 10.1007/s10311-021-01273-0.
[43] B. Pathak, S. Chaudhari, and M. H. Fulekar, "Biomass - Resource for Sustainable Development," vol. 2, no. 6, pp. 271–289, 2013.
[44] M. Parikka, "Global biomass fuel resources," *Biomass and Bioenergy*, vol. 27, no. 6, pp. 613–620, 2004, doi: 10.1016/j.biombioe.2003.07.005.
[45] M. Jaganmohan, "Global bioenergy capacity by country 2021," 2022.
[46] K. Ariyadasa, "Potential of Biomass Based Electricity Generation in Sri Lanka," *J. Trop. For. Environ.*, vol. 5, no. 2, pp. 1–12, 2015, doi: 10.31357/jtfe.v5i2.2654.
[47] N. Musafer, "Biomass energy policy perspectives of Sri Lanka: A review," *Int. J. Sci. Res. Publ.*, vol. 10, no. 12, pp. 674–681, 2020, doi: 10.29322/ijsrp.10.12.2020.p10879.
[48] Ceylon Electricity Board, *Long Term Generation Expansion Plan 2020-2039*, no. May. 2019. [Online]. Available: https://ceb.lk/front_img/img_reports/1560836289LTGEP_2020-2039_(Draft).pdf
[49] H. Shaheen, B. Azad, A. Mushtaq, and R. W. Ahmad Khan, "Patrón de consumo de leña y sus impactos en la estructura del bosque en Cachemira, Himalaya," *Bosque*, vol. 37, no. 2, pp. 419–424, 2016, doi: 10.4067/S0717-92002016000200020.
[50] W. Tong, "Fundamentals of wind energy," *WIT Trans. State Art Sci. Eng.*, vol. 44, 2010.
[51] S. Singh, T. S. Bhatti, and D. P. Kothari, "Indian scenario of wind energy: Problems and solutions," *Energy Sources*, vol. 26, no. 9, pp. 811–819, 2004, doi: 10.1080/00908310490465885.
[52] P. T. T. Hoa, N. T. Hoa, and P. T. T. Xuan, "Wind energy as a green trend for future perspective," *World Wide J. Multidiscip. Res. Dev.*, vol. 5, no. 10, pp. 91–95, 2019, [Online]. Available: http://wwjmrd.com/upload/wind-energy-as-a-green-trend-for-future-perspective_1572596473.pdf
[53] C. Vázquez Hernández, T. Telsnig, and A. Pradas Villalba, "JRC Wind Energy Status Report - 2016 Edition : Market, technology and regulatory aspects of wind energy," p. 62, 2017, doi: 10.2760/332535.
[54] Z. Chen, "Overview of Wind Power Development," *Aalborg Univ. Aalborg*, 2017.
[55] Global wind energy council, "Annual Wind Report," 2022.
[56] Public Utilities Commission of Sri Lanka, "Achievements of Renewable Energy Targets in Sri Lanka," 2011.
[57] M. Young and R. Vilhauer, "Sri Lanka Wind Farm Analysis and Site Selection Assistance," *Natl. Renew. Energy Lab.*, no. August, pp. 1–44, 2003.
[58] "Department of meteorology Sri Lanka," *Dep. Meteorol. Sri Lanka*, 2020.