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Review Article

Solar energy as a sustainable source of energy for industrial applications in Sri Lanka: a conceptual mini-review

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Abstract: The world's primary energy demand has increased significantly due to the industrial revolution and population growth, which create the demand for primary energy. The COVID-19 pandemic situation significantly damages the world's energy network, which critically affects developing countries like Sri Lanka. Therefore, this paper has been developed to discuss an important framework for the use of solar energy as a suitable energy source for various industrial operations. The application of solar thermal energy and solar PV systems into industrial processes can minimize the economic cost of energy usage in the country. The points discussed in this conceptual mini-review can help policymakers identify and explore industrial windows that can be structured with solar energy for a sustainable energy future in Sri Lanka.

Keywords: Industrial application; Solar energy; Sustainable sources of energy; Solar PV systems.

1. Introduction

Energy is the primary source for many industrial processes. There are two energy sources, renewable and non-renewable sources, available to meet industrial energy demand (Doytch and Narayan, 2016). Industrial energy demand is growing at a faster rate all over the world because of the growth in industrial operations to meet human needs (Asif and Muneer, 2007). Sri Lanka is one of the developing countries in the world, which has many industries that process various input materials so as to produce value-added products for exportation and local consumption. Industrial operations directly create environmental consequences that influence living organisms' natural processes and comfort. The importance of industrial evolution on climate change is highly critical in the world, including in Sri Lanka. It has been reported that the death related to climate change is 160000 per year (McMichael et al., 2006). It is expected to increase further in future.

Currently, around 80% of the total energy demand is met by non-renewable sources, especially fossil fuels (Acar and Dincer, 2014). The world's fuel supply has been disturbed significantly in recent years due to the COVID-19 pandemic and disputes among countries. This has led to increased fuel prices and a shortage of fuel reserves, particularly in developing countries. Moreover, disturbed industrial activities can significantly cripple the economy of developing countries. A significant reduction in exports has been observed in Sri Lanka. Therefore, there is a need to go for sustainable energy sources to mitigate the energy problem of the world, including Sri Lanka. It is also expected to increase the energy consumption for industrial operations till 2030, as shown in Figure 1.

Hence, industrial operations must be supported by renewable energy sources, particularly solar energy systems. Moreover, the consumption of fuel in the world for industrial operations during the period from 2006 to 2030 is shown in Figure 2 (Mekhilef et al., 2011). It is obvious that the growth in renewable energy sources for industrial usage during the period from 2006 to 2030 is from 1.5 to 1.8%. However, this increase is not highly important. It clearly shows the need for research and developmental activities in order to increase the use of renewable sources for industrial operations. Furthermore, industrial operations consume 50% of the total energy in the world. Agriculture, mining, construction, and manufacturing are four major sectors of industrial energy sources (Abdelaziz et al., 2011).

Figure 3 shows the scenario of industrial energy consumption (%) by some selected countries. Due to the economic crisis in the world and the rise in fuel prices, developing countries like Sri Lanka will be unable to afford fossil fuel resources for industrial operations in the future. In this regard, the use of renewable energy sources will help to fix the above problem in a sustainable manner. The Sri Lankan economy can be improved by improving industrial operations with the help of solar energy systems to meet energy demand. Solar energy is a freely available energy source that causes no significant harmful effects to the environment. The effective use of this freely available energy is supported by solar-collector mirrors and tracking systems for industrial applications (Das et al., 2015). Sri Lanka, a small island with no significant seasonal variation, is blessed with almost constant levels of sunlight all over the year. Hence, Sri Lanka has great potential to harness solar energy to meet the country's total energy demand (Dasanayaka et al., 2022).

Promoting solar energy sectors, solar photovoltaic (PV), and solar thermal industries in Sri Lanka will help the country achieve its industrial goals and earn foreign currency for economic stability. Moreover, solar energy can be utilized effectively for drying, hot water production,

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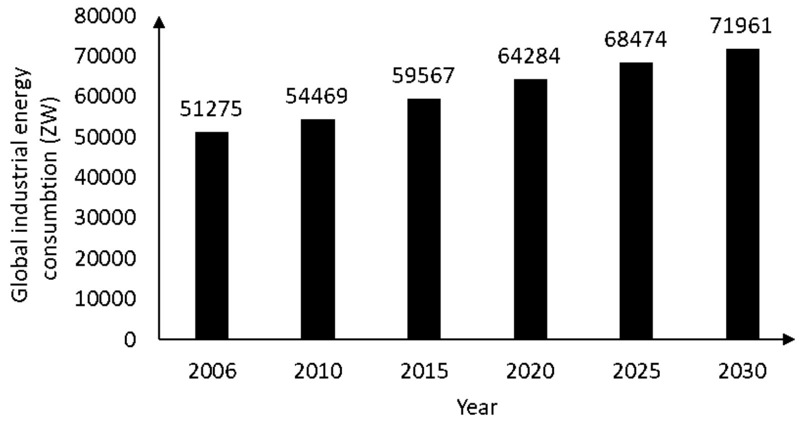

Figure 1: Global energy consumption (Abdelaziz et al., 2011)

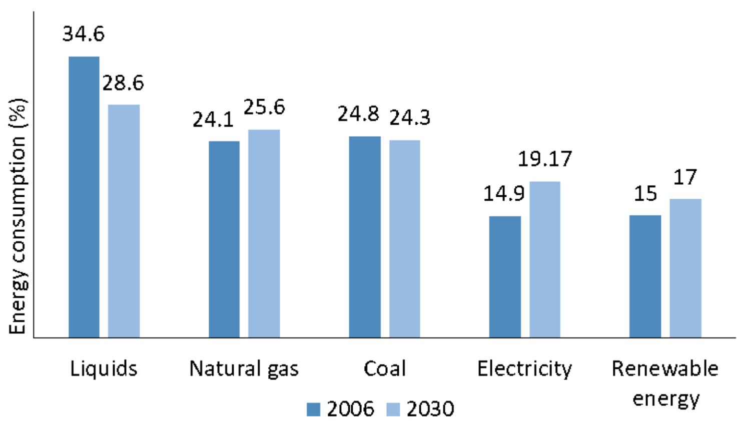

Figure 2: Energy consumption by fuel in two different years: 2006 and 2030 (Mekhilef et al., 2011)

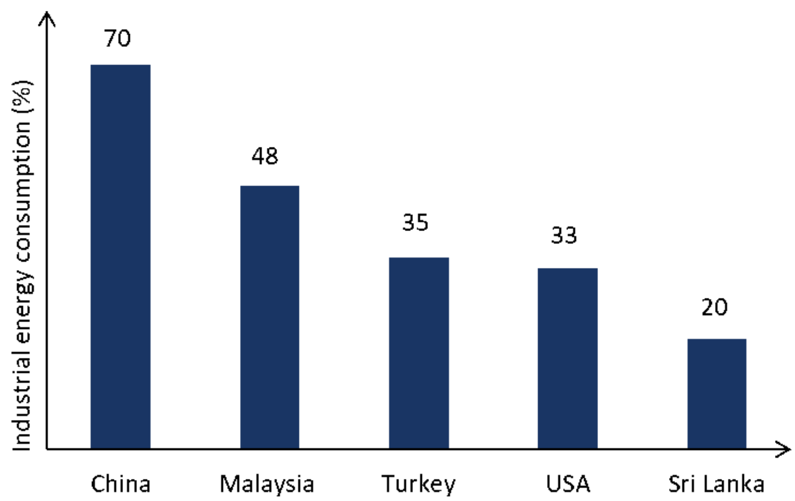

Figure 3: Industrial energy consumption by countries (Mekhilef et al., 2011)

steam generation, washing, steaming, and cleaning in textile and plastic industries (Kalogirou, 2004). This conceptual mini-review highlights fundamental technical aspects required to incorporate solar energy into industrial processes effectively. It starts with an introduction to solar energy and its industrial incorporation. It is then

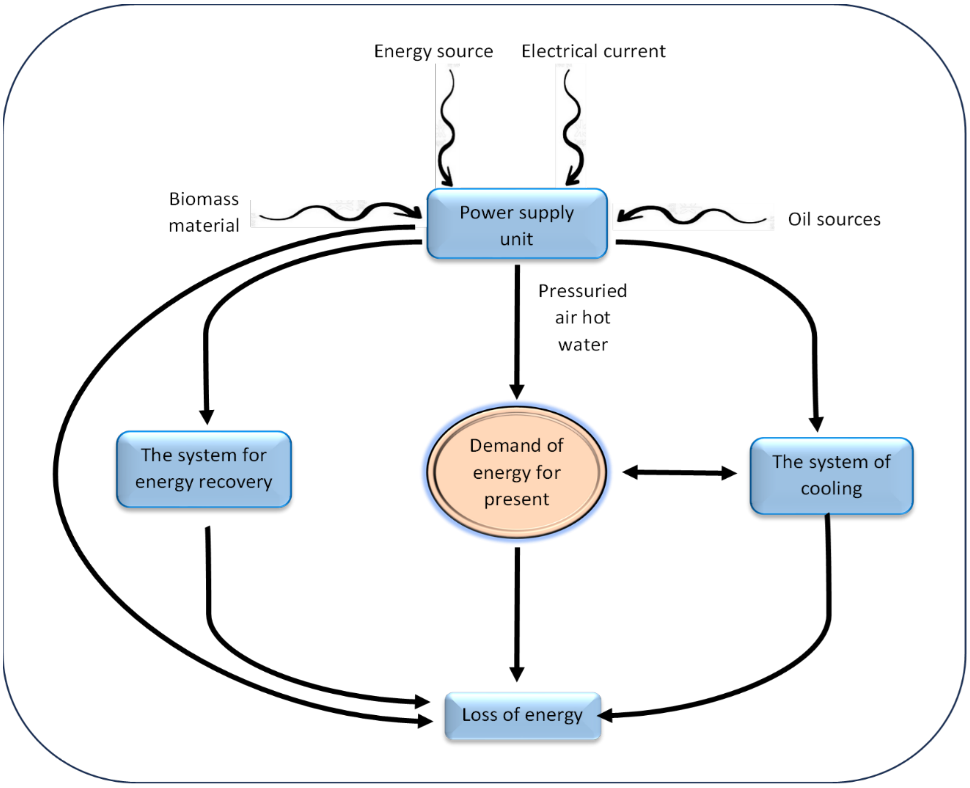

Figure 4: Simplified framework of industrial energy systems (Schnitzer et al., 2007)

followed by sections, such as the thermal energy process associated with industrial operations and photovoltaic systems, and a comprehensive summary. Moreover, it is highly emphasized that this paper will be significant for countries like Sri Lanka in developing a structured framework for the effective and sustainable incorporation of solar energy into industrial processes.

2. Effective integration of solar thermal energy into industrial systems

Industrial energy systems are mainly structured with a supply system for power, a production unit, an energy recovery unit, and a system for cooling (Schnitzer et al., 2007). Figure 4 shows the systematic arrangement for industrial energy systems that are mainly useful for sustainable operations. Based on Figure 4, the energy system of an industrial process can be understood by the status of energy sources: electrical current, biomass, and energetic gas and oil. All these sources are associated with limitations, like availability and price fluctuations. Therefore, developing countries like Sri Lanka can think of replacing the above-said sources with the help of solar energy systems for sustainable industrial operations. Solar energy incorporation can effectively meet the energy demand in industrial operations to operate various processing machines. Moreover, active and passive solar utilization systems can be considered for various industrial applications based on the need for and design configurations (Sharma et al., 2009).

Figure 5 explains solar energy conversion into mechanical energy (Kalogirou, 2004). For example, integrated water heating systems are active solar energy systems used for industrial water heating applications. In addition, solar refrigeration systems are set with adsorption and absorption solar system technologies, which are active types of solar systems. Furthermore, components of vapor adsorption-type solar stills, multiple effective boiling, and multistage flash techniques are used for solar salinization (Kalogirou, 2005). Moreover, parabolic collectors, solar towers, and solar chimney systems are active systems used commonly in solar thermal power systems (Sumathy et al., 2003). Approximate load calculations are highly important to design an effective solar system for industrial operations.

The location, collection type, storage fluid volume, and self-life of the produce are some important factors that contribute to the effective incorporation of solar energy systems into industrial processes in Sri Lanka. Appropriate alternative measures to supply energy continuously into industrial operations are also planned while developing solar systems for industrial applications since solar energy is not available continuously throughout the day. In this regard, attention has to be given to the development of hybrid solar systems for smooth industrial operations. The selection of the solar collectors is also made properly for high conversion efficiencies of the incoming solar energy. For example, flat-plate collector systems are used for low-temperature industrial operations; the parabolic trough collectors and solar trackers

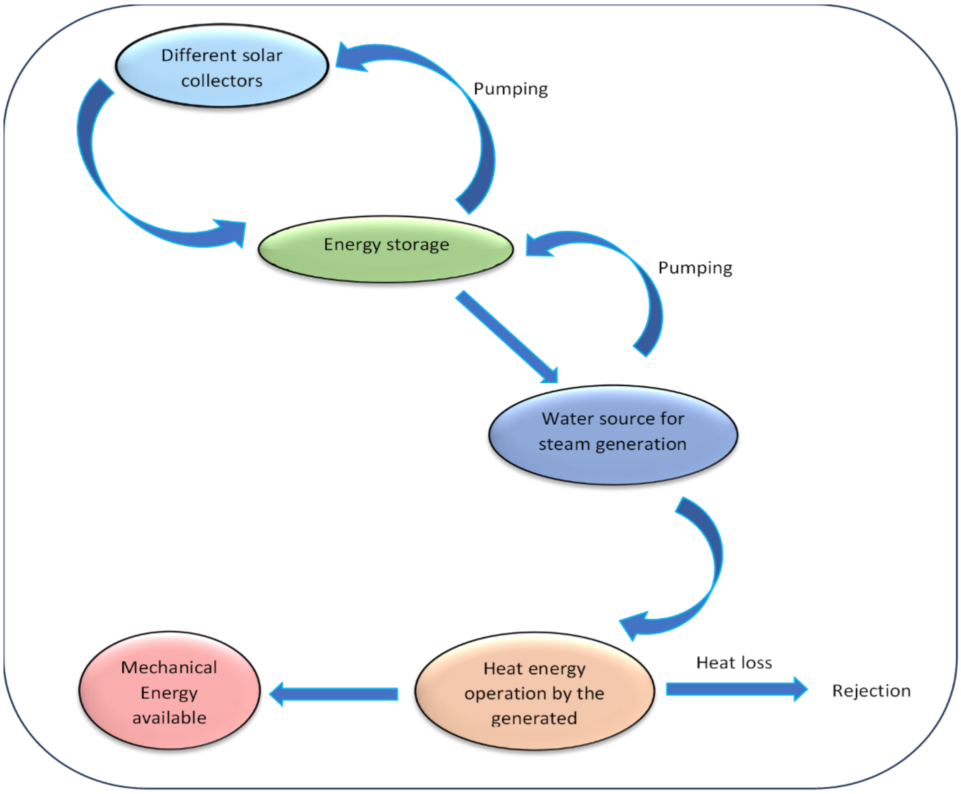

Figure 5: Overview of an solar energy conversion systems (Kalogirou, 2004)

are suitable for high-temperature applications (>250 °C); photovoltaic systems can be used for power generation; steady and non-tracker systems are used for industrial heating applications. Furthermore, the integration of solar thermal collectors with solar photovoltaic systems is highly efficient since the thermal collectors can use the reflected radiation from solar PV systems for heat generation (Kumar et al., 2019)

The cost of solar power systems varies from LKR 2,064,467.16 to LKR 3,440,778.60 per kW when storage is between 6 hours and 15 hours (Hoffschmidt et al., 2012). The cost of production can be minimized greatly if the solar plant can be used for solar heating. Based on the facts discussed above, it is highly important for developing countries, like Sri Lanka, to go for solar energy systems so as to facilitate industrial operations in a sustainable manner. The incorporation of solar energy into industrial operations is significant, along with the minimum effect on the environment. It can help to improve the economic status of the country.

3. The key applications of solar thermal energy for industrial operations

Solar thermal energy can be used effectively in various industrial operations. Developing countries like Sri Lanka can think of considering solar thermal energy for industrial operations to rebuild economic stability. It is important to note that almost all industrial energy systems are set to have energy from burning fossil fuels. However, around 13% of industrial applications require low-temperature thermal energy (<100 °C; around 27% of industrial processes require a temperature value up to 200 °C; the rest are above 200 °C (Schnitzer et al., 2007). Some key industrial processes and their temperature ranges are shown in Figure 6, given below. According to the above Figure 6, it can be seen that a lot of industrial processes are set between 80 °C and 240 °C (Kalogirou, 2004).

Moreover, thermal energy can be used effectively for solar water heating, solar drying, heating, cooling, and water salinization (Kalogirou, 2013). Therefore, solar input power can be used efficiently to heat engines. The external heat source is commonly used for Stirling engines, which is highly reliable, simple, and cost-effective. The Stirling engine can produce energy up to 100 kW for industrial applications effectively. The use of this engine for industrial applications can minimize greenhouse gasses (CO2, SO2, and NOx). Therefore, solar thermal energy can be incorporated into various industrial processes in developing countries like Sri Lanka for better economic return. There are many industries that benefit from this activity if it is properly structured: steam generation, drying, concentration, sterilization, building heating, food beverages, and plastic sectors. The above set of major sectors can be considered for the effective incorporation of solar thermal energy into industrial processes. The Sri Lankan industrial sector can also pay

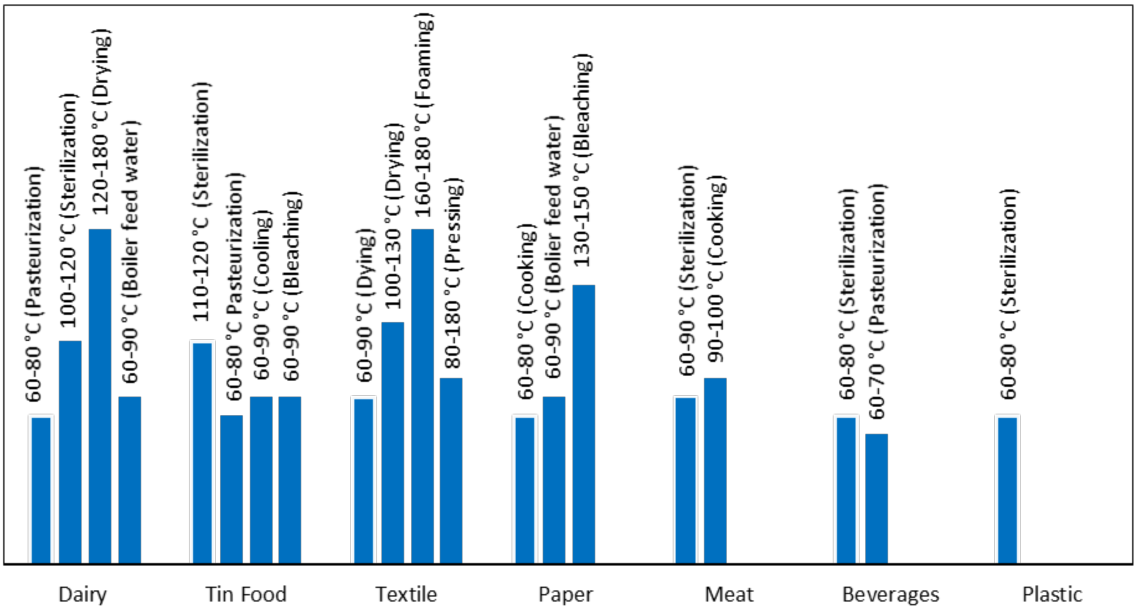

Figure 6: Industrial unit operations with respective temperature ranges (Kalogirou, 2004)

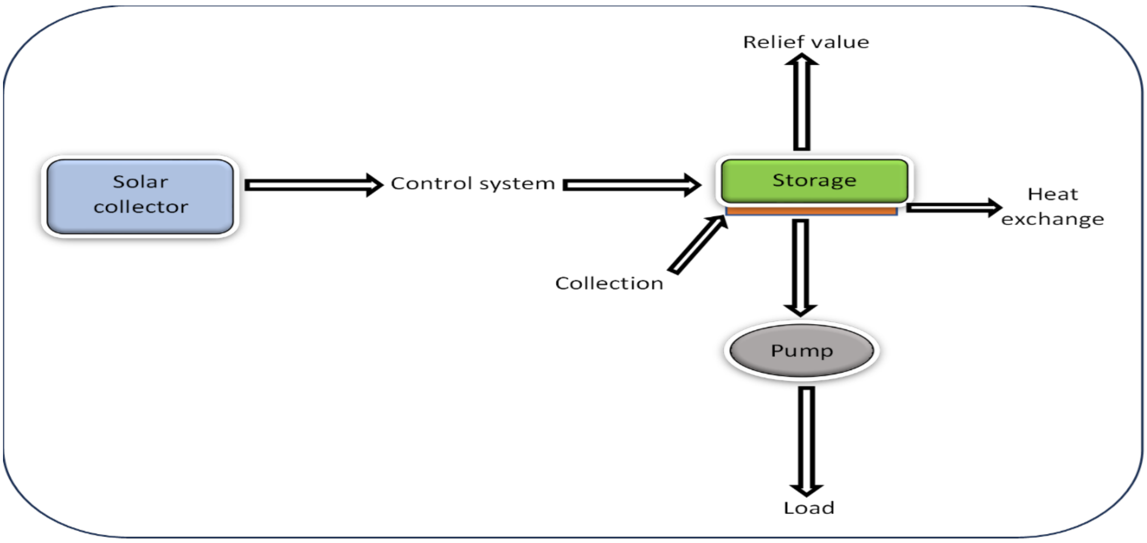

Figure 7: Diagrammatic representation of a simple solar water heating system (Gautam et al., 2017)

attention to this sector for better exploration. It can improve the economic status of the country. A critical discussion related to this is made below for the facilitation of industrial processes in Sri Lanka with the help of sustainable solar thermal input.

3.1. Solar thermal energy for hot water production

Solar thermal energy can effectively be used for the production of hot water for various uses. It is mainly useful at the domestic and industrial levels. This system is highly effective in terms of the cost component of all other technologies that are mostly used. Solar water heaters have solar collectors and storage space, and they work based on the density between hot water and cold water (Ogie et al., 2013). The sketch of the solar water heating system is indicated in Figure 7 for easy understanding (Gautam et al., 2017). The storage tank and solar collectors are properly assembled to have maximum efficiency. Moreover, solar heating systems are grouped into two major categories: the once-through system and a system with water circulation (Mekhilef et al., 2011). Mostly, the food industry has a once-through system due to the contamination of used water by microorganisms.

However, the re-circulation system is used for domestic purposes. The cost of production of the solar water heating systems will increase if the temperature is expected to rise above 100 °C (Hossain et al., 2011). It is because of the need for pressurization. Minimal pressure must

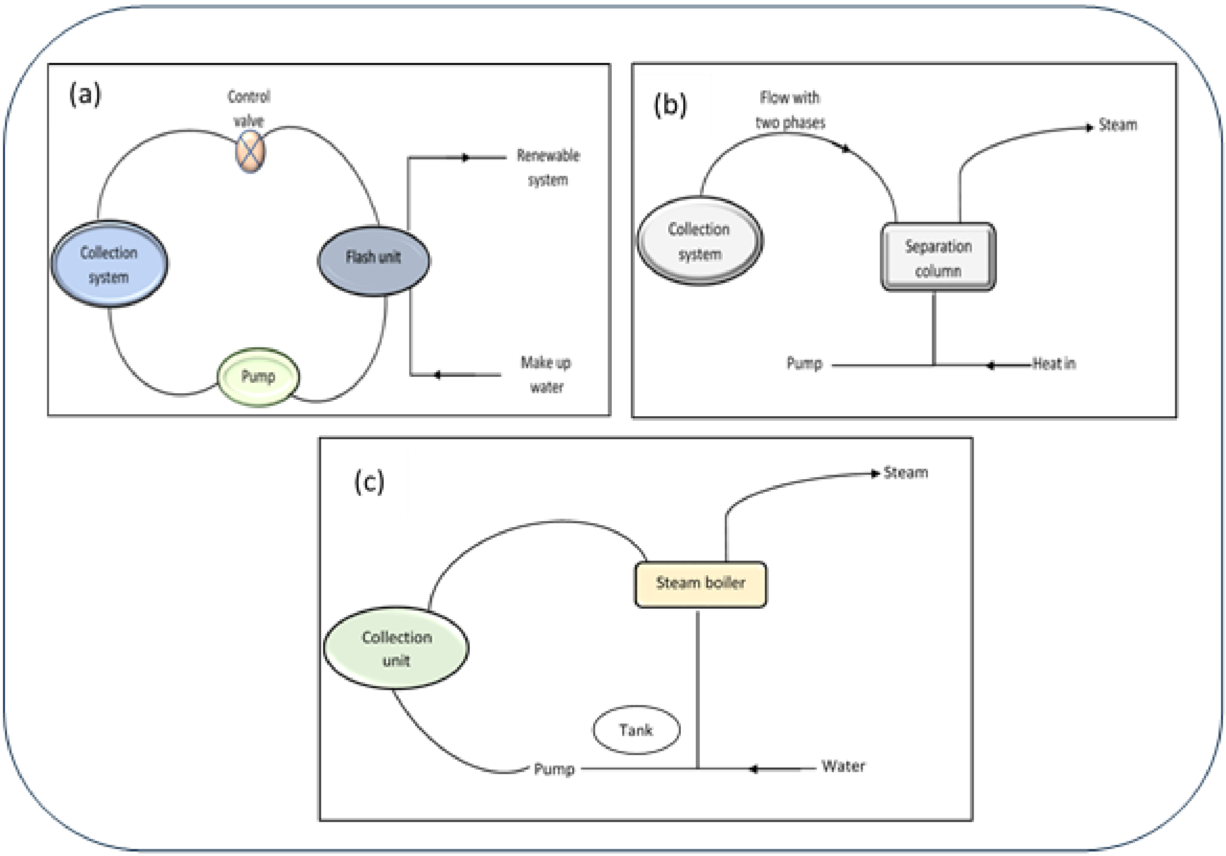

Figure 8: Steam generation systems: (a) steam flash unit; (b) direct generation; (c) unfired boiler system (Thomas, 1996)

be used to meet this requirement. Solar thermal energy is used to produce hot water for many industrial applications, such as cleaning, washing, drying, and steam generation. Solar thermal energy can efficiently be used in the thermal industry to heat water near 100 °C. It is mainly notable in Sri Lanka. Fuel-driven systems are used to produce hot water in the textile industry. Solar thermal energy usage in industries will significantly minimize the cost of production. Moreover, an appropriate selection of solar water heating systems can significantly help to minimize industrial units in Sri Lanka (Bhutto et al., 2012). In addition, the quality of water needs to be considered for the effective operation of solar water heating systems. In developing countries like Sri Lanka, the water quality may not be suitable for the installation of pipes and other accessories due to the increased hardness of water (Mostafaeipour et al., 2022).

3.2. Solar thermal heat for steam generation

Steam quality can be grouped into two major categories: low-temperature steam systems and high-temperature steam systems. The sterilization process requires low-temperature steam, whereas high-temperature steam is produced with the help of parabolic trough collectors (Kalogirou, 2005). Developing countries, like Sri Lanka, can think of incorporating solar thermal heat steam generation effectively. There are three methods commonly used in parabolic trough collectors to generate steam: steam flash, direct method, and boiler system (unfired) (Thomas, 1996). The pressurized hot water is flashed into a separate system to generate steam using the steam bath method. In the direct method, the flow is directed into both the collector system and the re-circulation system separately. However, a heat generation mechanism is used in the unfired boiler system to generate steam for industrial applications. The simple representation of steam flash, direct method, and unfired boiler systems are shown in Figure 8 (a), Figure 8 (b), and Figure 8 (c), respectively (Thomas, 1996). It is highly helpful for various industries in Sri Lanka to incorporate solar thermal energy for the effective generation of steam.

3.3. Dehydration by solar thermal energy

Solar heat is used to remove water from various products effectively. There are many industries using solar thermal energy for water removal: food, wood, textile, leather, and sewage sludge. However, the traditional drying system uses fossil fuels for the generation of heat (Pirasteh et al., 2014). The use of well-structured dryers, in this regard, is highly sustainable for countries like Sri Lanka. There are two types of dryers available: low-temperature dryers and high-temperature dry-

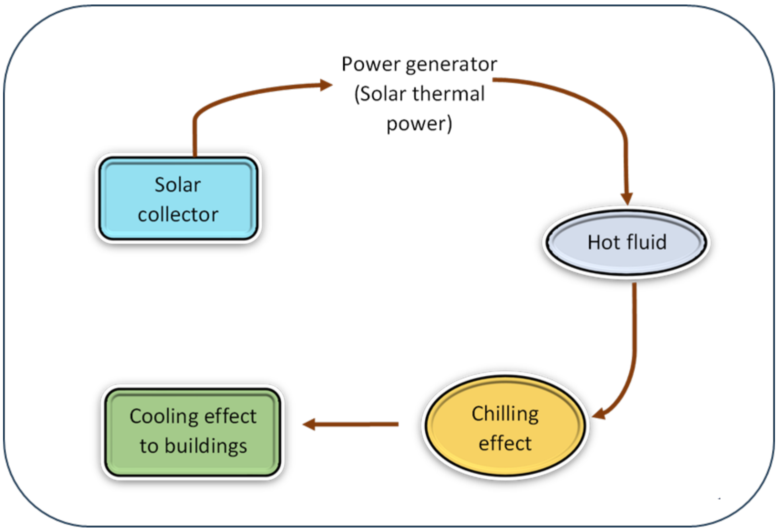

Figure 9: Schematic representation of a simple solar cooling system (Sumathy et al., 2003)

ers. High-temperature dryers can be driven by heat energy provided by fossil fuel burning, whereas low-temperature dryers can utilize solar thermal heat effectively (Ekechukwu and Norton, 1999). Moreover, solar dryers are grouped into three major groups: active dryers, passive dryers, and hybrid-solar dryers, based on the movement of heated air (Mohana et al., 2020). Developing countries, like Sri Lanka, can go for passive solar dryers for an effective outcome since the mechanism behind this is simple and cost-effective. It is good for the agricultural industries as well.

Passive solar drying systems are used to dry agriculture products in the field or after spreading them onto the field. Natural circular dryers are passive solar dryers that have many advantages as far as their effectiveness is concerned: small area requirement, efficient water removal, quick drying, the minimum influence of natural factors, simple mechanism, and user-friendliness. Moreover, active solar systems are confined to fossil fuel reserves and solar thermal energy. This system is complex compared to passive heating systems (Safari and Torabi, 2014). Some industrial applications require a temperature range of 140 °C - 220 °C. For these sectors, solar thermal dryers must be assisted by other types of heating systems, such as fossil fuel-driven dryers and electric dryers. Furthermore, much attention is needed to make the energy flow control for inefficient days. Therefore, hybrid-solar dryers can be designed with other drying techniques, including thermal storage systems, mechanical heat pumps, and forced convective systems for effective heat storage that can be utilized during off-sunshine periods (Mohana et al., 2020). Based on the factors discussed above, it is obvious that solar thermal energy is an effective source for developing countries like Sri Lanka in order to facilitate many agricultural and industrial operations. Agricultural industries in Sri Lanka can incorporate solar thermal energy into industrial processes for sustainable operation.

3.4. Use of solar thermal energy for cooling

The improved structures used for sophisticated living need an appropriate cooling system to manage existing weather conditions. The use of complex air conditioners is highly problematic as far as the environmental quality is concerned. Furthermore, the air conditioners generate a significant amount of effluent from their operations. Moreover, the energy demand for air conditioners is high when there is hot weather. Solar refrigeration systems can be considered at this point since they produce no harmful pollutants that damage the ozone layer in the atmosphere. The operational cost of solar cooling systems is 15% cheaper than normal cooling systems. It is highly important that the installation of solar-assisted cooling systems can save up to 50% of the primary energy consumption (Balaras et al., 2007). Developing countries, including Sri Lanka, can think of developing this system for the sustainable use of energy. The typical solar cooling systems can be designed by considering the schematic shown in Figure 9 (Sumathy et al., 2003).

There is another cooling system called "absorption air cooling" that creates a cooling effect on the required space, as shown in Figure 10 (Li and Sumathy, 2000). Solar-powered air conditioners are connected to cooling devices driven by solar thermal energy with the use of solar collectors, heat storage systems, heat distribution systems, and heaters (backups). Indoor air conditioner systems are mainly important worldwide as far as the tourism industry is concerned. For developing countries like Sri Lanka, the use of solar thermal energy for air conditioners is highly useful for the sustainable use of energy. It can successfully replace electricity in an efficient manner. Moreover, solar thermal research for cooling systems is growing at a faster rate in terms of environmental sustainability. The government and private sectors have to seriously consider the effective display of solar thermal energy for cooling. There are still some

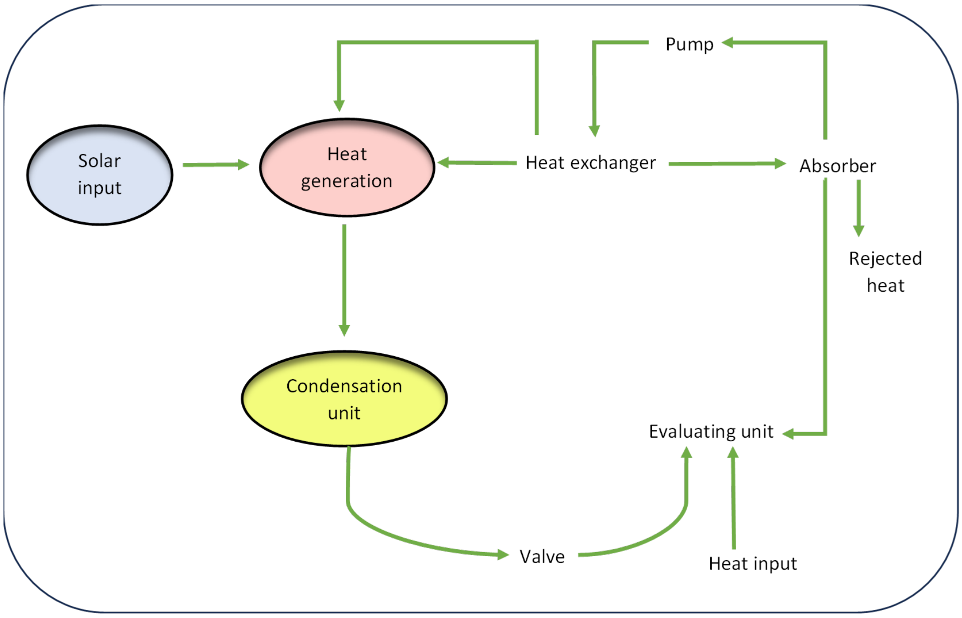

Figure 10: Adsorption type solar thermal cooling system (Li and Sumathy, 2000)

problems, such as the high cost of production and technical aspects comparatively associated with solar thermal cooling systems, which are to be fixed by meaningful research works.

3.5. Solar thermal energy for the food industry

The use of heat energy in the food industry is vital since most of the processing steps are set with heat inputs. Food industries: milk, meat, and beverages can effectively incorporate solar heat for cleaning, cooling, and drying purposes (Ravi Kumar et al., 2021). Moreover, it is used for many actions in the malt industry, such as steam generation, cooling, prevention of germination, and drying. In Sri Lanka, the effective use of solar energy can be planned for local processing activities, such as milk factories and meat processing. The milk processing can be made sustainable if solar energy is incorporated into machine operations. It can mainly be used for pasteurization (60 °C), sterilization (130 °C-150 °C), and for drying. For operating dryers, the solar thermal energy needs to be set to have temperature values between 120 °C and 180 °C (Kalogirou, 2003). In Sri Lanka, at present, many industries, including milk and meat factories, use fossil fuels for industrial processes. It is costly and considered problematic as far as atmospheric quality is concerned. It has been reported that around 20% of the annual cost of the food industry is consumed by the energy supply (Mekhilef et al., 2011). Therefore, appropriate arrangements can increase the probability of using solar thermal energy for various food industrial processes in Sri Lanka.

3.6. The use of solar energy to meet the energy demand by buildings

The energy demand by buildings is a significant contributor to the total energy consumption of a country (Pérez-Lombard et al., 2008). The use of solar energy in building systems is grouped into two categories: direct system and indirect system. Solar-green buildings with zero emissions will be a hot topic in the near future. These applications can minimize severe environmental problems that are caused by increased fossil fuel generation so as to meet the demand of builders. There are many applications now growing to use solar thermal energy in building systems efficiently: solar water heaters, solar cooling, and photovoltaic power systems. Developing countries, like Sri Lanka, can think of getting solar thermal energy for building needs with limited emissions.

There are several applications available as far as solar thermal building systems are concerned: direct radiation use, solar energy harvesters for improved applications (air conditioning and milling devices), and photovoltaic systems for electricity generation. Developing countries, like Sri Lanka, can make plans to use either active solar technology or passive solar technology to make green buildings that are environmentally compatible. Furthermore, building construction is important to harvest as much solar energy as possible for building industries (Jelle et al., 2012). Buildings should, therefore, be built oriented to the south to meet the above-mentioned criteria. An appropriate ventilation system must be made available inside the building to distribute the harvested heat effectively along building segments. It is, therefore, important for the sustainable application of solar energy in Sri Lanka.

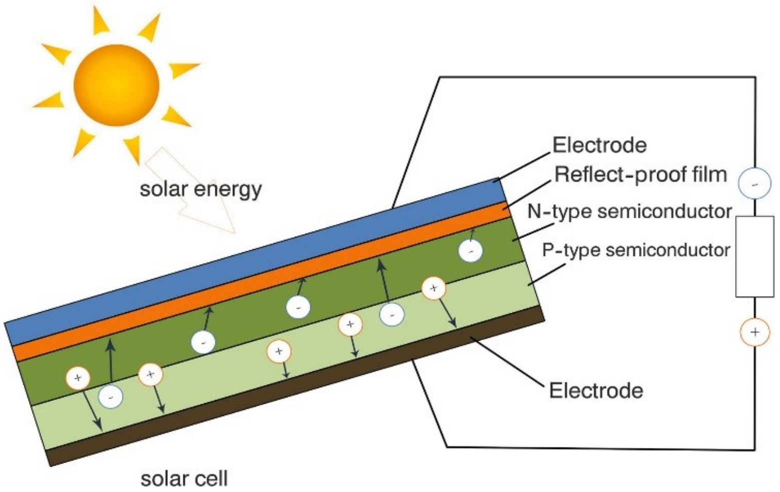

Figure 11: Fundamental schematic of solar PV technology (Husain et al., 2018)

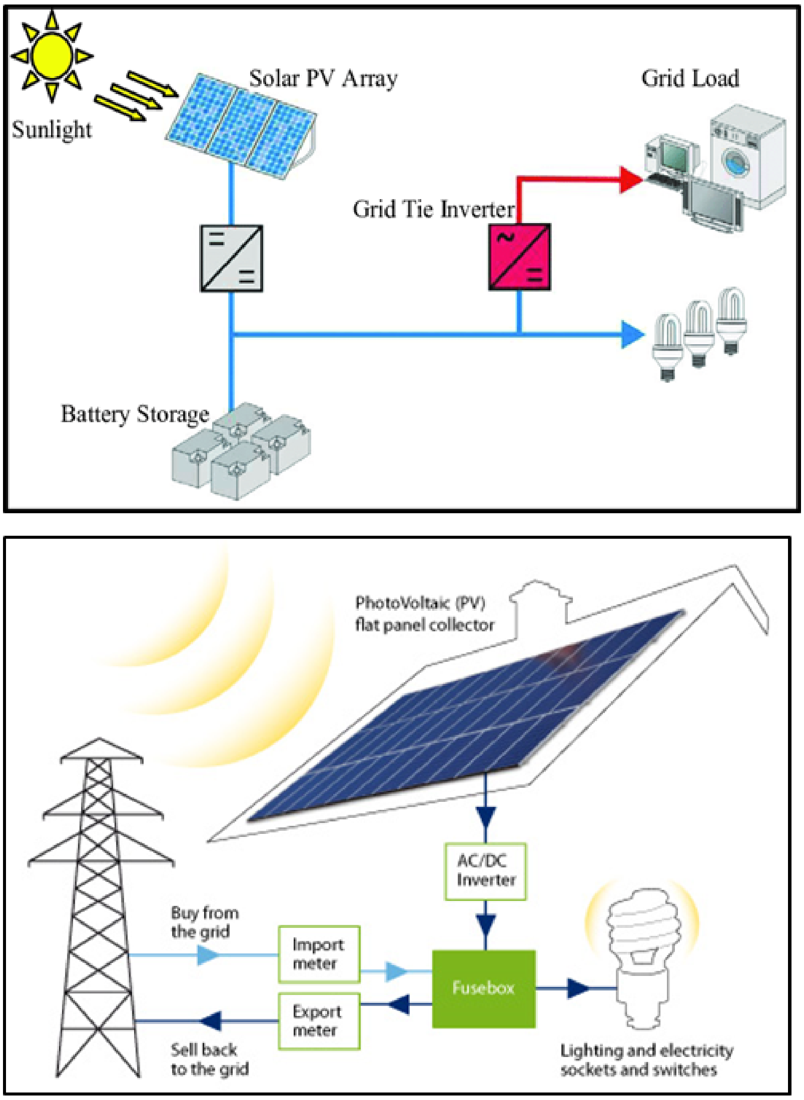

Figure 12: (a) Stand-alone PV system; (b) grid connected PV system (AlShemmary et al., 2013)

Table 1: The initial capital cost of components of a grid-solar power plant (Adapted from (Salamov et al., 2020))

Items	Cost (LKR)
PV modules	320,896.84
Mounting system	52,758.61
Inverter	175,273.26
Switching and protection devices	23,118.76
Installation costs	114,456.68

3.7. Solar energy for industrial applications

Photovoltaic (PV) technology is used to produce current from solar energy with the help of semiconductors, as shown in Figure 11 (Husain et al., 2018). The performance of the solar PV system in industries is governed by many factors: temperature, solar radiation, solar cell type, and insulation system (Makki et al., 2015). The use of PV technology must be promoted in Sri Lanka as it has the ability to minimize the cost of fuel energy. It can also develop a path towards environmental sustainability. The PV systems are grouped into two major categories: stand-alone systems and grid-connected systems. The stand-alone systems are used to meet the load set, whereas grid-connected systems are set to have a connection to the daytime grid to sell the excessive electricity. However, stand-alone PV systems need storage batteries to make the supply continuous. It is also possible to incorporate hydropower plants or wind turbines into solar PV systems so as to make them stable. This system is called the "solar-PV-hybrid-system". The concept called "grid connection of solar PV" is now growing significantly in Sri Lanka.

It provides considerable income to the investor with little or no environmental damage. The following Figure 12 explains a stand-alone PV system and a grid-connected PV system. Therefore, there is a possibility in Sri Lanka to go for the development of a village called "solar village," which is eco-friendly in nature. There are some more applications for the effective use of solar PV technology: solar cars, solar cabins, ticket machines, traffic lights, crop irrigation, and water purification. It is interesting to note that the effectiveness of PV systems has been increased by 20% due to systematic research activities. Therefore, this process can systematically be used to sustain industrial operations. Moreover, a concept called "saving-integrated photovoltaic-system" is a new opening of this solar PV technology, where solar cells are set to replace traditional construction materials for better harvesting of solar energy (Crawford et al., 2006). This concept can also be applied to the energy system of Sri Lanka for better expansion.

3.8. Solar PV technology for industrial operations

As many industries in Sri Lanka have many machines driven by electrical power, the use of solar PV technology could be highly effective for energy sustainability. Solar PV technology has many applications in industries located in remote areas, such as the operation of telecommunication instruments and traffic lights. Two solar PV systems have been installed for various applications: an off-grid unit and a hybrid unit. The off-grid system functions as a single-load device, whereas hybrid systems have storage and other relevant accessories. It is highly useful for telecommunication industries in Sri Lanka. It has also helped to manage the country's economic crisis. However, significant attention needs to be paid to improving the PV system for different industrial applications. Furthermore, DC can be driven by solar PV systems to cool cabinets used outdoors in telecommunication industries.

In addition to these, many agricultural industries can use this solar PV electricity for lift machines, drying machines, coolers, chillers, conveyors, and evaporators. For example, egg incubation solar PV current can effectively be used. Therefore, the fact discussed above will give new interest to expanding solar PV electric systems into the industrial network of Sri Lanka in a sustainable way. Table 1 presents the cost for the installation of the solar PV panels for a total rated power of 1.86 kWh (Salamov et al., 2020).

4. Conclusion

This article highlighted the major points that are to be considered for the effective incorporation of solar energy into various industrial applications in Sri Lanka, which has been facing severe economic problems since the occurrence of the COVID-19 pandemic situation. Also, this article critically discusses the need for solar energy for sustainable energy development with minimum environmental damage. There are many agricultural operations, such as food processing, drying, pasteurization, sterilization, and evaporation, which can be effectively performed with the help of solar thermal energy. Moreover, solar PV electricity has many industrial applications: water purification, food drying and preservation, and food processing. It is, therefore, important for policymakers of the country to think of incorporating solar energy into the Sri Lankan industrial energy network for a sustainable energy future in the country.

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