Design and Evaluation of a Novel Solar Biomass Hybrid Dryer with Cutting-Edge Resistive Heating Backup Technology

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Candidate's Declaration

This is to certify that the work presented in this thesis, titled, "Design and Evaluation of a Novel Solar Biomass Hybrid Dryer with Cutting-Edge Resistive Heating Backup Technology", is the outcome of the investigation and research carried out by me under the supervision of Dr. Arafat Ahmed Bhuiyan, Associate Professor, MPE Dept., IUT, Board Bazar, Gazipur-1704, Bangladesh.

It is also declared that neither this thesis nor any part of it has been submitted elsewhere for the award of any degree or diploma.

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Abstract

Over population can have adverse effects on the food balance of a county. One of the major issues is the poor processing and preservation of food. it is a very big challenge for any country to meet the demand of the increasing mass. Many countries are still far away from ensuring electricity to the rural areas, let alone better food processing and storage technologies. In these scenarios solar dryer, which is, a very promising technology can be used to mitigate some of the problems related to food processing. However, traditional types of solar dryers have some disadvantages. A better efficient drying system can ensure more food safety and can be of financial help to farmers. This research was done to assess and enhance the drying efficiency of a hybrid solar-biomass dryer. Load of 4, 8 and 12 kg of cabbage were taken for the drying operation. The dryer was operation in three configurations based on energy source; sunlight heating, biomass heating and combination of sunlight and biomass heating. Different process parameters such as temperature of inlet, drying compartment and outlet, solar intensity, relative humidity, moisture amount of the product has been recorded. For 4 Kg batch, time require for drying were recorded to be 13, 8 and 7 hours for sunlight heating, biomass heating and combination of sunlight and biomass heating respectively. For 8 Kg load, the needed time was 19, 13 and 12 hours respectively and for 12 Kg load it was 20, 17 and 12 hours of drying. The highest moisture evaporation rate was observed to be 766.15 g water per hour for 12 Kg load during drying with combined source of sunlight heating and biomass heating. Lowest margin of 261.53 g water per hour was found for sunlight heating. From the analysis it is found out that Hybrid heating configuration has the highest thermal efficiency of 61%. Compared to hybrid, using only biomass heating and sunlight heating has efficiency of 33% and 39% respectively. Exergy efficiency was also analyzed which showed that hybrid configuration has the height exergy efficiency of 46% followed by 37.7% and 33% by sunlight heating and biomass heating combinedly. The results shown that the combination of sunlight and biomass heating has better drying rate and efficiency thus can be a very promising method for food drying. To increase the efficiency and drying performance even more resistive heating mechanism in place of biomass heating has been considered. It was observed that the sun intensity has a major influence on the system's total efficiency. To reduce dependency on the sun and ensure continuous drying capability even in off sunshine hours resistive heating coil has been selected as alternative power source. Solar energy combined with resistive heating makes the system lighter and more portable in the field, where it is essential to have this

alternative in rural areas. It may also be powered by energy from the main grid, making it more useful for residential use and food processing when necessary.

The assessment of the resistive heating dryer's performance will also make it possible to determine whether the technology is still viable for use in large-scale industrial production with a precise drying process control system. The study's discussion of future possibilities and adaptability in light of the Fourth Industrial Revolution will serve as a foundation for further research on this technology.

Key Words: Hybrid Dryer, biomass, solar power, exergy, food processing and preservation, resistive heating.

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Nomenclatures and Symbol

$Ex_{in} = Exergy\ entering$

$Ex_{out} = Exergy\ leaving$

$Ex_{dest} = Exergy\ destroyed$

$T_a = ambient\ temperature$

$T_i = Inlet\ temperature$

$T_o = Outlet\ temperature$

$T_s = 5770k; temperature\ of\ the\ sun$

$Q_{bio} = Heat\ input\ from\ biomass\ energy$

$Q_s = Heat\ input\ from\ solar\ energy$

$Q_a = Heat\ added\ to\ inlet\ air$

$I_s = Solar\ enerdy\ density\ flux\ or\ irradance$

$A_s = Solar\ energy\ collector\ area = 0.135\ m^2$

$\dot{m}_a = mass\ flow\ rate\ of\ air = \ 0.1486\ kg/s$

$m_w = mass\ of\ evaporated\ water$

$m_g = mass\ of\ product$

$\Delta H = h_{out} - h_{in} = enthalpy\ difference$

$\Delta S = s_{out} - s_{in} = entropy\ difference$

$S_{gen} = Entropy\ generation$

$W = amount\ of\ biomass\ used$

$L_v = latent\ heat\ of\ water\ vaporization$

$H = heating\ value\ of\ biomass = 13.1\ MJ/Kg$

$t = total\ drying\ time$ (Hours)

Chapter 1: Introduction

1.1 Overview of the project

The enormous issue of the food problem in emerging nations frequently results from the inability to efficiently store or preserve food, rather than from insufficient production rates. For many countries, the failure to guarantee long-term food security is a grave and critical concern. Due to this circumstance, food is wasted during a time when production is higher but there is less immediate need. When the harvest period is shorter, the situation is completely the opposite. During times of bad crop, so many nations have food shortages. One of the best ways to taint common crops has been drying since ancient times.[1]

Outdoor drying in the sun, like any other method of food preservation, provides a variety of intrinsic constraints and drawbacks for instance as insects, extreme weather conditions, fungal attacks, birds or rat attacks, contaminations, insufficient drying or over drying. All these leads to high food deterioration.

Solar drying technology is very promising considering all these conditions. This technology can also be adapted to fourth industrial revolutions as well to ensure less human interaction. It will help many peoples who find these modern technologies very hard to operate.

For safe storage of foods or crops, the low relative humidity of the samples is mandatory. It should be lower than the ambient conditions. Equilibrium moisture content must be ensured to store for longer period. However, this situation is highly dependent on the climate conditions. It has great impact on the crop deterioration. Even though in warm and dry conditions it may seem feasible to have crops dried in field. Nevertheless, different statistics such as Meteorological data indicates that this is not feasible even considering the most favorable conditions.

1.2 Problem statement

In most rural areas of Asia, Africa and other developing countries food problem is a major concern. With increasing population, this sometimes leads to famine as well. However, it is very saddening that this happens due to unavailability of modern technologies in those areas. Poor farmers often cannot push the barrier of large initial set up cost of advanced fuel powered food preservation technologies that are present today. There is also running cost with most of the facilities that is very hard for them to meet with.

It is also notable that in many areas electricity and other sources of non-renewable energy are not available. Even if some of they are available, most of the farmers are not capable of affording these. Modern technologies are often too expensive. In addition to these, electric powered mechanical systems are often too complicated to understand for village area farmers. Therefore, they cannot operate these things easily as most of these technologies are meant to be for industrial sectors or modern areas.

In warm, damp conditions, fungi, mites, insects, or bacterial diseases are more deadly. To achieve the desired moisture content, however, it takes more time. Extreme heat and humidity can make it difficult for food to dry. Weather conditions that are warm and dry are preferable. Excessive relative humidity of the air would make direct field drying inappropriate, a more efficient and effective drying procedure is needed.

1.3 Objective of the Project

This study's main goal is to thoroughly evaluate the operational effectiveness of a recently fabricated hybrid Solar-Biomass drier while simultaneously developing and investigating operational modifications to improve its drying capacities. The goal of the research is to develop and evaluate strategies that maximize the performance of this novel drying system, ultimately resulting in more effective and efficient drying procedures.

The primary focuses of this research are:

1. Development of sustainable, efficient and affordable solar dyer for food processing and preservation.
2. Exergy and energy assessment of different operating configuration of solar dryer.
3. Calculation of first and second law efficiency of existing solar dryer.
4. Enhancement of first and second law efficiency of solar dryer with resistive heating.

1.4 Scopes of the project

The study included an evaluation of energy and exergy aspects along with a thorough review of the hybrid dryer's overall drying performance. The research's objective was to get an in-depth comprehension of the dryer's efficiency, efficacy, and energy usage patterns by using sophisticated methods and analytical techniques. The research revealed important information about mass and heat transfer processes as well as prospective areas for improving the hybrid drying system. Effect of modification with resistive heating has also been presented. This will allow further improvement in this technology such as integration with advance automatic control systems to maintain drying process for better food quality. Some of the future scopes of this project are:

1. Industrial production of sustainable solar hybrid dryers
2. Adaptation to IR 4.0
3. Result and data collection
4. Analysis and evaluation of the result

1.5 Report Outline

There are in total seven chapters in this study. The first chapter discusses the project's overall scope and the problem under investigation. This chapter provides an overview of the research field and its relevance. It also gives an overview of the overall problem area and methodology.

The second chapter is a literature review in which previous works are analyzed and scoped out to comprehend the methodological approach and the current developments of research in this field. Existing studies in related fields are designed after for comparison and initiation, and a proper method of analysis algorithm is developed to address the issue. The problems and limitations are briefly explained and a comprehensive picture of the current situation has been provided.

The third chapter is about the experimental setup and methodology. The hybrid dryer's construction details are discussed, as well as various auxiliary components. Furthermore, previous work knowledge is applied to develop working procedures, and mathematical equations are derived to achieve a specific result. The data recording system's description for various operating modes was discussed, and software analysis was performed.

The key innovation of the project is chapter four, which demonstrates and identifies the issues and displays actual results via various graphs. This gives us a complete picture of the solution and offers sufficient data to draw a conclusion.

The discussion section is in Chapter Five. The outcome and its importance, as well as any recommendations for the future and difficulties encountered during the process, are all extensively discussed. This gives people the option to do similar fields-related research in future iterations or extensions of this kind of work.

In the end, references and appendices are provided for a clearer view of the results and work progress.

Chapter 2: Literature Review

2.1 Drying Process

Drying often refers to removing moisture from the sample with a view to preserving it for a long period of time. This decrease in water content in food product is accomplished by allowing hot air to pass through a channel, commonly referred to as a drying compartment, to absorb water content from the analyzed sample. After doing so, the air simply exits the dryer chamber through a chimney. The process's duration depends on the amount of water that is present on the sample in equilibrium with the surrounding conditions. Typically, it goes on until the saturation pressure of the food is equal to the atmospheric pressure. [2]

The process takes longer when the moisture content is at equilibrium. For safe crop preservation in a climate with a higher relative humidity, the equilibrium moisture content should be low. Contamination of food is frequently caused by an excessive moisture content and is strongly correlated with climate. [2]

The basic goal of the drier is to produce more heat than the ambient air since this lowers relative humidity and increases the heated air's ability to absorb more water, enabling it to retain a low optimum moisture content while absorbing extra water from crop samples. [2]

In the vast majority of solar dryers, solar energy serves as the main power source. However, it may be substituted for or utilized in addition to other sources. Heated airflow is generated by mainly natural convection in open solar dryers. However, it can also be generated with help of electricity by motor powered fan as forced convection. The heated air temperature have to be greater that than the ambient air temperature so that it can absorb more water from the food product. [2]

Evaporation takes place on the product's outermost layer during the drying process. This is why it is essential in this situation to give a significant quantity of heat to cause water to vaporize. The product's surface temperature rises as a result of the heated air. This raises the moisture on the surface's vapor pressure. When this adequately exceeds the evaporation pressure of the ambient air, water vaporizes. The necessary energy for the vaporization of water is ensured via heat absorption.

The rate of moisture evaporation directly affects how long the drying process takes. When water is vaporized, due to diffusion, the food's exterior surface becomes moist from the inside. The rate at which this happens varies depending on the product's nature and moisture level. It indicates the limiting factor when rate is low. In contrast, when the diffusion rate is high, the rate of water evaporation from the outer surface is thought to be the determining factor of process time. It describes the point at which the drying process commences.

A part of the solar radiation helps in direct drying. The interior membrane of the product directly absorbs radiation. Thus, It raises the temperature of the product's interior and outside, improving heat transfer.

The product's rate of radiation absorption is another factor in influencing drying time. The majority of cultivating crops absorb solar energy more effectively. (0.63-0.90) [3]. However, this tends to increase or decrease depending on the drying procedure. Additionally, the product's thermal conductivity has a considerable impact on the procedure. This is usually the case where the drying membrane is very thick and heat conduction occurs between particles.

Considering energy utilization and economics feasibility higher drying rate is preferable in most of the situation. However, it is very important to maintain a better food quality. Higher temperature can surely effect the food properties. Favorable temperature changes from product to product. After a certain period, it may be necessary to reduce the rate as some produced have the tendency to have dry surface layer even though the interior is not totally dried up. In this situation, the process must be controlled with a slower drying rate for the remainder of the time. Like this depending on the food, process should be controlled carefully in order to obtain optimal drying rate.

This type of specialized control is however very difficult to achieve in natural circulation dryers as they are intended to have minimum capital and maintenance cost. So most feasible way would be incorporate this type of control system in the structure so that dryers can operate according to the climate conditions and product properties.

2.1.1 Methods of Drying

There are some traditional methods of drying which are being used from old times. Such as,

1. Open- air dying
2. Solar energy assisted drying
3. Fossil or biomass drying etc.

2.1.2 Open air and sun drying process

These two moisture reduction techniques have been around for a very long time and are the most common. There are no sophisticated constructional elements and they are quite inexpensive. They are therefore particularly well liked in rural areas. However, there are a number of drawbacks to using these antiquated drying techniques. Food product contamination is a serious issue with this drying technique. Numerous factors, including dust, birds, insects, and animals, can cause contamination. These processes are extremely susceptible to climatic conditions, such as intense rain, extreme cold, excessive warmth, and moist weather, etc. These variables frequently cause food products to degrade.

The method needs a lot of labor, is unclean, unreliable, takes a long time, and results in uneven drying of the fruit. Additionally, this practice prolongs drying and raises the possibility that the crops' or grains' quality would deteriorate.

2.1.3 Mechanical Dryers

Industrial and technological advancements have almost replaced open air and sun drying process with effective mechanical dryers. Various Mechanical components are incorporated in these types of dryers such as boiler to heat up the inlet drying air, fan for force flow for higher drying rate, automatic control system to monitor and control the drying process for better food quality. For this equipment, the required drying is less and better food quality is achievable. However due to complex construction these are very expensive.[4] For operation of these entire equipment energy source such as fuel or electricity is required which adds high operation and management cost. A continuous-flow dryer that functions at high temperatures and a recirculating type that also operates at high temperatures are the two main types that are the most common configurations.

2.2 Solar Dryers

The solar dryer is another excellent and prospective solar energy use. It is mostly utilized in the agriculture sector. By lowering a food's moisture level and guaranteeing safe storage over time, this method aims to prevent degradation. There are three major components:

1. Drying compartment
2. Solar collector to heat the drying air
3. Airflow system

Heat transmission and mass transfer must be integrated as part of the operation of drying. Heat transfer is the process by which heat is transferred from the heat source to the exterior of the food product. Mass transfer, on the other hand, is the removal of moisture from an object's interior, moving it to the object's surface, and then discharging it into the atmosphere around it.

When the moisture's vapor pressure rises, moisture starts to evaporate from the food samples. As a result, the heated air's relative humidity drops substantially, improving its capacity to hold moisture. To accomplish this, the food product must be heated above the temperature that the ambient temperature and atmospheric pressure would normally supply.

The dryer introduces the food product to hot air by sending heated air through a tube. Direct solar radiation can also be used simultaneously. Convection can be induced or natural to move the hot air through the dryer. The main goal of the sun dryer is to dry out food samples by using heated air to remove moisture by convection and conduction. When biomass or resistive heating are utilized as the main heating resources, solar dryers can act as the primary heating source or as a secondary heating source, acting as a backup.

2.3 Classification of Solar Dryers

Solar dryers exist within a wide range of classifications, each one distinguished by unique constructional features, infrastructure design, material preference, and the use of alternate heating systems or energy sources.

Based on solar radiation incidence criteria solar dryers can be classified in mainly four types as

1. Direct type
2. Indirect type
3. Mixed type
4. Hybrid type

Based on how the heated air flow system is set up, solar dryers can be further divided into two different types as

1. Passive type
2. Active types

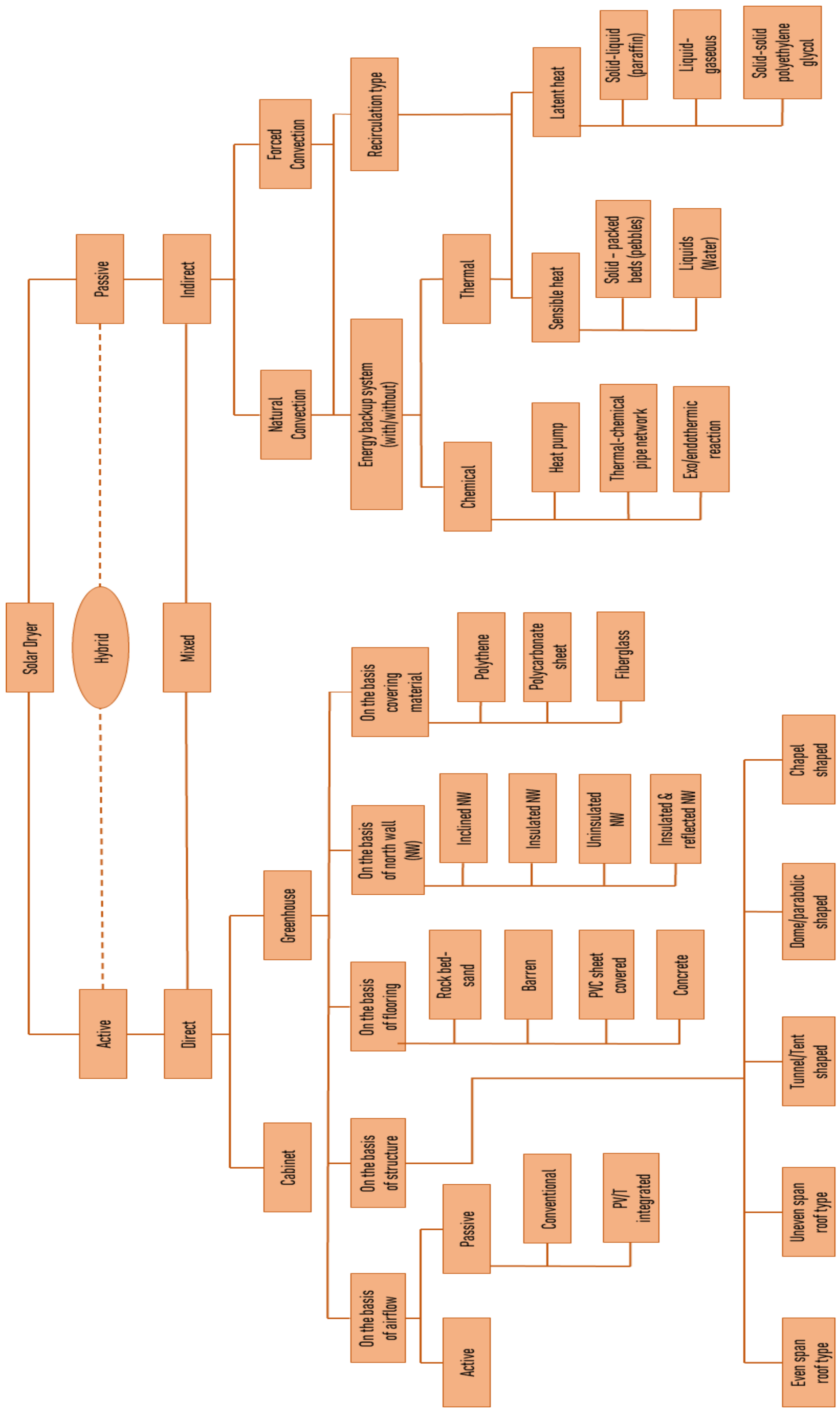


Figure 1 : Classifications of solar Dryers

2.3.1 Direct type

These dryers are also known as box dryers. The sample is exposed to direct intensity of sunlight inside the drying chamber, which is wrapped in a transparent material to create shade. [5] .This enables the sun energy to reach the product and later be received by the product and its immediate surroundings. The product becomes hotter due to solar radiation. The temperature inside the drying compartment rises to a level that allows for the drying of various foods, including fruits, vegetables, meats, and spices.. Absorbed radiation emits from the product body, which is restricted by glass cover. These increases the thermal efficiency but the overall quality of the food product are not that good in general [6]. This is a major drawback of these types of solar dryer. Inappropriate drying is another limitation for large-scale applications.

2.3.2 Indirect type

Under this arrangement, energy from the sun goes through a solar collector and warms the air circulating above it. This heated air is directed toward the drying chamber, where it draws humidity from the sample. The water content is decreased through convective heat transfer between the sample and the heated air.

This kind of solar dryers are an upgrade over direct type solar dryers, which got beyond their thermal efficiency and product quality limitations. Controllable factors include the rate of moisture evaporation and heat transfer. Experimental tests have demonstrated that the dryer performs more effectively and efficiently when forced convection is used in place of natural convection.[7]–[9]

2.3.3 Mixed type

Using mixed-type solar dryers, which combine both direct and indirect operating principles, is an intricate approach in the field of solar dryers. These clever devices combine the benefits of both direct and indirect sunlight dryers, increasing the drying process' overall efficiency and efficacy. These dryers offer a clear drying compartment with the additional capability of preheating the air[10]. As heat is delivered through convection and radiation, Comparing this sort of dryer to direct and indirect solar dryers, it ensures a better thermal utilization hence increasing the efficiency.[11]. An extensive analysis showed that the general dryer exergy efficiency and energy efficiency were much greater when compared to open sun drying techniques.[12]. When incorporated with forced convection the process time was significantly shorter and product quality was satisfactory level. Various fruits, meats, spices and vegetables can be preserved using this type of dryer.

Direct sun radiation is used in mixed-type solar dryers by including translucent or transparent materials like glass or plastic coverings. In the drying compartment, these covers trap solar energy, causing a greenhouse effect that raises the air temperature and facilitates convective heat transmission. The initial heat input and drying process are both aided by direct sun radiation.

On the other side, a heat exchanger system is used to use indirect solar energy. This system is made up of a number of to the sun's rays exposed tubes or channels. Through these tubes, a heat-transfer fluid, such as air or water, moves, absorbing solar energy and transporting it to the drying compartment. The heat exchanger technology ensures continuous drying operation by enabling efficient heat transfer even during cloudy or periods of low sun radiation.

When compared to conventional sun dryers, a mixed-type solar dryer, which makes use of indirect as well as direct solar radiation, offers a number of benefits. First off, it offers more versatility when drying various product types with differing moisture contents and heat sensitivity. The dryer can be customized for particular drying needs by adjusting the ratio of indirect and direct solar radiation. The mixed-type solar dryer, on the other hand, provides superior control over drying variables including temperature and airflow. This management makes drying uniform and reduces the possibility of product deterioration or quality loss. Furthermore, even in poor weather, the use of indirect sun radiation assures consistent drying performance. Numerous research studies have examined the efficiency and potential applications of mixed-type solar dryers.

2.3.4 Hybrid type

Hybrid dryers uses other sources of energy such as biomass combustion or grid electricity to provide continuous drying assistance when solar power is not enough or not available at all. The drawbacks of both active and passive types of dryers are somewhat mitigated by this type of dryer and are more effective and efficient. Some of the hybrid dryers are incorporated with advance control system, which can ensure temperature and moisture, control to provide better food quality and drying performance.

The ability of hybrid solar dryers to be combined with renewable energy sources is one of its most encouraging features. This ensures better energy efficiency and availability to rural area farmers. Complex construction with additional power source and control system adds excessive cost to this, which is a major challenge to overcome.

2.3.5 Passive type

The process of drying is only facilitated by fresh air from the atmosphere around in passive solar dryers. This arrangement is frequently used in sun dryers in cabinets and greenhouses [13]. A solar power collector, a drying chamber, and a device for regulating the airflow inside the chamber are the usual parts of passive solar dryers. To stop heat loss, the solar collector is tightly insulated. By the use of vents, flaps, or other flexible mechanisms that control the input and outflow of air, the circulation of air within the drying chamber is managed. Due to the air's weak buoyancy effect, the drying effectiveness of such solar dryers is frequently constrained. Blowers and other auxiliary equipment can be used to get around this restriction. [14], [15]

The air that flows over the collector is heated by the sunlight in the heating cycle, which captures the water content from the sample. The drying compartment is subsequently filled with warm, dry air, which eliminates the product's moisture.

There are several advantages to using a passive solar dryer over other methods of drying food or agricultural products. One of the biggest advantages is that passive solar dryers require no energy input other than sunlight, making them extremely energy efficient. Efficiency is generally in between 20-40% [16].

Additionally, the product's quality is kept and the chance of rotting is decreased because the drying process takes place at comparatively moderate temperatures. Other benefits of using passive solar dryers include its lower cost, Easy to build and maintain, portability, and its low environmental impact. It is important to note, however, that passive solar dryers can be less effective in certain climates, particularly those that are cloudy or have high humidity. Furthermore, in certain regions, the solar intensity is not high enough to dry the product effectively or some products has special requirements like temperature or humidity that cannot be achieved by a passive solar dryer alone.

2.3.6 Active type

Active dryer configuration, the heated drying air is generated with external source such as pumps or fans.

Fans and other mechanical devices powered by solar energy are utilized to circulate the flow of air through the drying compartment. Solar collectors transform solar energy into the power that runs the pumps or fans that move air through the drying compartment.

This faster airflow dries the product more quickly and eliminates moisture more swiftly. The air circulation system can be enhanced in order to speed up drying even further.

When the sunlight is not available, drying can be provided by an appropriate air heating system. The quality and preservation of the food can be improved with this kind of arrangement. Particularly in cloudy or humid climates, different studies have reported that the both efficiency and drying performance of active solar to be better than passive types[17]. The drying process is hastened and the product's quality is maintained because air is moved throughout the drying compartment. Additionally, more sophisticated sun tracking systems can be used by the active solar dryers to boost the solar radiation that the solar collector receives, leading to a faster drying process.

Active solar dryers also have the advantage of being applicable to a wider range of goods, including grains, meats, fruits and vegetables, and poultry. This is because the drying compartment's temperature and humidity can be carefully controlled, allowing for a more accurate drying of the product.

One of the main downsides to active solar dryers is that they are more complex and costly to build and maintain than passive solar dryers. They also require more maintenance, such as regular cleaning of the solar collector and the mechanical components of the dryer.

Active solar dryers can be applied in settings such as industrial, farming, and small-scale enterprises. They are best suited for more industrialized setups where more control over drying process and increased efficiency is needed.

2.4 Energy

The concepts of energy, entropy, and exergy are integral to the principles of thermodynamics, and their understanding is essential to a wide range of disciplines across science and engineering. These three ideas are connected and have a strong foundation in the basic rules of thermodynamics.

First law, which describes the conservatively of the energy states that energy is only allowed to change from. Creation and destruction of energy is not possible. This concept establishes as a fact that the universe's overall energy is a constant, and by adhering to this fundamental rule, it becomes possible to distinguish and relate different forms of energy.

Sir Isaac Newton is credited with pioneering the concept of energy in mechanics, introducing the ideas of kinetic and potential energy. However, the idea of energy wasn't established as an integrating concept in physics until the 19th century, and this development is regarded as one of the major scientific breakthroughs of the century.

Energy, as a scalar quantity, is a fundamental concept that cannot be directly perceived but can be indirectly measured and recorded. The determination of the absolute value of a system's energy can be challenging, however, the measurement of the change in energy is comparatively straightforward using indirect methods. The sophisticated applications and understanding of this concept of energy in physics and other related fields have led to significant advances in technology and the optimization of energy systems. It has played a crucial role in the advancement of science and technology, which is continuously being explored and understood by experts in different fields.

Energy studies and their implementation have made significant advancements in the past few decades, which has greatly contributed to the advancement and expansion of human civilization. The various manifestations of energy usage can be observed in daily life, nevertheless, the sun continues to be the planet's most plentiful and reliable source of energy. Studies and observations have established a clear correlation between energy and the structural properties of matter, and have identified various means through which energy can be released, such as chemical and atomic reactions.

Energy is a multifaceted concept that encompasses various forms, both internal and transient, which can be transformed from one form to another. Microscopic, macroscopic are the two broad classification of energy.

According to the macroscopic perspective on energy, a system's overall energy can be determined by comparing it to an outside reference frame. This perspective encompasses two distinct types of energy, namely potential and kinetic energy. An object’s speed and elevation as well as external forces including surface tension, magnetism, gravity, and electricity influence the macroscopic form of energy.

The whole microscopic energy that makes up a system is included in its internal energy, which is composed of complex states of energy and interconnections. It is not effected by any external reference point, system’s chemical composition or by environmental conditions.

Temperature, pressure, magnetic and electric field are among the parameters that can affect the system’s internal energy. The overall energy within a system remains constant regardless of the method or form of conversion. Though determining the absolute energy of a system can be a challenging task, the measurement of energy transfer or the change in energy within the system is relatively straightforward. However, the first law alone does not account for an essential aspect of thermodynamics: the direction of energy flow. For example, implication of heat transfer from direction of lower to higher temperature source is not possible without any external energy source in contrast to the opposite process which occurs naturally.

It is worth noting that not all forms of energy are completely convertible. There is a limit to the amount of energy that can be extracted from a system before it is converted into another form. In thermodynamics and classical physics, the concepts of equilibrium and stability are of paramount importance. However, in actual processes and cycles, fluctuations and instability are inevitable. This instability or irreversibility occurs when equilibrium is disrupted. To fully understand and explain natural phenomena and life cycle in nature, the fundamental concepts of entropy and exergy are crucial.

2.5 Entropy

Entropy is a metric for how molecularly disordered a system is. A system with high entropy indicates a high level of molecular chaos. It is a property that can only be generated by a system and cannot be destroyed. The transfer of energy across the boundaries of a system can increase or decrease the entropy of it. Internal energy changes through energy transfer.

it is always accompanied by either heat or work. Work requires the application of a force and incase of heat, finite temperature gradient. From hold to cold source, this occurs naturally. In simpler terms, heat energy can be understood as the kinetic energy associated with heated gas system, which is a result of the random motion of the gas molecules. At the quantum level, it can be challenging to define a reference point against which kinetic energy can be measured. Instead, in this scenario, energy availability is assessed through the concept of uncertainty, which can be further classified into ordered and disordered motion. The relationship between these two can also be derived.

The relationship between the probability of a system being in a given state and its entropy is a fundamental concept in thermodynamics. State transition occurs due to energy transfer, which is typically a transition from a state of lower to higher probability. Higher probability of disorganized states are the reasons behind this type of trend.

System's entropy, at a given state, is fixed and is determined by the probability of that state. It serves as a powerful tool for determining the degree of order required to explain the direction of energy transfer and conversion. Furthermore, it is crucial to understand that the natural tendency in thermodynamic systems is for the condition of the system to evolve from a state of higher order to one of lower order, a trend that entropy helps to describe. Entropy, as a measurement of order, have a vital implication in determining the natural direction of energy transfers and transformations in thermodynamic systems, and its application demands a sophisticated level of knowledge and expertise.

The concept of entropy allows for the evaluation of different energy sources on a thermodynamic scale. Energy forms with zero entropy, such as work, gravitational, or kinetic potential energy, are considered the most beneficial as they are the most efficient forms of energy. On the other hand, energy forms associated with high entropy, such as heat transmission, are less efficient.

Therefore, the conceptualization of the transmission of energy or conversion procedures should reduce entropy generation to ensure improved thermodynamic efficiency. This necessitates that the energy sources used have a similar entropy level.

Thermodynamics second law governs the direction of heat flow. It states that the overall entropy increases or remains the same after a process.

In an ideal or reversible process, the equality can be observed. The second law defines entropy as a measure of the uncertain energy in a random state that is not directly convertible to work. It also states that various physical and chemical processes eventually reach a state of maximum entropy, resulting in the conversion of energy to a less available form.

The second law of thermodynamics (SL), which is experimentally validated, is a fundamental tool for understanding thermodynamic processes. It allows for the definition and explanation of thermodynamic equilibrium states. In this regard, thermodynamic equilibrium is defined as the condition in which the system's relative entropy is at its maximum. Thus, in the absence of any external influence, it is impossible to increase or decrease the disorder within the system. Any changes to the system's state can only occur due to external factors. Therefore, in equilibrium, there can be no energy transfer without affecting the system's state.

An essential feature of the second law is that the generation of entropy will always be either positive or zero. This implies that any process will result in the production of entropy. A process must increase the entropy of both the system and its environment for it to occur. In another way to see, this indicates that the universe is moving towards disorder, moving closer to an equilibrium state that is characterized by the highest possible entropy in a hypothetical state of absolute energy.

There are a variety of mathematical formulations that encapsulate the second law of thermodynamics, however, the Clausius inequality provides a general explanation of entropy. According to this principle, the cyclic integral of heat transferred divided by the temperature at which it is transferred must be less than or equal to zero.

It highlights that the amount of heat transferred in any closed cycle is less than or equal to the amount of work done. This inequality encapsulates the fundamental concept of entropy and thermodynamic equilibrium and it's a fundamental tool for thermodynamic analysis and understanding.

It's worth mentioning that, in thermodynamics, thermodynamic cycle analysis, inequality is typically used to express the second law, which is the foundation for numerous applications across a wide range of scientific and technological disciplines. The second law's assertion, known as the Clausius inequality, is one that is frequently used in the subject of thermodynamics and other areas, and therefore, it requires a deep understanding of thermodynamics, mathematics, and thermodynamic cycle analysis to properly use and interpret it.

$$\oint (\delta Q/T) \leq 0$$

This term describes how a system generates entropy, which for reversible processes can be 0 and for irreversible processes can be more than zero. It can't, however, be less than zero.

2.6 Exergy

Exergy is derived based on the Greek word’s ex and ergon, which imply "from work." Exergy is a measurement of a system's maximal practicable work capacity at the point of balance with environment. When the temperature of system in the process becomes equal to the ambient temperature, the balance or equilibrium is considered to be achieved. This condition is the stable condition for any system. Systems that are not in a stable condition possess work potential that can be obtained in the form of mechanical or thermal work.

Exergy is a quantitative parameter, and its value can be determined by considering the equilibrium state of the system with the environment. It can be understood as the maximum possible output of shaft power from a system in a specific environment. Changes in surroundings also changes a system’s exergy.

Chemical composition, pressure and temperature are the main factors that characterize the environment. Exergy can be increased by inputting exergy, or in other words, by performing work on the system.

One fundamental difference between exergy and energy is the concept of destruction. Exergy is conserved in reversible processes, and external reversibility is also maintained. Any irreversibility present within the process or the environment results in the destruction of exergy. It's also worth mentioning that exergy concept is usually used in the field of thermodynamics, energy and power engineering, thermal systems analysis, and sustainability analysis.

Thermodynamic inefficiencies in various systems such as power plants, chemical plants, or any HVAC system can be viewed as exergy destruction, signifying the loss of potential work that could have been converted into useful work.

Exergy exchange is only possible between system and its environment through boundaries of the system. Exergy transfer is linked to different types of energy transfers. Exergy transfer can take place as either work or heat. Mechanical work represents the most common form of work transfer, while exergy transfer in the form of heat primarily pertains to heat transfer due to temperature differences.

It is essential to note that the system's exergy analysis is an effective tool for assessing how it performs and locating the causes of exergy degradation, and to develop the strategy to improve the system's performance and efficiency. The exergy analysis is widely used in many fields, such as power plants, chemical plants, and HVAC system, and it requires a thorough understanding of thermodynamics and thermodynamic systems to apply it correctly and to interpret the results correctly.

The system's most achievable work capacity when it is in equilibrium with the environment is measured by exergy. Among exergy's crucial attributes are:

1. At the equilibrium the exergy is zero, as state change is not initiated by anything.
2. Exergy increases as the deviation from equilibrium with the environment increases.
3. Exergy loss is closely tied to the quality of energy, as it represents the potential for useful work.
4. Exergy is defined by the conditions of the ambient environment and the current state of the process.
5. Exergy efficiencies can be used as an indicator of how close a system or process is to ideal or reversible conditions. It can be a powerful tool for evaluating system performance, identifying sources of exergy destruction, and developing strategies to improve system efficiency. Thus it has wide applicability.

2.6.1 Exergy efficiency

The efficiency is used to evaluate the utilization of energy. In conjunction with energy efficiency analysis, exergy efficiency calculations provide a comprehensive and powerful approach for assessing the performance of a given system, as well as for identifying and analyzing any inefficiencies that may be present due to violations of the second law.

The exergy balance of a thermodynamic system is a fundamental principle in thermodynamics that plays a critical role in performing exergy analysis on a system. As a system goes through a process, The difference between the quantity of energy transferred across system borders and the quantity of energy that is destroyed inside the system due to irreversibility determines the rate of change in exergy.

Exergy can only be introduced or removed from a system in two ways: as work or as heat. Heat is considered to be thermal in nature, while work is classified as mechanical work.

2.7 Energy Sources

2.7.1 Renewable Energy

With the development of technology and industry, energy usage has been rising every year. It is seen from the **figure 2** showing the industrial sector's global energy usage from 2006 to 2030. Given that, the world's energy resources are finite; this raises questions about the future generation's access to energy.

Utilizing the field of renewable energy is crucial and highly promising in this scenario. The potential for renewable energy is immense because of its abundance. It has the capacity to meet the demand for electricity around the world. Energy from a variety of sources, including solar, biomass, hydropower, wind, and geothermal, can be very sustainable.[18]

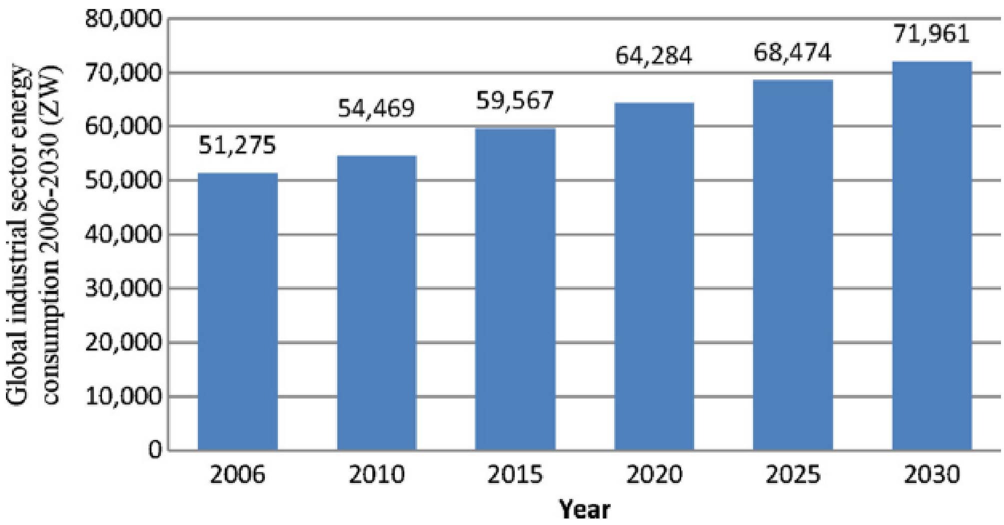


Figure 2: Energy Consumption in different sectors globally during 2006-2030

The cost of different systems, including as solar and wind, has considerably fallen over the last 30 years with greater technology progress, making the transition and adaptation to renewable every system more promising which encouraged the use of alternative energy. In the **figure 3**, the trend in energy usage through the years up to 2040 is depicted. Fossil fuels are being quickly replaced by renewable energy sources in industrial sectors due to price increases and environmental effects[19]. According to the chart, the utilization of renewable energy sources is steadily rising in comparison to other energy sources with a much faster increasing rate.

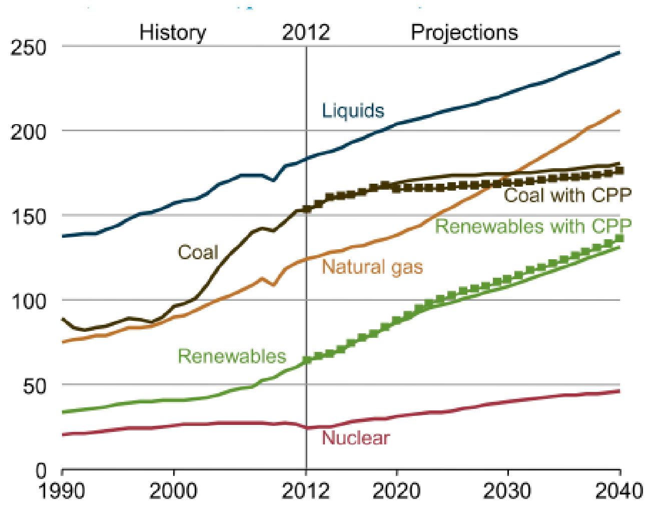


Figure 3 : Global energy usage by different energy source, 1990–2040 (quadrillion Btu)

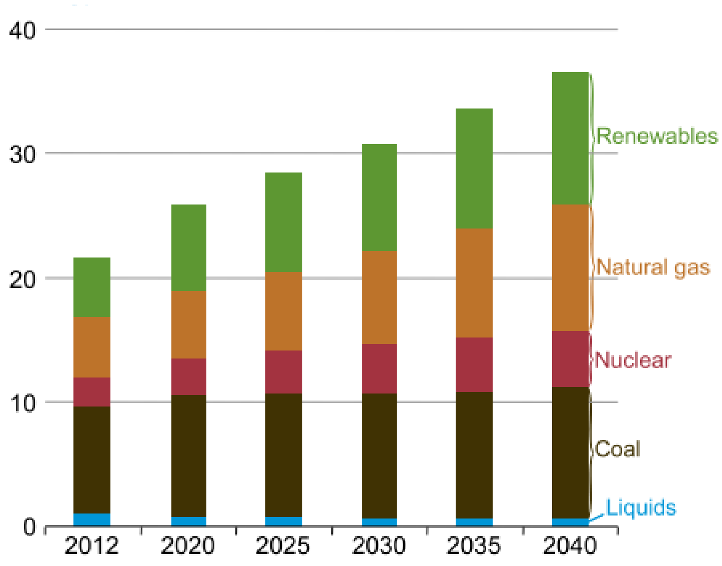


Figure 4: Total electricity general by different energy sources 2012-2040 (Trillion KWh)

Research on renewable energy and its potential for the future produced some very encouraging findings. According to a study done in 2022, renewable energy sources provided around 25% of the global energy consumption of 2021 [20]. According to researches, net electricity generation from renewable sources during the next 15 to 20 years will be increased up to 50% of the total demand. In addition to reducing carbon emissions and negative environmental effects, this will encourage industry to migrate to renewable energy-compatible technologies.

2.7.2 Solar Energy

Sustainable energy, such as solar energy, is produced by using the sun's energy. Solar panels employ photovoltaic cells to turn sunlight into electricity, which is subsequently used to power a variety of buildings, including houses, offices, and more. Solar energy has numerous advantages, including being clean and renewable because it doesn't produce hazardous substances like greenhouse gases. Solar energy may also be counted on to be a consistent energy source because the sun consistently shines somewhere in the world. Solar energy may be used for many different things in addition to producing electricity, like heating homes and water and powering cars. be put to use, such as for electricity production, building and water heating, and vehicle propulsion.

Sunlight provides the necessary energy for the living things in the earth. Sunlight, which carries this energy incidents in earth. When sunlight reaches the surface, some of it is absorbed and turned into heat energy. This raises the surface temperatures of the earth and radiates heat away from it. It is very interesting that this sunlight, which leaves as the radiation, has no exergy.

Thermal radiation from the heat of the sun that enters the Earth is emitted, leaving the planet with no net energy. At the elevated temperatures of the Earth's surface and atmosphere, this radiation is released. As a result, solar radiation carries energy that is delivered to the Earth, whereas nearly all of the energy that the Earth receives from the sun is ultimately discharged as heat back into space.

Currently, the production of electricity and heat are the two main industries using solar energy. According to predictions made by the International Energy Agency (IEA), solar energy will supply more than 45% of the world's energy needs by the year 2050.[19] Figure 5 shows how solar energy is becoming more and more common as technology develops, not just in industrial sectors but also in other fields. Particularly when compared to alternative technologies, solar cells are being preferred as an energy source more and more frequently.

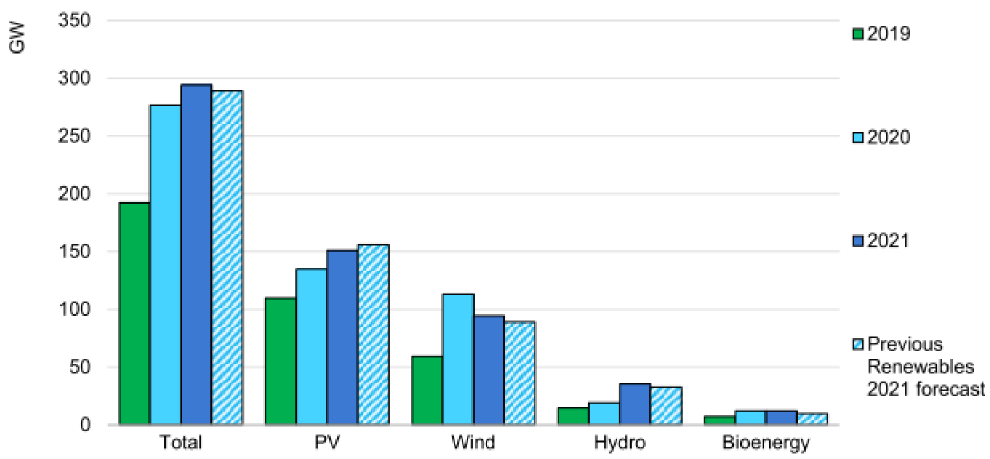


Figure 5: Renewable net capacity additions, 2019-2021

Solar thermal energy can be used as the alternative source of producing electricity, process heat and other type of heating requirements.

It can be used in household usages, in agricultural sector, along with different industrial applications with proper arrangements.

Figure 6 depicts the energy generation percentage of different renewable energy sources. Around 70% of the renewable energy capacity is generated by PV cells.

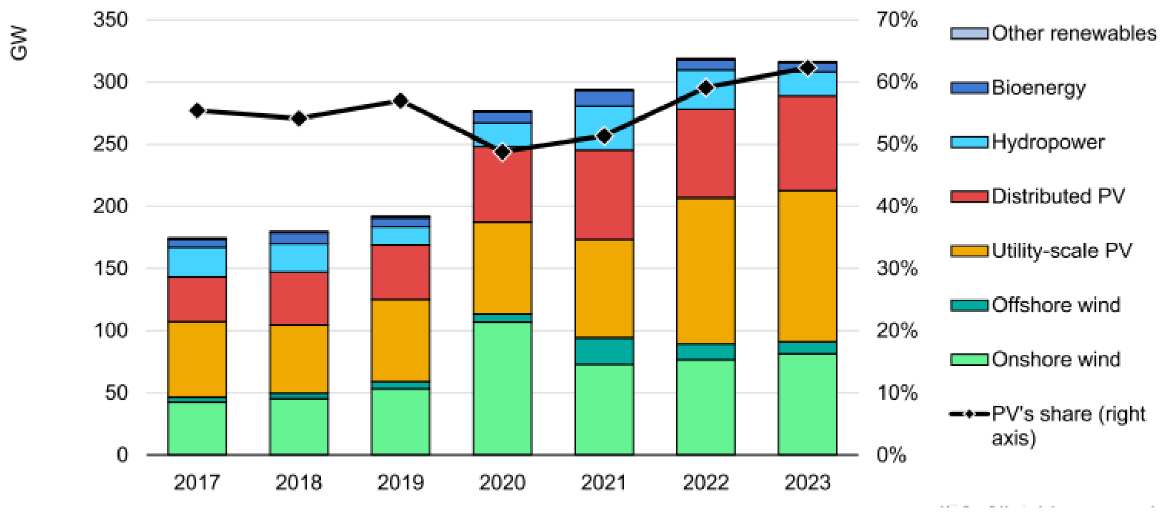


Figure 6: Renewable capacity additions by technology

Solar power has drawn a lot of attention as the most promising choice for industrial applications among all renewable energy sources. Solar energy stands out for its many benefits, which include being abundant and cost-free as well as being ecologically benign, and generating no noise or emissions. Solar power is also regarded as a clean form of energy.

To date, a number of initiatives have been made to use solar energy for industrial uses, utilizing innovations like solar power collectors, sun trackers, and big mirrors. Photovoltaic and solar thermal systems make up the majority of solar energy use in industry. The creation of hot water, steam, drying and dehydrating processes, concentration methods, pasteurization, sterilization, cleaning, washing, chemical reactions, commercial heating, and the support of industries like food, plastic, building, and textile, among others, are just a few of the many applications that fall under these categories. Even business-related problems can be resolved using solar energy.[21]

Considering the global shortage of energy resources and various harmful environmental effects, solar energy utilization has caught significant attentions engineering scientists over the last years. Developed countries such as China, United States, Japan, and Germany are trying to increase their energy production capacity from solar power each year. **Figure 7,** shows the solar energy capacity increment for top 10 countries in the world.

Research into more efficient and less expensive ways to collect, store, and convert solar energy into usable energy should be intensively pursued.. [19]

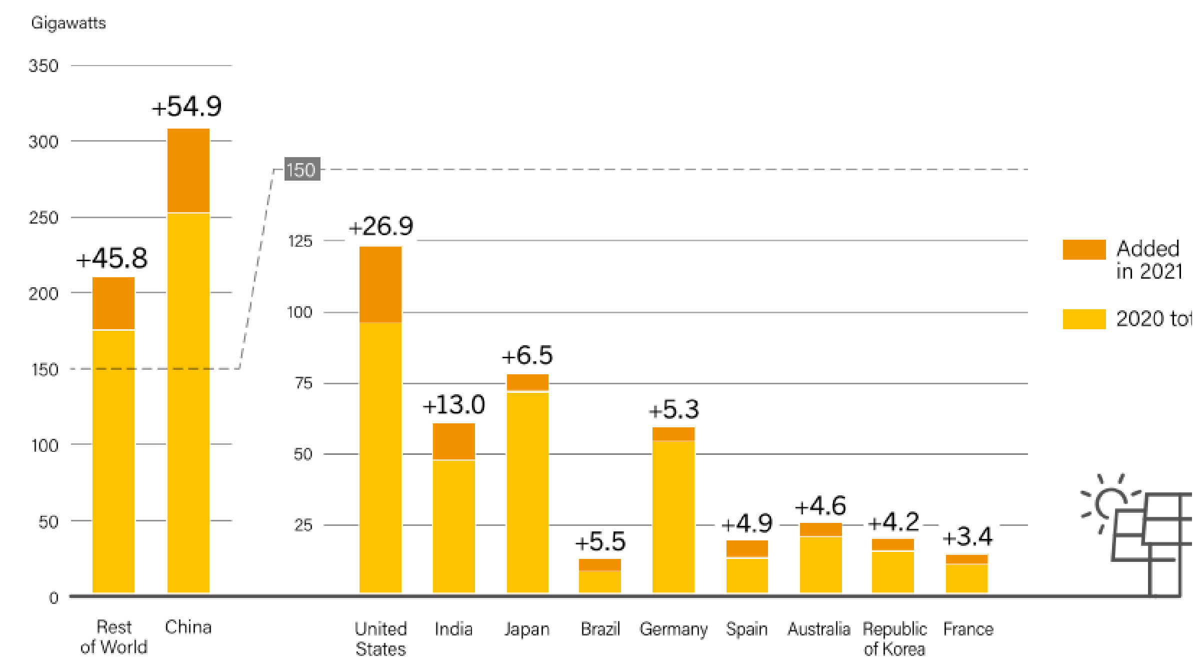


Figure 7: Solar PV Capacity and Additions, Top 10 Countries for Capacity Added, 2021

The term "solar thermal" describes the process of turning solar radiation into heat energy. It is regarded as the renewable energy source that is most commercially practical. In homes, businesses, or industrial scenarios, solar thermal systems typically entail the harvest of solar energy, its preservation, and later use for heating air or water. These systems are made to effectively capture solar energy for a variety of uses..[22]

Globally, industrial operations use solar heat from more than 791 MW of solar thermal capacity.

2.7.3 Biomass Energy

Organic substances that can be used as an energy source is referred as biomass such as agricultural crops, garbage or municipal and industrial wastes and most importantly woods. Heat generates when these substances are burned. Thus, they work as source of energy. When burned they turn into ethanol or biodiesel. In general, they are called as biofuels, which are used for power generation. **Figure 8** shows the energy production flow chart from biomass source.

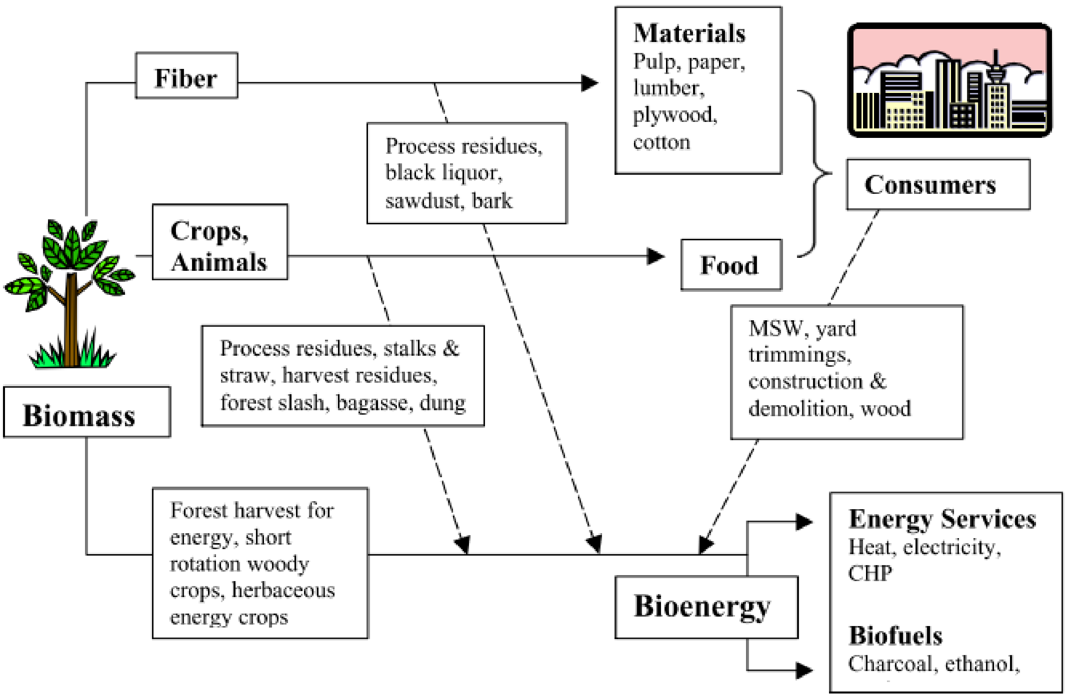


Figure 8: Energy production flow chart from biomass source

It has been estimated that primary energy source of present world such as natural gas, fossil fuels, coal, etc. will last for only next 40-50 years. So alternative energy source and efficiency of present power producing systems are of great importance these days. At the same time climate, change is always a threat and global warming rises huge concern to the present power and technology industries. [23] However, renewable energy sources with less environment effects solves both the problems. Biomass is really one of that renewable energy source which can come in top in both the aspects. Thus can help in the goal of reducing carbon emission by 80% over the future years. [24], [25]. This indicates significant possibilities of obtaining worldwide Kyoto protocol, which refers to reducing harmful gas emissions such as most greenhouse gases. This would help climate in the end. [26]

Availability of biomass energy is a very important feature for the sustainability of technologies related to power generation from this source. According to world's forest report china has the largest source of wood as biomass energy[27]. Global distribution of forest and percentage has been presented in the **figure 9**.

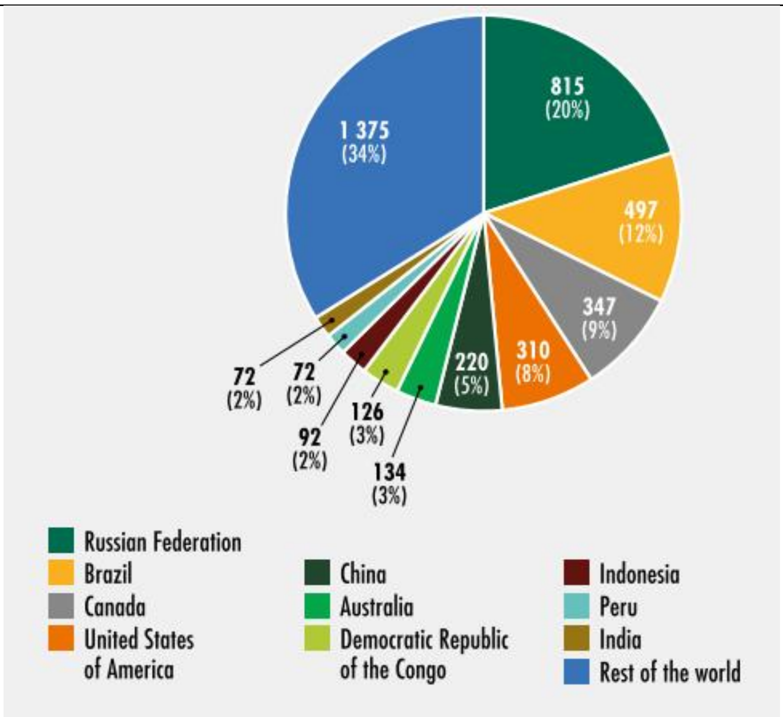


Figure 9: Global Distributions of Biomass (Forest Wood)

Bases on current studies, biomass has the potential to meet the energy demand of most developed and underdeveloped countries.[28][29]. Main conversion of bioenergy as electricity or heat satisfies 14% of the World's basic energy need besides with 75% of the usage is in developing countries, with only about 25% occurring in industrialized nations. [30] . Power generation from biomass will increase in the future as predicted by many studies. **Table 1**, presented below shows global energy production projection from biomass in the future.

Table 1: Global Energy Production from Biomass

Source	Time frame (Year)	Total projected global energy demand (EJ/year)	Contribution of biomass to energy demand, EJ/year (% of total)	Remarks
IPCC (1996)	2050 2100	560 710	180 (32%) 325 (46 %)	Biomass intensive energy system development
Shell (1994)	2060	1500 900	220 (15%) 200 (22%)	- Sustained growth* - Dematerialization+
WEC (1994)	2050 2100	671-1057 895-1880	94 - 157 (14 -15 %) 132 - 215 (15-11 %)	Range given reflects the outcome of three scenarios
Greenpeace (1993)	2050 2100	610 986	114 (19 %) 181 (18 %)	Fossil fuels are phased out during the 21st century

The potential, performance, and restrictions of biomass as the main source of energy have been thoroughly investigated. Pyrolysis, gasification, and combustion are the three basic methods through which biomass can be transformed into energy. Each procedure uses a unique technique to convert biomass into heat or power. [31] These conversion lead to chemicals, heat, electricity, transport fuels.

Some of the experiments and research projects that have been conducted in this area include:

1. Testing different feed stocks for biofuel production: Researchers have experimented with using a wide range of materials as feed stocks for biofuel production, including corn, soybeans, wheat, and even algae. These experiments have helped to identify the most promising materials for biofuel production, and to develop more efficient methods for converting these feed stocks into biofuels.

2. The technique of gasification, which may be used to turn biomass into gaseous fuel that can be utilized to produce power, is being looked into. Experiments have been carried out by researchers to investigate the possibility of biomass gasification as a source of clean, renewable energy.

3. Technological advancement to direct conversion of biomass into energy source: Researchers have been working on developing new technologies that will have capabilities of more efficient energy conversion from biomass, such as biofuels or electricity. This includes efforts to develop new enzymes and microbes that can break down biomass more efficiently, as well as new processes of effective and efficient conversion.

4. Overall, the experiments and research projects that have been conducted on biomass have helped to identify the most promising uses for this renewable energy source, and to develop new technologies and processes for harnessing its potential.

In this study the for the biomass source wood has been used and its performance such as efficiency and change in drying rate has been analyzed. The future of the world's energy supply is likely to be shaped significantly by the advancements in biomass energy. Environmental effect of combustion of fossil fuels is a huge concern rather than the scarcity of fossil fuels, as new reserves of oil and gas have been found and there is still a significant amount of coal resources. Biomass energy is considered a promising source for the 21st century in many parts of the world, because it is carbon neutral when produced sustainably and it can be found in relatively even geographic distribution. Additionally, as the energy demand in developing nations is expected to increase and affordable alternatives are often not available, biomass energy may play an important role in meeting that demand.

2.8 Recent works on Solar Dryers

Solar drying technology has been developed and improved over the past decade as a means of preserving food, particularly in areas where traditional drying methods may not be possible or practical. Reducing the energy needed to dry food and making the process less hazardous to the environment are two of the key objectives of solar drying technology. There have been several advancements in solar drying technologies in the past few decades, including the usage of better solar dryer designs and more effective solar collectors.

One of the main advancements in solar drying technology over the past decade has been the development of more efficient solar collectors. These collectors are designed to capture as much solar energy as possible, and to convert it into heat that can be used to dry food. There have also been improvements in the materials used to construct solar collectors, with many newer designs using materials that are more durable and able to withstand extreme temperatures.

To examine the effectiveness of the direct drying capacity of solar dryers, a study was done on the drying performance of cabbage with the help of solar energy. [32]. Product samples were prepared by taking single slices and they were put on the trays to investigate effect of solar drying rate. After the study it was found out that solid content on those products were higher compared to protein, fat etc. Drying rate and the final condition also depended on the product packaging system. Low and high-density polyethene bag was used for packaging and products were divided in single layer and double layer. Study indicated that double layer with low density polythene wrapping had lower moisture. All the products appeared as acceptable after organoleptic testing by the panelists using 1-9 hedonic scale. The quality indicated storage capability of about 3 months. The Drying time was very long however, there was no analysis regarding the temperature and the drying rete as there were no system to control the temperature.

The limitation of natural solar drying was investigated in a hybrid dryer with integrated biomass burner made of local available materials. [33] Some of the limitation such as the exposure to drying, dependency on the solar intensity, pests and rodents liabilities and overall economic feasibility of mechanical dryers were considered. The construction was simple with a solar

collector along with drying compartment and airflow system. The alternative heating section was there to provide when sunlight was not enough to get desired temperature.
A solar collector area of 3.77 m^2 was required for a food sample of 100kg maize grains. Ambient condition such as outside temperature of 26ºC and with relative humidity of 72% was considered which lead to drying time of 6 hours with natural convection. The moisture content reduction was from 21% to finally 13%. Experimental setup with 0.6 m^2 collector area was constructed. Forced convection with air velocity of 2.2 set up. Analysis showed the energy efficiency of the solar and hybrid dryers were about 39.9% and 57.7% respectively.

Alternative energy storage such as thermal incorporated with the solar dryers for drying of vegetables and foods resulted in better product quality. [34] Cost durability, efficiency and performance were considered while designing the dryers. In addition, the overall performance was analysis after taking various different parameters such as air velocity, collector efficiency, air temperature, moisture removed content etc. The drying time reduced significantly in this set up in comparisons with conventional methods.

Experimental study on a hybrid photovoltaic-thermal roof integrated solar dryer was conducted in the climate condition of New Delhi, India. [35] In both the forced and natural convection modes of operation, the thermal modeling received experimental validation. The effects of flow rate and packing factor were taken into account as various performance measures, such as total energy effectiveness, thermal performance, solar cell performance, and overall thermal efficiency, were evaluated. It was observed that the thermal energy decreased but the electrical energy grew when the packing factor rose. It was established that the equivalent magnitudes were 76.39% and 88.73%, respectively.

An experimental comparison between natural and forced convective solar dyer indicated much better performance in case of natural convection. [36] The study was conducted on various foods and vegetables in order to reduce moisture content and preservation. The performance of the solar dryer with different food product and different operating condition was presented was well. For comparison reduction of moisture content and weight were considered.

New solar greenhouse drying system was modeled and evaluated for the drying of red peppers. [37]. Hybrid drying mode with flat plate solar collector along air with greenhouse was constructed after simulation of and development of mathematical model with TRNSYS software in order to forecast the drying kinetics. Performance of the solar collector was analyzed experimentally and the efficiencies was found to be in between 0.5 and 0.65. Optimal area of product, airflow of exhaust and collector area were obtained from the simulation to be 40 m^2, 250 Kg/h and 2 m^2 respectively.

A hybrid photovoltaic solar dryer was constructed in order to investigate the performance in comparison to open sun drying in the climate of Yola, Nigeria. [38]. The performance was studied with tomato as food samples. Temperature of maximum 62ºC and 54ºC was recorded in the two different operation condition hybrid and only solar power respectively. The drying time was observed to be affected in different operating condition considering same moisture removal. For the hybrid drying mode and the solar drying mode, it was found that it would take 6 hours and 9 hours, respectively, to decrease the amount of water from 94% to 10% on a wet basis. The hybrid dryer's average rate of drying and efficiency was calculated as 0.0800 Kg/h and 71%, and the solar-energy dryer's average drying rate and efficiency were 0.0578 Kg/h and 65%, respectively. It was found that the hybrid drying mode produced better results than the solar drying method when assessing the nutritional value of the food product, notably tomato slices. From the study, it was clear that hybrid solar dryers are very promising in case of food preservation and storage especially for different vegetables and foods. The performance and effectiveness were very promising in case of increasing sustainable production and food security.

Solar photovoltaic system and flat plate solar collectors were used in order to increase the performance of a hybrid solar tunnel dryer. [39]. Features such as portability, direct and indirect mode of operation was incorporated in the dryer. Forced convection mode was obtained with a PV powered DC axial fan. Mint was taken as food product to dry and analyze. Thermal curtain was provided to block direct solar radiation. Performance of two operation mood; solar tunnel and open sun drying was evaluated with three typed of product samples such as single, double and three layer of mint. Experimental moisture content of the leaves was compared with the analytical data of the solar tunnel dryer with different models of thin-layer drying. The drying time was recorded to be from 210 to 360 min for developed layers and 270 to 420 min for solar drying. Dryer and PV efficiency was found to be 30.71% and 9.38% respectively whereas the overall efficiency was about 16.32%. The energy usage of the combined dryer was also looked at in terms of its effects on the environment. According to the study, the dryer's energy payback period was about 2.06 years, which is the amount of time needed to make up for the energy wasted during operation. Additionally, a considerable reduction of 31.80 tons of net carbon dioxide (CO_2) emissions was made over the dryer's lifetime.

In terms of the quality of the product, it was found that using a black heat barrier to exclude solar radiation led to better products.

Drying performance of solar dryer with integrated paraffin wax based thermal storage was investigated with the sliced black turmeric. [12]. In order to improve performance, the dryer was designed with a hybrid mode of operation that combines forced convection. The purpose of the study was to contrast the solar dryer's drying kinetics with the conventional method of open-air sun drying. Two samples of black turmeric, 200g each, were carefully chosen for this use. The direct sun drying method was used on one sample, and the solar dryer was used on the other. The investigation's main goal was to thoroughly compare the solar dryer's thin layer drying process of sliced black turmeric to the more traditional open sun drying method. The moisture content reduced from 73.4% to 8.5% on wet basis in solar dryer during 18.5 hours, which was about 46.5 hours in sun drying. The results showed that simulation with ten thin layer were very close to the experimental findings whereas two-term model and page model were more effective in perception of the drying kinetics of the product in solar dryer and in open sun drying respectively. Efficiency was calculated for both of the drying arrangement along with food quality testing. Efficiency was about 25.6% and 12% respectively for overall solar air heater and solar dryer.

The comparison of different types of solar dryers based on their main components, different operating parameters and classifications were presented in a review study.[15] Advantages-disadvantages along with other limitations associated with different operating modes based on airflow system; natural or forced convection, heat transfer; direct or indirect and drying compartment construction were discussed. Cost effectiveness, sustainability and eco friendliness of these different types of dryers were estimated based on economic and environmental analysis. Various indicating parameters such as payback period and carbon dioxide recitation amount were determined.

Performance of open sun and indirect solar dryer were investigated in a study taking grapes as product and observing its drying rate and quality in both of the operation configuration.[40] Ambien conditions were taken in accordance with the climate of Morocco where the experimental study was conducted. Heat supply from the water storage tank ensured appropriate temperature at the drying compartment during off shine hours. Results shown significant reduction on the drying time required in order to obtain same moisture content removal in case of indirect solar dryer. For removal of 79.8% (w.b.) to 20.2% (w.b.) moisture the required time were 120 hours and 201 hours for indirect and open sun dryer respectively. In addition to this effective moisture, diffusivity of the product was also estimated for both of the operating modes.

The limitations and constructional details were presented in a review study on currently existing different types of solar dryers in order to guide and provide resources for betterment in the future.[41] There were many disadvantages of open sun drying. Continuous researches have improved the drying technology significantly. However, search for more effective and efficient solar dryer still is very promising. Many recent research statuses were presented and future scopes in this renewable energy sector were discussed so that more advanced and sustainable technology can be achieved in the days to come.

Two types of solar dryers were developed and their performance were evaluated in order to investigate alternative source of solar thermal energy. [42]. In the study energy source such as wood was analyzed as potential source of alternative energy source, which can be used to dry crops, food samples, vegetables and spices. In the study post-harvest food preservation condition in Bangladesh was described as well as various limitations were pointed out such as; exposure to rain and dust, inappropriate drying rate, insect attacks, direct solar drying etc. Due to these, a significant amount of food source is lost per year according to different studies. In the study, Bangladesh climate conditions were taken as ambient parameters and performance of the two type dryer; low cost solar dryer for low production and high production were evaluated. Different food products such as vegetables, fishes, fruits, medicinal plants were dried. Efficiency and drying rete performance of the solar driers was observed to be more in comparison to open sun drying. In addition, the product quality was better.

The drying kinetics and overall performance of indirect solar dryer coherent with inlet fan powered by PV panels was evaluated using green chili and okra were used as food product[43]. Inlet fan ensured forced convection. Results showed that moisture content reduction was from initial 8.3984 to final 0.01001kg/kg of dry basis for green chili. For the okra, it was about from 10.1234 to 0.12675 kg/kg of dry basis. The performance of solar dyers was better in comparison with traditional types of dryers. From the analysis, solar collector and overall drying efficacy were about 74.13, 9.15% and 78.30, 26.06%, respectively for green chili and okra drying.

Performance of an indirect solar dryer as meteorological environment of Himalayas were evaluated in an experimental study.[44] Forced convection along with coherent heat storage material and phase change material were the key feature of the set up. The solar collector and absorber plate were integrated with copper tube with automotive engine oil and mixture of iron scrap and gravel respectively. The drying compartment was modified with paraffin RT-42. Performance analysis of the drying of Valeriana Jatamansi(product) showed moisture removal of from 89% to 9% in the final product. The dryer rate was also much better with heat storage system and modified drying compartment arrangement in comparison with no storage and traditional drying configuration. The required time was recorded to be around 120 hours in modified dryer whereas for no storage and traditional system it was about 216 hours and 336 hours respectively. Exergy and energy efficiency were reported to be 0.14% and 9.8%, 0.81%. and 26.10% respectively for dryer without modifications and with modifications.

Renewable, sustainable, most effective and efficient solar drying technologies for food preservation in Asian and Sub-Saharan African Countries was investigated. [16]. The study reported various types of solar dryers that were used before and present day technologies in those countries. Different factors of these technologies such as food quality, social, economic and environmental impact were observed and analyzed. The study also reported the effectiveness of these drying technologies in these areas based on the financial and infrastructural aspects.

In an experimental study, double pass indirect solar dryers with and without mesh absorber were designed, developed and then evaluated in order to improve the thermal efficiency of the solar air collector with incorporation of iron meshes[45]. CFD analysis of both of the system and drying compartment was carried out. In the experiment, Pepino fruit samples was used. The performance of the solar collector was found to be improved in case of mesh modification both in simulation and in experimental analysis. Two important features of dryers; average efficiency and final product quality (antioxidant activity, TFC and TPC) were improved in case of meshed modification. Highest average efficiency was recorded about 23.08%. Experimental set up was developed according to most used mathematical models.

A case study was conducted to observe the effect of both traditional and improved solar dryer on quality and nutrition content of the final product such as mangoes and pineapples[46]. Five different operation mode of solar dryer; conventional solar dryers, open sun dryers, while-cloth shade dryer, black-cloth shade dryer and improved dryer were considered in the study. Solar concentrator for improved system was constructed with metallic solar collectors arranged in series. Inlet air temperature of the drying compartment was 26.8, 26.7, 24.5, 32.6 and 40.3 °C respectively. Best on the results it was observed that the quality of the final product and its nutrition content were better and higher in case of improved system compared with other drying modes. Comparison of the improved solar dryer with other traditional dryers were discussed and future scopes were stated.

The performance of indirect solar dryers and its drying kinetics were evaluated using watermelon and apple as the product[47]. For both types of samples, the experimental investigation included the measurement of a number of metrics, such as the surface's activation energy, diffusion coefficient, and heat transfer coefficient. Through examination, it was determined that the thermal effectiveness and collector efficiency for the apple and watermelon samples, respectively, were roughly 54.5% and 25.39% and 56.3% and 28.76%.

It was noted that changes in solar intensity caused temperature oscillations inside the drying chamber. For apples, the mass transfer coefficient varied from 1.58$\times 10^{-4}$ to 3.15$\times 10^{-4}$ m/s while for watermelons, it was between 5.17$\times 10^{-4}$ and 4.98$\times 10^{-4}$ m/s. In addition, it was found that the heat transfer coefficient for apples varied from 0.16 to 3.19 W/m2K and for watermelons from 0.52 to 5.04 W/m^2k

Experimental study was carried out in order to investigate the performance and effect of mass flow rate on efficiencies of indirect solar dryer with porous heat storage arrangement in Coimbatore climate condition for bitter gourd slices drying.[48] Environmental and impact assessments were used to evaluate the dryer's efficiency and sustainability. The mass of the product was seen to decline from 4000 g to 723 g throughout the course of a 7-hour process at an average flow rate of 0.0636 kg/s. For mass flow rates between 0.0141 and 0.0872 kg/s, it was discovered that the dryer's energy efficiency varied from 28.74% to 40.67%. Calculations, however, showed that when the air mass flow rate rose, the air's pickup efficiency fell from 54.29% to 17.18%. Moisture diffusivity estimation showed that for the sun drying it was the lowest. Energy payback period were estimated to be around 2.21 years along with CO_2 mitigation parameters were determined from environmental impact analysis.

The performance of indirect and mixed mode of solar dryer in climate condition of Algeria were investigated and comparisons were provided to demonstrate a better understanding.[49] Potatoes were taken as the product samples. The drying time was recorded to be 4 hour 45min and 3 hour 40min respectively for mixed and indirect operating configuration despite the drying compartment temperature being higher for mixed mode of operation. Several theoretical models were developed and they were validated based on relative accuracy with the experimental data. Moisture diffusivity was also investigated along with drying process of different vegetables, fruits etc. in different operating configuration. Obtained results were reported.

Performance and features of different types of indirect solar dyers were investigates and a comparisons between conventional types of indirect solar dyers were presented.[50] Effect of different modification in order to improve the heat transfer are also discussed along with the effectiveness of pre-treatment. Effect of different parameters such as; solar intensity, inlet air velocity and temperature, types and product weight in addition to moisture content on the overall drying performance of the solar studied and results were presented. Comparison between active and passive solar dryers were provided along with different environmental analysis such as energy payback period were discussed in addition to cost effectiveness.

A very in detailed study was conducted in order to provide design concept, challenges, advantages and disadvantages of modern solar dryers.[51] Considering various factors, this study presented a comprehensive discussion on different types of solar dryers, their constructions and features along with wide scopes of applications for various foods. The study also reflected on the effectiveness, enhancement and limitations in recent solar drying technology based on environmental and economic feasibility study in addition with sustainability in order to encourage further improvement in this sector.

The effectiveness and performance on drying rate of a forced convection solar dryer with paraffin integrated solar collector as phase changing material (PCM) was investigated to enhance the drying capability without sunlight.[52]. For sliced potatoes as the product, different drying parameters such as moisture ratio, amount of moisture removed, and removal rate along with inlet air temperature were recorded for two operating condition; solar dryer with and without PCM. Airflow rate for forced convection was maintained at 0.065 kg/s and drying time was between 10.00 a.m. to 7.00 p.m. Based on the parameters performance was evaluated for two modes of operations. Influence of PCM on the overall drying capacity was investigated. The results showed that incorporation of PCM increased the drying compartment temperature significantly in addition to the increase of moisture content removed. Usage of paraffin improved moisture removal about 5.1%

Experimental study was performed on solar dryers incorporated with thermal storage capability in order to mitigate the limitations of off sunshine hours. [53]. The objective of the study was to develop and evaluate the performance of solar dryer with continuous drying capability. There were three system of storage; sensible heat, latent heat and combination of both of them. Effect of different operating conditions such as different storage systems, types of materials used, and solar dryer types such as direct or indirect was investigated both in natural and for convection flow. Results were shown in order to make clear understanding of different parameters and operating conditions. Thermal storage implementation limitations, future scopes and different recommendations were provided in order to enhance its performance more in the future.

Chapter 3: Description of the Model

3.1 Overview

In the present investigation, a novel solar biomass hybrid dryer was engineered and its efficaciousness was comprehensively evaluated through a series of experiments aimed at assessing its drying capabilities. The selected test material for these experiments was the leafy green vegetable, cabbage, which was chosen for its widespread cultivation and its notable nutritional value, specifically for its high content of vitamins C and E. The outcomes of the study give information about potential applications and effectiveness of this hybrid dryer in reducing losses incurred after harvest perishable farming products and improving the preservation of nutritional value in dried foods.

3.2 Description of set up

The dryer's dehydrating chamber is a semi-circular tunnel covered with transparent polythene sheet. The dryer's components include a dehydrating chamber, solar heating compartment, biomass heating component, solar PV driven axial fan component, and exhaust compartment. The functional components of the dryer are shown in the **figure 10** and are described briefly in the following sub-sections.

Figure 10: Solar-Biomass Hybrid Dryer

3.2.1 Drying Compartment

The 4-meter-long drying chamber of the solar biomass dryer was its main component. Two parts, each measuring 2 meters in length, made up this drying chamber. The drying chamber had a semi-circular tunnel shape and was 0.76 meters in width. Galvanized iron sheets were used to build the drying chamber's floor, which was then painted black to improve heat absorption. A translucent polyethylene cover was placed on top of the container for drying, allowing sunlight to enter the space.

3.2.2 Solar Heating Compartment

A two-meter-long section near the air entry end of the drying compartment was left blank and painted in black to allow absorbing sunlight. The sunlight enters the drying compartment through transparent polythene sheet. Hence the black surface generates radiated heat to make air hot inside the chamber.

3.2.3 Biomass Heating Compartment

Biomass was used as an alternative energy to raise the temperature of the drying air. It is just a heat exchanger made of mild steel pipe to a perpendicular direction of the flue gas. The ambient air heats up from the pipe surface and flows through the drying compartment.

3.2.4 Air Supply System

The existing 5-watt direct current fan was replaced with a 10-watt DC fan to enhance the air supply through the drying compartment, hence increased the drying capacity per time. An additional 50-watt PV module was added in parallel connection to the existing one to ensure optimum power supply to the new fan. As the power supply system was increased to 100-watt solar PV, there is some surplus in electricity generation when there is proper sunshine. A 12-volt 30 ampere hour battery was installed in parallel connection to PV module to store surplus electricity The fan was powered by solar photovoltaic module directly when the sunshine produced sufficient electricity and the battery provided backup power when the sunshine is not enough to run the fan.

3.2.5 Exhaust Component

An exhaust component with a chimney attachment was at the tail end of the chamber. The moist air exhausted the environment through the chimney.

3.2.6 Baffle

At the precise intersection of the solar-powered heating compartment and the drying compartment, a baffle was built in the upper area of the drying compartment. The purpose of installing this baffle was to enable a steady, consistent airflow across the goods being dried.

3.2.7 Vegetable sample used in the experiment

To assess the effectiveness of the dryer, cabbage was selected as the test material. Cabbage is a green or purple plant that is cultivated for its dense crowns of leaves, which are harvested as a vegetable crop. It is an important source of vitamins C and E, and its consumption is considered a daily necessity. A significant amount of vegetables is wasted because of seasonal surplus, poor post-harvest management, shipping, preservation and lack of food processing facilities. The test was conducted using fresh cabbage.

3.3 Experimental layout:

3.3.1 Drying load:

Freshly harvested cabbage was chopped into 1cm (about 0.39 in) x 4 cm (about 1.57 in) pieces. The chopped cabbage was loaded in the drying compartment with three different loads of 4 kg, 8 kg, 12kg. Each load of cabbage was dried by blowing hot air through the drying compartment. The sliced cabbage was spread on perforated plastic tray. After that, the trays were placed in the drying compartment. In the Drying compartment we used 12 trays for 4 kg sample, 16 trays for 8 kg sample and 220 trays for 1 kg sample. For loads of 4 kg, 8 kg, and 12 kg, the mass density in the drying compartment is 2.5 Kg/m^2, 3.7 Kg/m^2, and 4.44 Kg/m^2, respectively.

3.3.2 Energy sources for the hot air

The air was heated from three different sources of energy: sunlight heating, biomass heating and combination of sunlight and biomass heating.

Sunlight: It is one of three energy sources used in the study. In this case, the dryer tunnel was covered with transparent polythene sheet. Here sunlight generate radiated heat on the black surface and heat up the cabbage sample directly.

Biomass heating: In this case, the dryer tunnel was covered with black opaque polythene sheet to resist the sunlight. The air gets heat up while passing through the heat exchanger.

Combination of sunlight and biomass heating: In this case, the dryer tunnel was covered with transparent polythene sheet. The air gets heat up from both sunlight and biomass heat exchanger.

3.3.3 Relatively humidity

Ambient air relative humidity (RH) was recorded using a digital hygrometer at energy 30 minutes Figure. Also, the RH of dryer exhaust was recorded using the same hygrometer at same interval.

3.3.4 Moisture content of cabbage sample

Cabbage sample moisture content was found by gravimetric method using a hot air type oven. The sample was dehydrated in oven at 120 degrees Celsius for twenty-four hours. The cabbage sample was taken from the dryer at one hour interval.

$$Moisture\ Content(\%) = \frac{W_2 - W_3}{W_3 - W_1} \times 100$$

Here,

W_1 = Empty crucible weight.

W_2 = Crucible weight containing sample.

W_3 = Crucible weight containing dehydrated sample.

3.3.5 Solar irradiance

Solar irradiance was measured while drying process was going on. A pyrometer model Hukseflux LI-19 was used for logging the irradiance data (figure). The data was downloaded on computer every day after stopping the drying process. The logger recorded the data in watt per m^2 unit.

3.3.6 Drying rate:

Rate of dehydration the cabbage was computed utilizing the equations stated next

$$Drying\ rate(gram\ moisture\ removed\ per\ hour) = \frac{Amount\ of\ moisture\ remove(g)}{Total\ time}$$

3.4 Modification of the Set up

There are some limitations of traditional hybrid dryers such using the alternative power source always adds extra cost. Using wood as the biomass energy source incorporate some dangers as well. CO_2 is produced from the incomplete biomass burning and it has negative impact on the environment. In most of the hybrid dryers with biomass as the alternative source heating compartment is constructed outside the bed which is open to the environment. It imposes risk of damage or causing fire in lack of caution.

Also in the rural areas biomass may be available but to make this technology more effective and at the same time affordable and integrated with industrial technologies such as automatic control more precise control of the drying process is required.

With this in view, a modified hybrid dryer with resistive heating as the alternative energy source has been developed and its performance will be evaluated with same product type and load capacity to understand the difference in performance in details. This modification also includes the economic justification for initial set up cost over long-term use and performance in preserving better food quality.

Changes in set up: Biomass heating compartment will be replaced by resistive heating element to ensure continuous drying.

3.4.1 Construction Details

There are three major components in this arrangement; heating coil, insulated case and axial fan. Design of the setup is illustrated on the **figure 11.**

3.4.2 Heating Coil:

Nichrome heating wire, made up of 80% nickel and 20% chromium, is a highly dependable and versatile heating element, due to its strong electrical resistance, resistance to oxidation and corrosion. This wire is commonly used in many applications because of its effectiveness and efficiency, which is a result of its high electrical resistance. This feature makes it suitable for both residential and industrial applications. Additionally, it offers precise temperature control and safeguards against overheating.

The exceptional resistance to oxidation and corrosion exhibited by nichrome heating wire makes it an ideal choice for high-temperature environments and situations where the heating element is likely to be exposed to corrosive agents such as moisture. This remarkable attribute assures the longevity of the heating component, thereby eliminating the need for frequent replacements and providing a sophisticated solution for various heating needs. The configuration was chosen based on various reports and studies to ensure better heat transfer.

3.4.3 Stainless Steel Case:

The utilization of food grade stainless steel in the food industry is of paramount importance as it guarantees the preservation of the safety and integrity of food items. This material was specifically chosen for its remarkable durability, ease of cleaning and suitability for contact with food products. Made from alloys that are non-toxic, non-reactive and non-absorbent, and containing minimal traces of impurities such as lead, copper, and nickel, it is widely acknowledged as a sophisticated material for various food processing and packaging applications. The inherent hygienic and safe characteristics of food grade stainless steel make it an ideal material for ensuring the purity and wholesomeness of food items.

The use of food grade stainless steel in the food industry is not only essential for preserving the safety and integrity of food items, but also notable for its exceptional durability, making it suitable for long time usage and applications in an environment with high temperatures. Additionally, its ease of cleaning and sterilization further enhances its value, as it minimizes the risk of food product contamination. Furthermore, its resistance to rust and corrosion not only maintains its aesthetic appeal but also guarantees the preservation of the quality of the food. All of these features make it a sophisticated material for various food processing and packaging applications that demand the highest level of hygiene and safety.

3.4.4 Axial fan

The utilization of a fan in the drying system makes the drying quality better and significantly diminishes the drying time. The fan is crucial in ensuring precise temperature control through precise airflow management. Moreover, the incorporation of a solar cell panel to power the fan makes it an environmentally friendly and sustainable technology.

The application of forced convection in the drying system is a notable advancement, drying time can be diminished to half by it comparing to that of the natural convection method and also it can reduce the size of the collector needed by three times. This allows the use of a fan-powered dryer to carry out the similar capacity as a dryer that uses natural convection would require a collector that is six times the size of current dryer, making it a sophisticated and efficient drying solution.

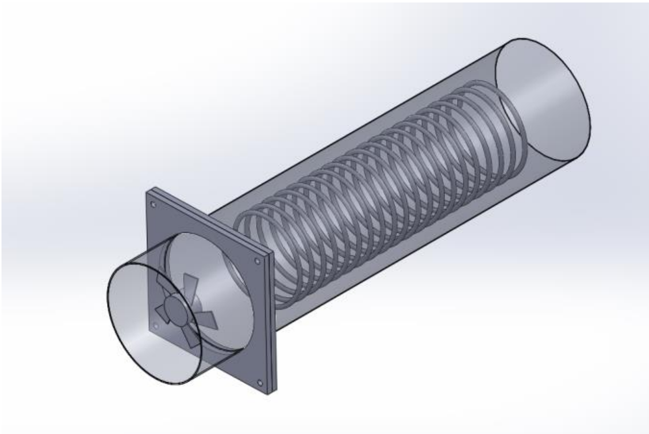
	Specification
	Heating Coil
	Nichrome Wire, with quality electrical insulation
	Capacity 700 Watt, 12-volt DC powered
	Length:
	Case
	Food grade stainless Steel case
	Thickness: 1.2 mm
	Length: 35 cm
	Outer Diameter: 20 cm
	Axial Fan
	Power input: 10 Watt , 12 Volt DC

Figure 11: Resistive Heating compartment

Chapter 4: Methodology

4.1 Study Progress

The research initiates with analyzing the problem statement regarding food processing and limitations of convectional drying technologies. With a view of accomplishing the goals of the study, extensive studies have been conducted regarding the related field in various journals, thesis, books, websites etc.

After pointing out the requirements, a combination solar-biomass dryer was made sand its drying performance was tested with cabbage as drying load. Various parameters related to the process such as ambient temperature and pressure, RH, temperature of inlet, drying compartment and outlet, initial moisture content and final moisture content of the product, air velocity, solar intensity and total drying time was recorded.

Mathematical models of different drying processes that have been investigated in this study, were developed based on thermodynamics principles and studying various journals and books related to particular analysis.

Once the models were validated various calculations were performed based on the derived governing equations in order to check out the drying capability of different drying modes.

Depending on the performance analysis, sustainability of the technology for large scale industrial production was investigated. After sustainability analysis, problems were identified and search for alternative energy source was initiated. Validation of the selected alternative was carried out and after that selected modification was proposed for fabrication.

After construction, drying process with same drying load was conducted and different parameters related to the process was recorded.

Based on the collected data, performance of the drying was analyzed using previous validated governing equations and mathematical models.

Obtained results were presented to understand the capacity of the dryer. Comprehensive discussion on drying process has been provided with a comparative analysis of performance.

The study was concluded with future recommendations for more improved and efficient technology after discussing its possibility for adaptation to fourth industrial revolution.

4.2 Work Flowchart

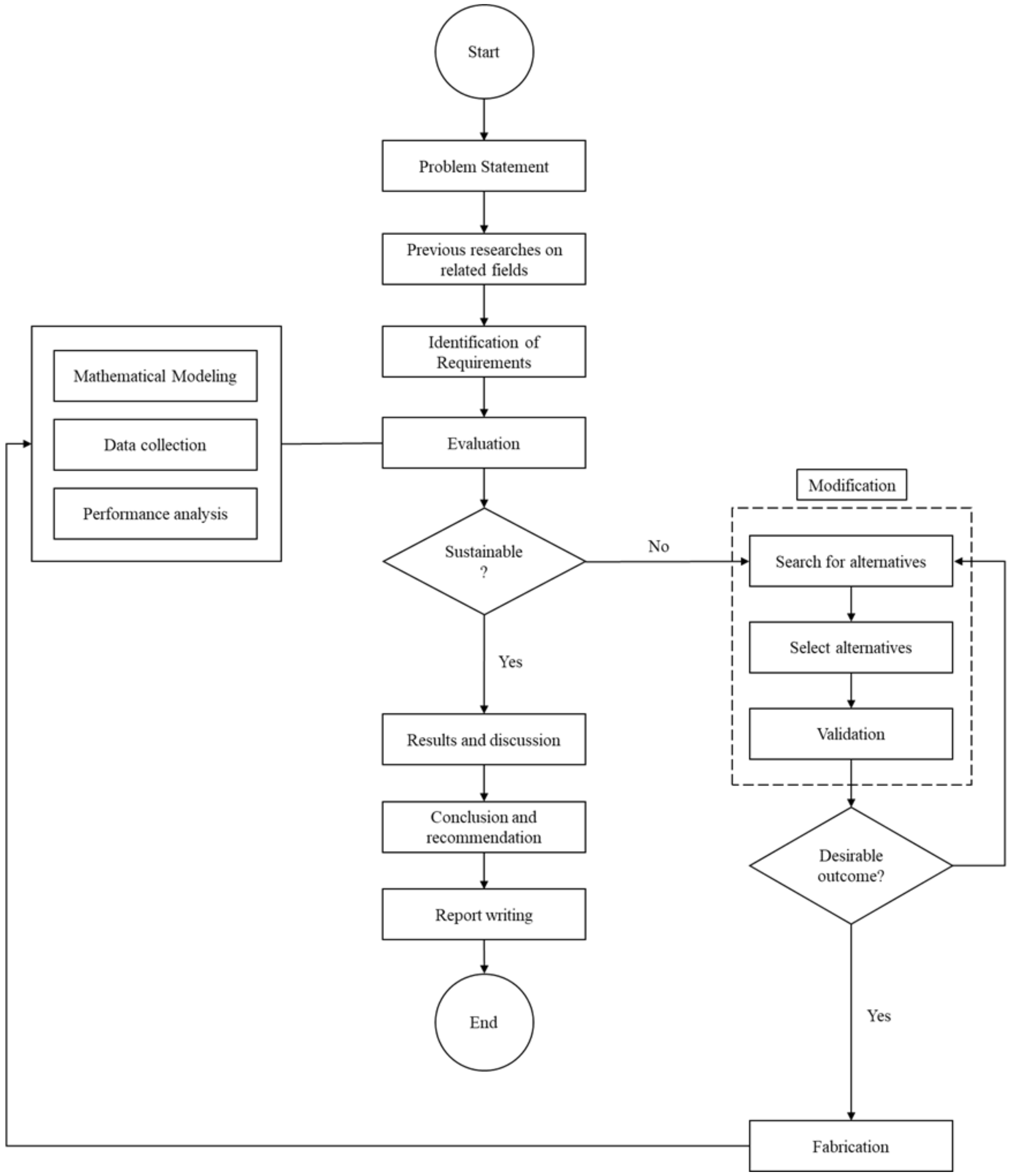


Figure 12: Work-flow Flowchart

4.3 Governing Equations

1st Law efficiency:

First law of efficiency of a system indicates how efficiency the system or the equipment can convert energy from one form to another. Usually how efficiency it can use the given energy and produce workout.

In this study, provided energy is the heat energy given to the inlet ambient air to increase its temperature so that it can absorb moisture from the foot content. Obtained work output is the heat needed to remove moisture from the food content.

2nd law efficiency:

A system's 2nd law efficiency is defined as the actual thermal efficiency divided by the theoretical maximum thermal efficiency. In another way, it is the useful work output/maximum possible work output. From exergy –

$$\eta_{II} = \frac{Exergy\ recovered}{Exergy\ expended}$$

$$= 1 - \frac{Exergy\ destroyed}{Exergy\ expended}$$

Exergy expanded is amount of exergy that has been given in the system.

From energy balance: $\delta E_{in} - \delta E_{out} = dE_{system}$

Heat and work are the only forms of energy a fixed mass can entail. Hence,

$$-\delta Q - \delta W = dU$$

Exergy of a flow stream or flow exergy: Flow energy is an additional form of energy that fluids possess. The exergy associated with flow work and boundary work are equivalent.

$$X_{flowing\ fluid} = X_{non\ flowing\ fluid} + X_{flow}$$

Total useful work ($W_{total,useful}$): Total useful work is the sum of all work performed by a system during a reversible process.

$$W_{total,useful} = (U - U_o) + P_o(V - V_o) - T_o(S - S_o)$$

Exergy balance: The exergy balance is defined as the discrepancy between the total exergy transfer through the system boundary and the exergy destruction within the system during a process.

$$(Total\ Exergy\ entering) - (Total\ Exergy\ leaving) - (Total\ Exergy\ destroyed) = (Change\ in\ the\ total\ exergy\ of\ the\ system)$$

Balance of exergy for a closed system:

$$\left(1 - \frac{T_o}{T_k}\right) Q_k - [W - P_o(V_2 - V_1)] - T_o S_{gen} = X_2 - X_1$$

If reversible $X_{destroyed=0}$. It indicates that the system is internally reversible but not certainly completely so.

Total exergy destroyed can be determined by applying exergy balance to an extended system. Where external irreversibility might be occurring.

Exergy Balance for controlled volume: Mass flow across the boundaries must be considered.

Exergy balancing for the system with steady flow: For devices (Turbines, nozzles, heat exchangers, compressors, diffusers, pipes and ducts) that functions steadily, there is no change in mass, energy, exergy and entropy.

Exergy entering a steady-flowing system in all forms (heat, work, mass transfer) must equal exergy departing plus exergy destroyed.

If we are interested in determining the exergy destructed during the procedure. along with system boundaries, then extended system should be considered. Extended means intermediate surroundings should also be considered

These theories have been applied to analyze the effectiveness of the dryer in its three operating conditions.

4.4 Mathematical Model

4.4.1 Biomass heating

Energy efficiency:

$$n_{overall} = \frac{heat\ transfer\ to\ the\ air\ entering\ the\ drying\ chamber}{heat\ generated\ by\ biomass\ combustion}$$

$$Q_{air} = \dot{m}_a \times C_p \times (T_i - T_a) \times t$$

$$Q_{bio} = W \times H$$

Exergy Balance:

$$\sum Ex_{in} - \sum Ex_{out} = Ex_{dest}$$

Exergy destroyed:

$$Q_{bio}\left(1 - \frac{T_a}{T_i}\right) + \dot{m}_a[(h_{out} - h_{in}) - T_a(s_{out} - s_{in})] - [(m_w \times L_v) + (m_g \times C_{pg} \times \Delta T)]$$

$$\Delta h = C_p(T_o - T_i)$$

$$\Delta s = ln\frac{T_o}{T_i} - R \times ln\frac{P_o}{P_i}$$

Exergy Expended:

$$Q_{bio}\left(1 - \frac{T_a}{T_i}\right)$$

4.4.2 Solar Heating

Energy efficiency:

$$n_{system} = \frac{[(m_w \times L_v) + (m_g \times C_{pg} \times \Delta T)]}{Q_{air}}$$

Exergy balance:

$$\sum Ex_{in} - \sum Ex_{out} = Ex_{dest}$$

Exergy destroyed:

$$Q_s\left(1-\frac{4\times T_a}{3\times T_s}+\frac{1\times {T_a}^4}{3\times {T_s}^4}\right)+\dot{m}_a C_p\left[(T_o-T_i)-T_o\times\left(ln\frac{T_o}{T_i}-R\times ln\frac{P_o}{P_i}\right)\right]-[(m_w\times L_v)+(m_g\times C_{pg}\times\Delta T)]$$

Exergy expended:

$$Q_s\left(1-\frac{4\times T_a}{3\times T_s}+\frac{1\times {T_a}^4}{3\times {T_s}^4}\right)$$

4.4.3 Solar-Biomass combined heating

Energy efficiency:

$$n_{system}=\frac{[(m_w\times L_v)+(m_g\times C_{pg}\times\Delta T)]}{Q_{air}}$$

Exergy balance:

$$\sum Ex_{in}-\sum Ex_{out}=Ex_{dest}$$

Exergy destroyed:

$$Q_{bio}\left(1-\frac{T_a}{T_i}\right)+Q_s\left(1-\frac{4\times T_a}{3\times T_s}+\frac{1\times {T_a}^4}{3\times {T_s}^4}\right)+\dot{m}_a C_p\left[(T_o-T_i)-T_o\times\left(ln\frac{T_o}{T_i}-R\times ln\frac{P_o}{P_i}\right)\right]-[(m_w\times L_v)+(m_g\times C_{pg}\times\Delta T)]$$

Exergy expended:

$$Q_{bio}\left(1-\frac{T_a}{T_i}\right)+Q_s\left(1-\frac{4\times T_a}{3\times T_s}+\frac{1\times {T_a}^4}{3\times {T_s}^4}\right)$$

Chapter 5: Results and Discussions

5.1 Dryer performance

5.1.1 Exergy and Energy efficiency

Dryer efficiency and effectiveness has been studied for 8 kg load condition analyzing recorded different operating parameters. system efficiencies were calculated using stated governing equation which were derived by basic law of thermodynamics. Obtained results has been presented in the table.

Table 2: Result Table for dryer drying 8 kg load:

Operating Configuration	Drying time (hr.)	Energy efficiency (n_1)	Exergy efficiency (n_2)
Sunlight	19	39%	37.7%
Biomass	13	33%	33%
Sunlight-Biomass Hybrid	12	61%	46%

5.1.2 Exergy destruction in different operation configuration

Destroyed exergy is the amount of exergy which cannot be converted into useful work and goes out of the system. In order to calculate the amount of exergy destroyed in sunlight heating, biomass heating and combined sunlight-biomass heating configuration; exergy balance has been applied. Obtained amount of exergy destroyed are presented below:

Table 3: Exergy used and destroyed in drying process:

Configuration	**Exergy used (MJ)**	**Exergy destroyed (MJ)**
Sunlight heating	20.238	33.917
Biomass heating	91.960	167.540
Sunlight-biomass combined	83.938	107.425

5.1.3 Drying model

Drying model has been obtained by studying the dying rate and moisture removal rate during the drying process. Obtained drying model has been presented which in good accordance with other model obtained by different studies. [54]

Table 4: Drying model for the drying process

Drying method	Obtained model
Sunlight heating	$(mc)\% = 128.8e^{-0.114\times t}$
Biomass heating	$(mc)\% = 147.7e^{-0.176\times t}$
Sunlight-biomass combined	$(mc)\% = 121.97e^{-0.156\times t}$

Drying model relates to the moisture removal rate with total drying time. Obtained models for different heating configuration are similar to models obtained by Newton model. [55]
Although this model is very similar, another close model has been obtained and described by Henderson and Pabis.[56] According to it drying rate significantly depends on the total drying time. In the study the found drying rate can be described and understood from these two studies.

5.2 Drying processes

5.2.1 No load condition:

Dryer performance at no lead condition was evaluated recording the inside and ambient relative humidity and temperature. As the temperature inside the chamber increased the relative humidity decreased. The temperature and relative humidity were observed to be very dependent on sunlight intensity. Highest temperature recorded were 45 $°C$ and 68$°C$ for sunlight and combination of sunlight and biomass heating respectively. Humidity reduced to 6.5% for combination of sunlight and biomass heating which is an indication of increasing drying power.

5.2.2 4 kg (2.50 kg/m^2) load condition:

I. Sunlight heating:

The drying process for sunlight heating as the only source of energy was observed and from the recorded information it was found out that total drying time required was about 13 hours. During this time highest solar intensity was recorded to be 821 w/m^2 with an average intensity of 614 w/m^2. Average ambient temperature and inlet temperature were 29.3 $°C$ and 36.5 $°C$ respectively. It indicates an average increase of temperature 7.2 $°C$. Average humidity of inlet air was found to be about 24% with 12% decrease compared to ambient air humidity.

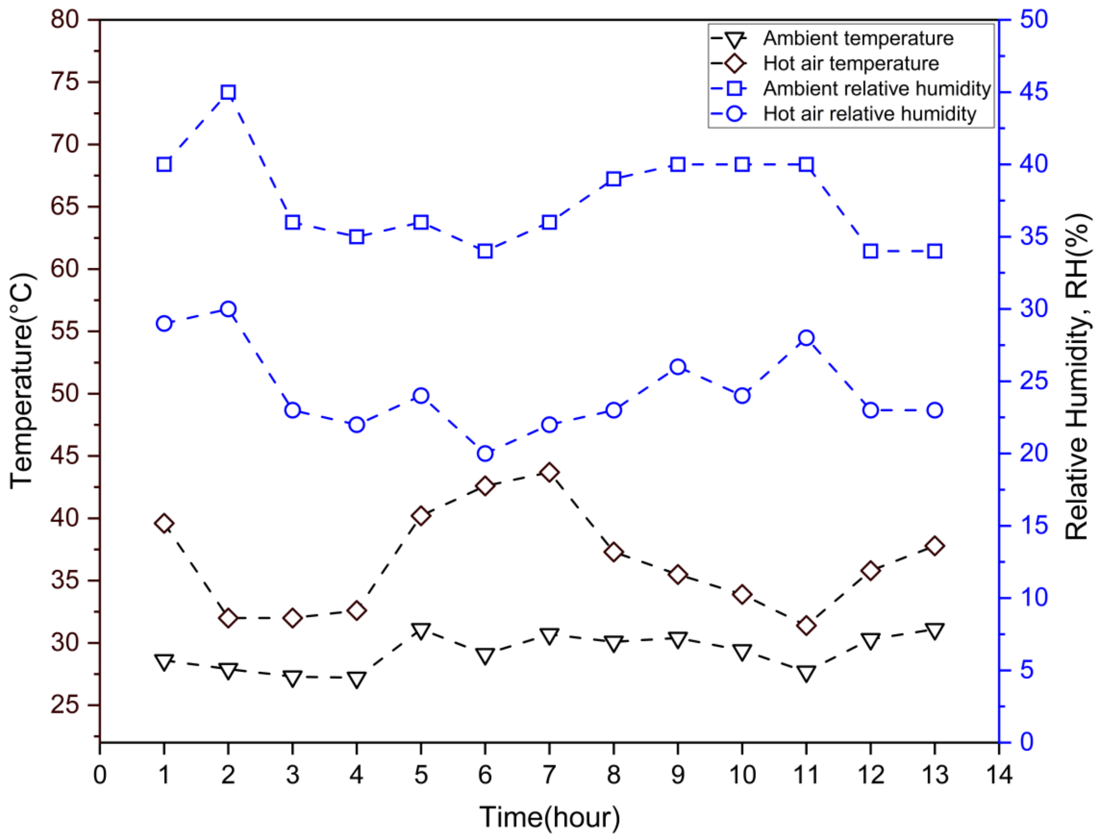


Figure 13: Temperature and relative heating profile for 2.50 kg/m^2 sample in Sunlight heating

II. Biomass heating:

The average inlet temperature in case of biomass heating was about 58.5 $°C$. It indicates a significant increase compared to sunlight heating. The average temperature increases when compared with ambient temperature was about 26.7 $°C$. As a result, the relative humidity reduced significantly. The recorded average relative humidity was about 24% which is 18% lower than average ambient air relative humidity. Total drying time recorded was about 8 hours.

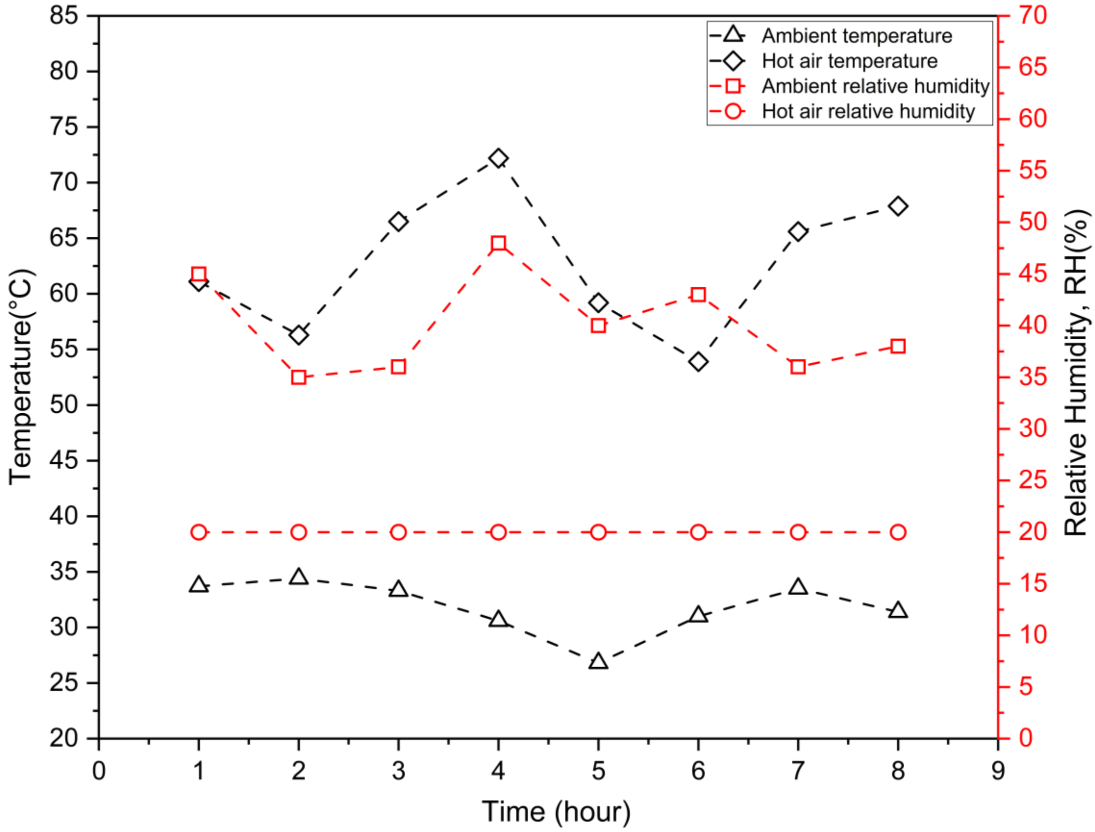


Figure 14: Temperature and relative heating profile for 2.50 kg/$\boldsymbol{m^2}$ sample in biomass heating

III. Combination of sunlight and biomass heating:

The drying performance increased further in case of combined heating as the total time required lowered by 1 hour. Due to heat addition the average temperature of air went up to 58.51°C from 30.8°C with an average increase of 27.7°C. the hot air had an average relative humidity of 23%.

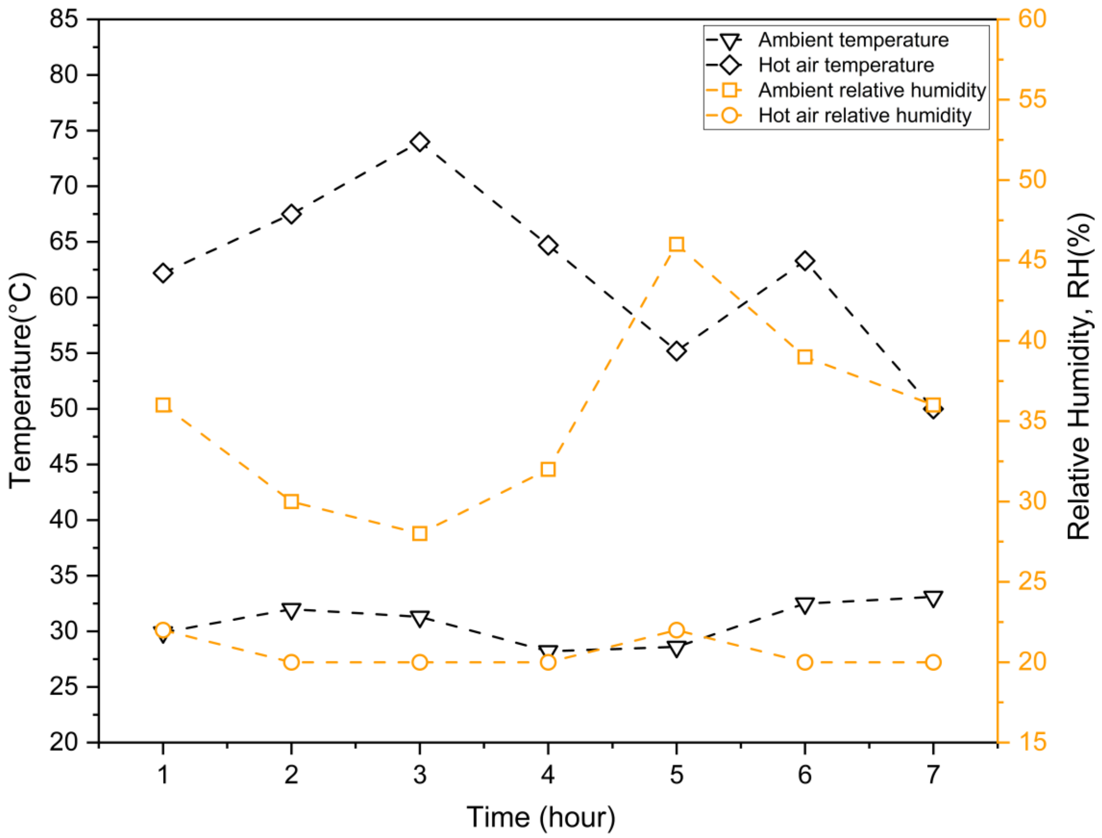


Figure 15: Temperature and relative heating profile for 2.50 kg/m^2 sample in combined sunlight and biomass heating

5.2.3 8 kg (3.70 kg/m^2) load condition:

I. Sunlight heating:

Total drying time required for the process was recorded to be 19 hours. The ambient temperature varied due to fluctuation of sun intensity. Average sunlight intensity was about 400.8 w/m^2 . Average air temperature at the inlet increased from 27.5°C to 32.3°C. Average relative humidity reduced 9% from ambient air to inlet air. Relative humidity of inlet air was about 27.7%

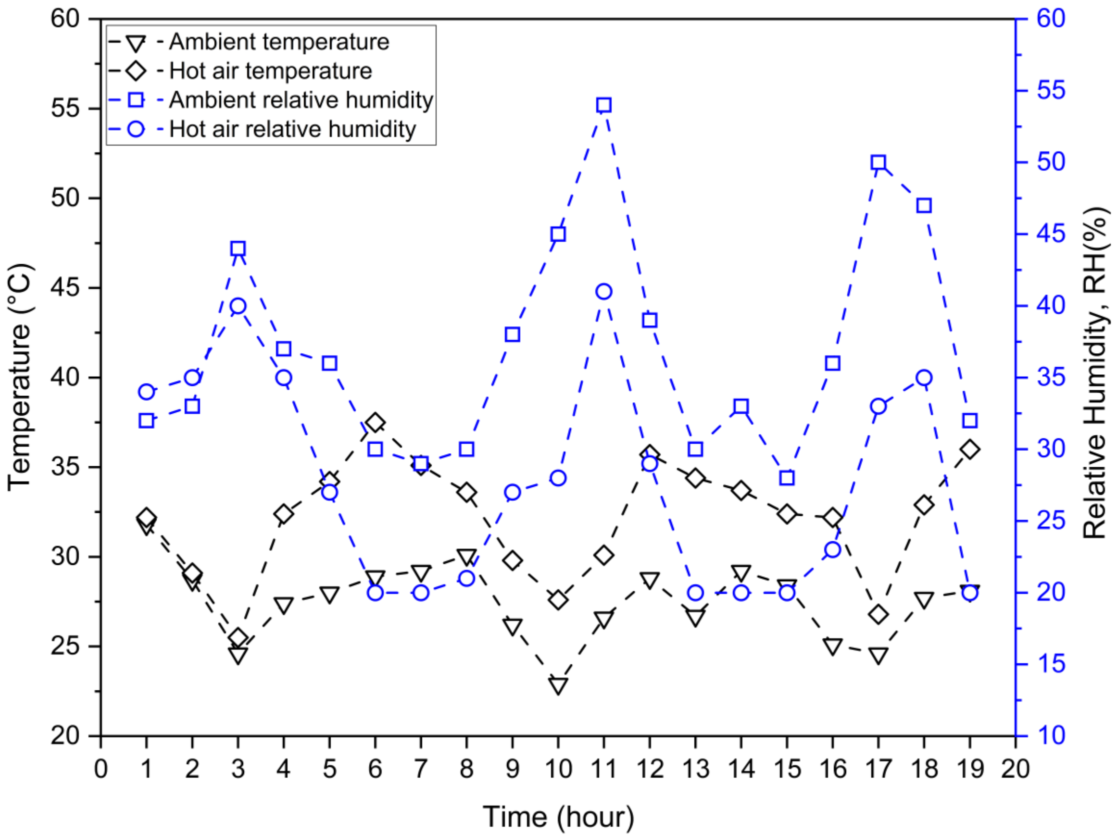


Figure 16: Temperature and relative heating profile for 3.70 kg/$\boldsymbol{m^2}$ sample in Sunlight heating

II. Biomass heating:

Average inlet air temperature increased from 21.5°C ambient temperature to 49°C. Total drying time was recorded to be 13 hours. with increased average temperature of about 27 °C relative humidity at the inlet of the drying compartment reduced to 24.23% from ambient air humidity of 62.15%.

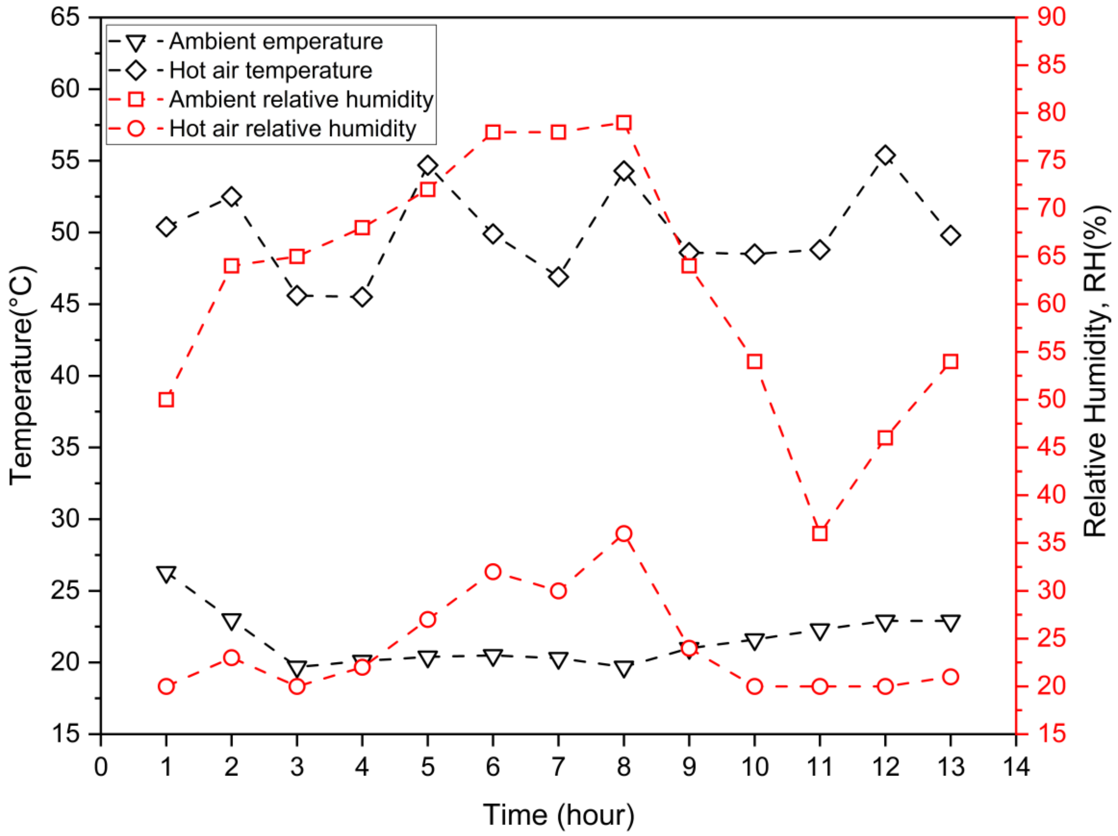


Figure 17: Temperature and relative heating profile for 3.70 kg/m^2 sample in biomass heating

III. Combination of sunlight and biomass heating:

The drying time reduced to 12 hours due combination of sunlight and biomass heating. Average sunlight intensity during this period was found to be 374 w/m^2 . The average air temperature at the inlet increased to 51.5°C from ambient air temperature of 28.5°C. The relative humidity reduced significantly. It reduced from 50.6% to 24.8%. This indicates the drying process to be better.

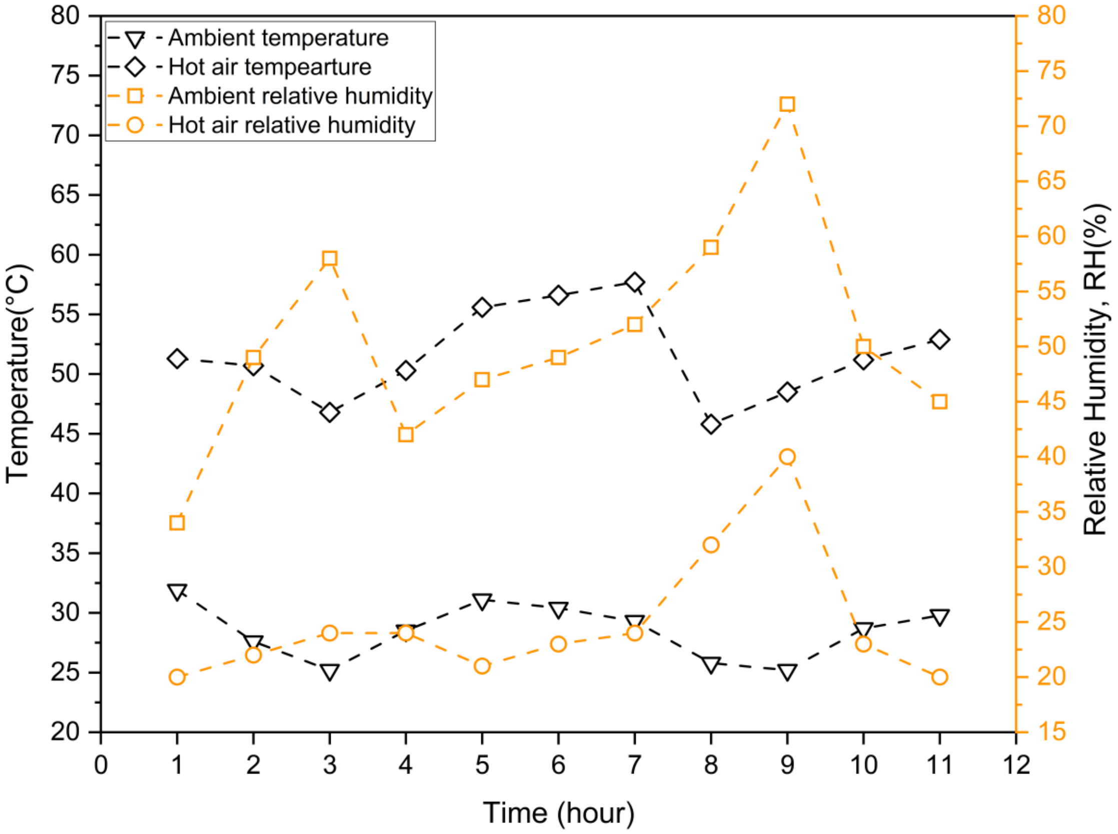


Figure 18: Temperature and relative heating profile for 3.70 kg/$\boldsymbol{m^2}$ sample in combined sunlight and biomass heating

5.2.4 12 kg (4.44 kg/m^2) load condition:

I. Sunlight heating:

Total drying time was recorded to be 20 hours with average sunlight intensity 533.5 w/m^2. Average air temperature increased from 27°C to 32.3°C at the inlet. The relative humidity of hot air reduced to 27.6% on average.

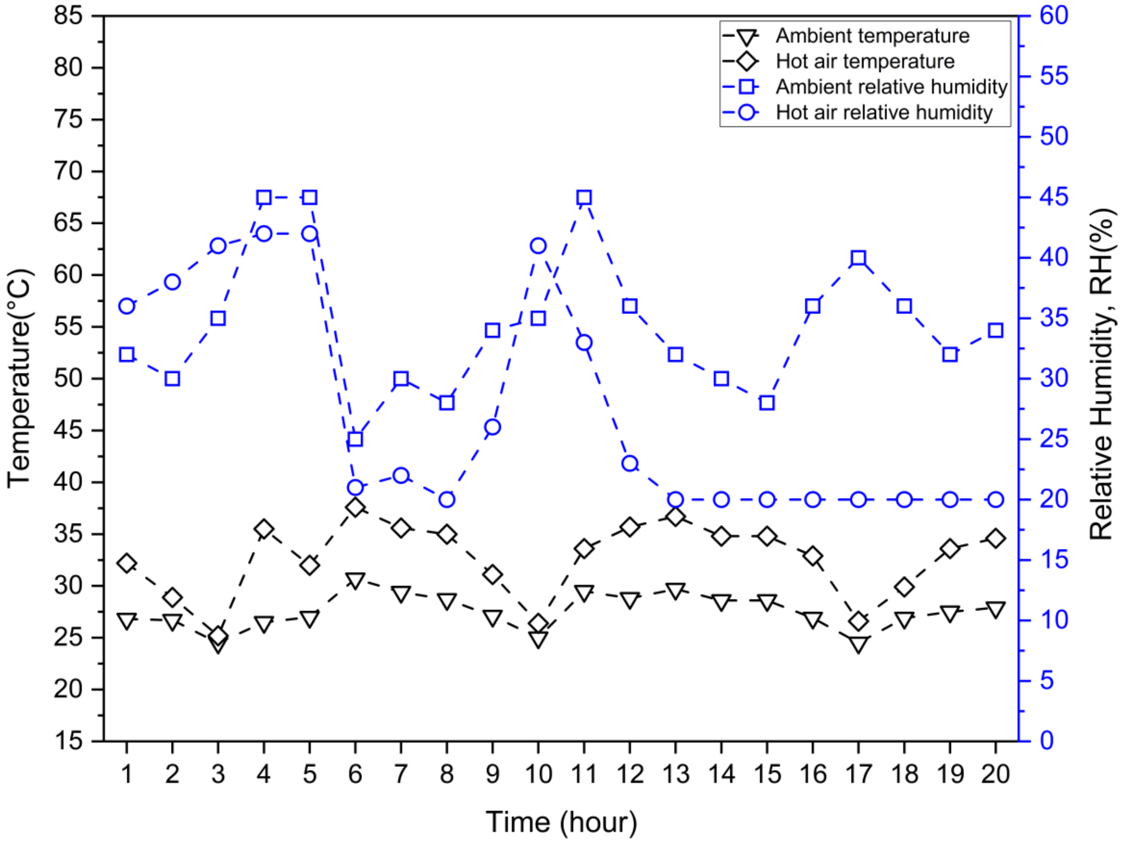


Figure 19: Temperature and relative heating profile for 4.44 kg/$\boldsymbol{m^2}$ sample in sunlight heating

II. Biomass heating:

Average ambient air temperature was recorded to be 22°C which increased to 51.7°C during 18 hours of drying time. The average relative humidity reduced from 50.5% to 23.9%.

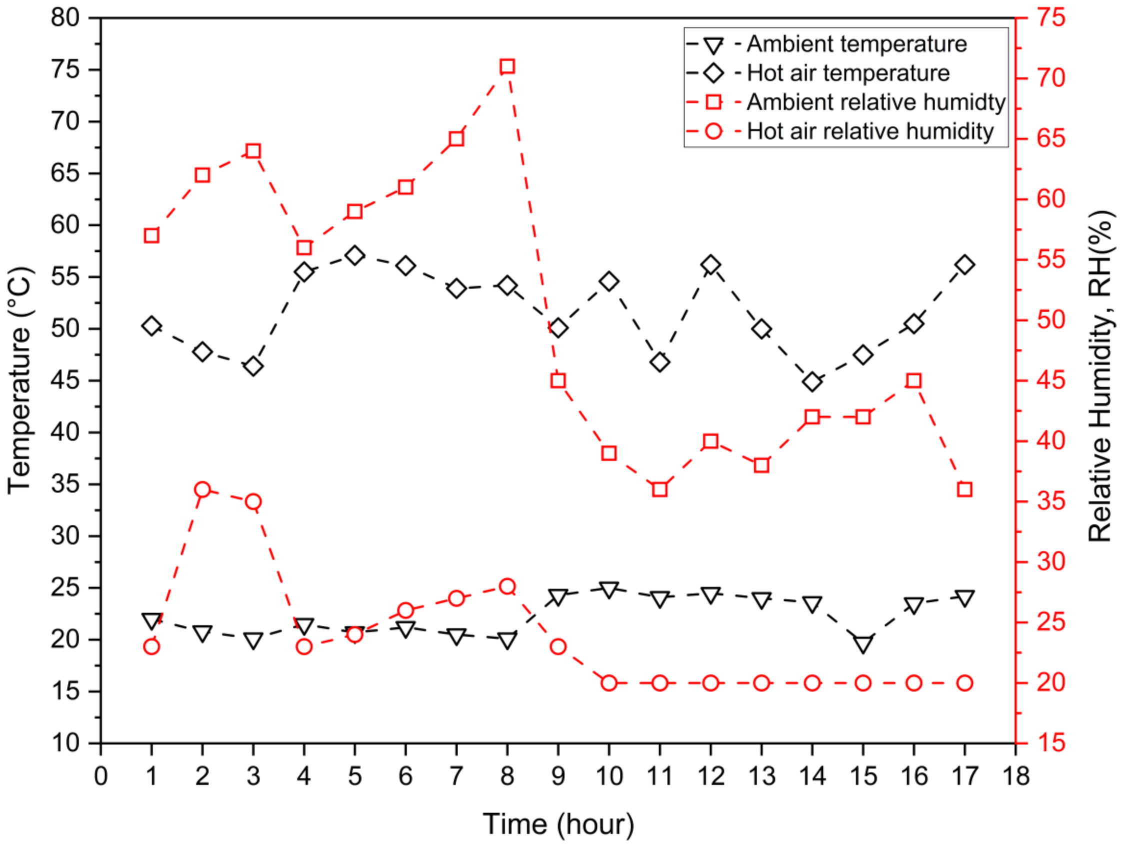


Figure 20: Temperature and relative heating profile for 4.44 kg/$\boldsymbol{m^2}$sample in biomass heating

III. Combination of sunlight and biomass heating:

The drying time reduced to 13 hours because of combination of energy source. The average air temperature increased from 27.2°C to 51.2°C. The average relative humidity reduced from 35.14% to 21.42%.

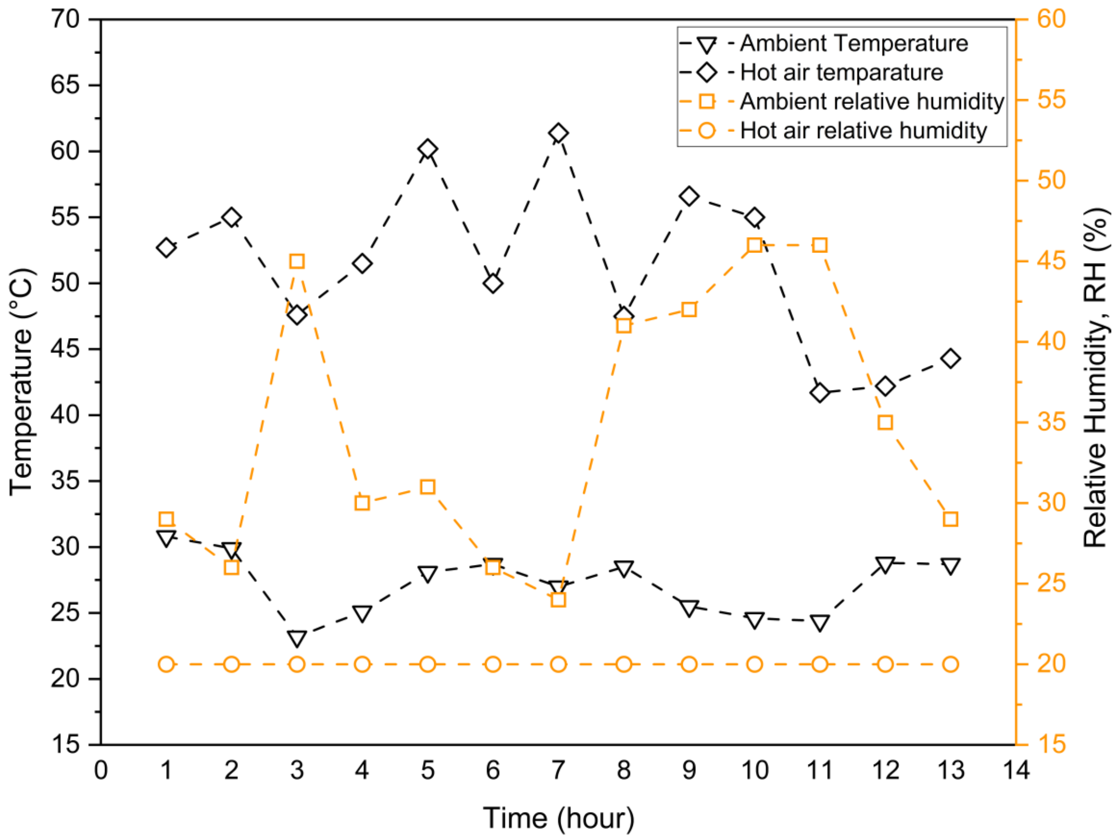


Figure 21: Temperature and relative heating profile for 4.44 kg/$\boldsymbol{m^2}$sample in sunlight and biomass combined heating

5.2.5 Moisture content reduction

I. 4 kg (2.50 kg/m^2) load condition:

For moisture content reduction of 90% to 8% the time required for sunlight heating, biomass heating and combination of sunlight and biomass heating was about 13,8 and 7 hours respectively. It indicates drying process efficiency. Sunlight heating drying process was very dependent on sunlight intensity.

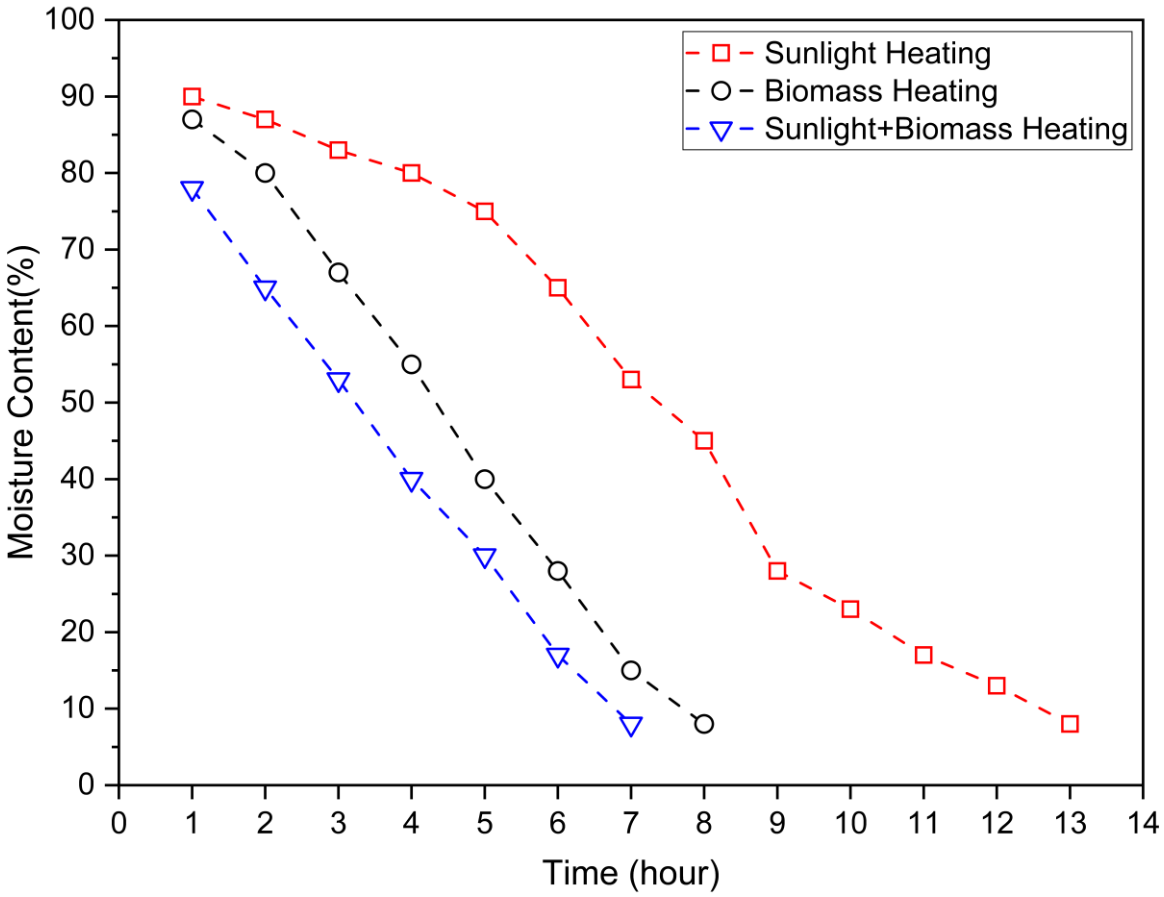


Figure 22: Moisture content reduction for 4 kg load upon sunlight, biomass and sunlight-biomass combined heating

II. 8 kg (3.70 kg/m^2) load condition:

Sunlight heating, biomass heating and combined biomass and sunlight heating took 19, 13 and 12 hours respectively to reduce moisture content from 90% to 8% in the final product. Combination of both biomass and sunlight heating was more effective and less time consuming compared to others. Sunlight was very effected by fluctuating ambient air temperature due to sunlight intensity variation over the drying period.

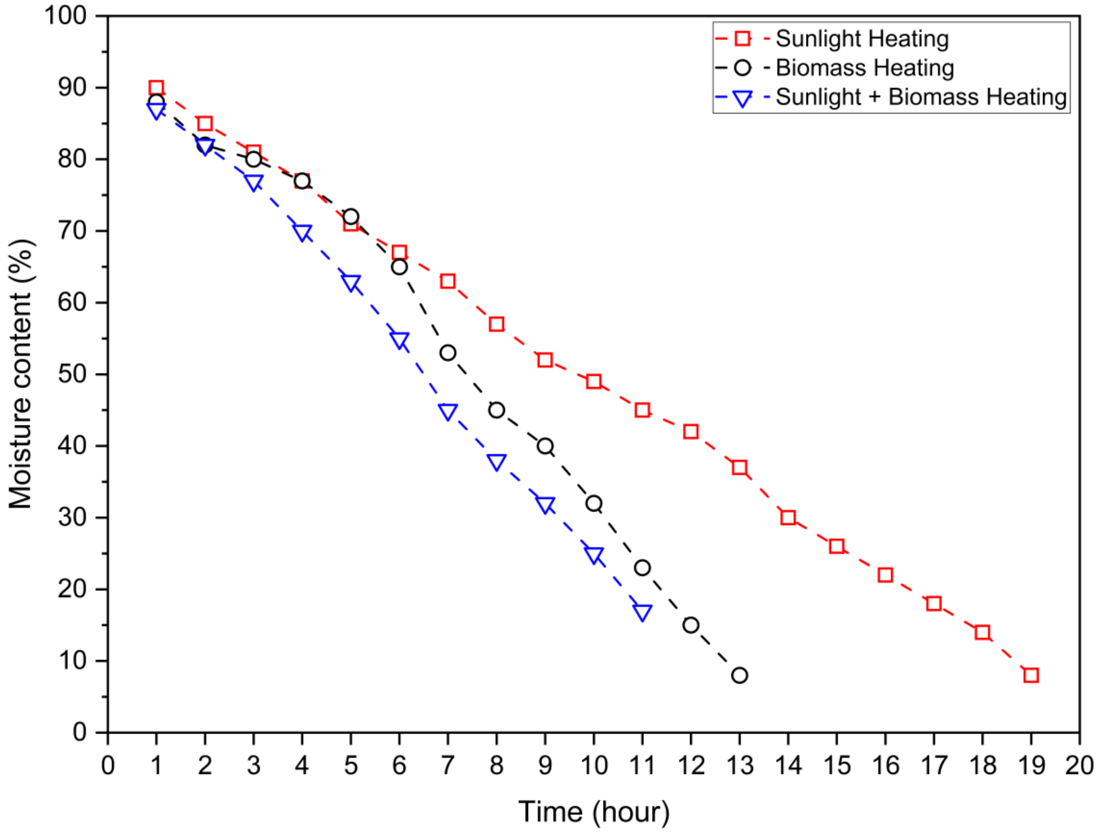


Figure 23: Moisture content reduction for 8 kg load upon sunlight, biomass and sunlight-biomass combined heating

III. 12 kg (4.44 kg/m^2) load condition:

Initial moisture content was 90% wet basis which reduced to 8% with drying time and it took 20, 17 and 13 hours for sunlight, biomass and combination of biomass and sunlight heating respectively. The moisture content reduced gradually with drying time. Combination of biomass and sunlight heating took about half time the open sun drying which was about 24 hours.

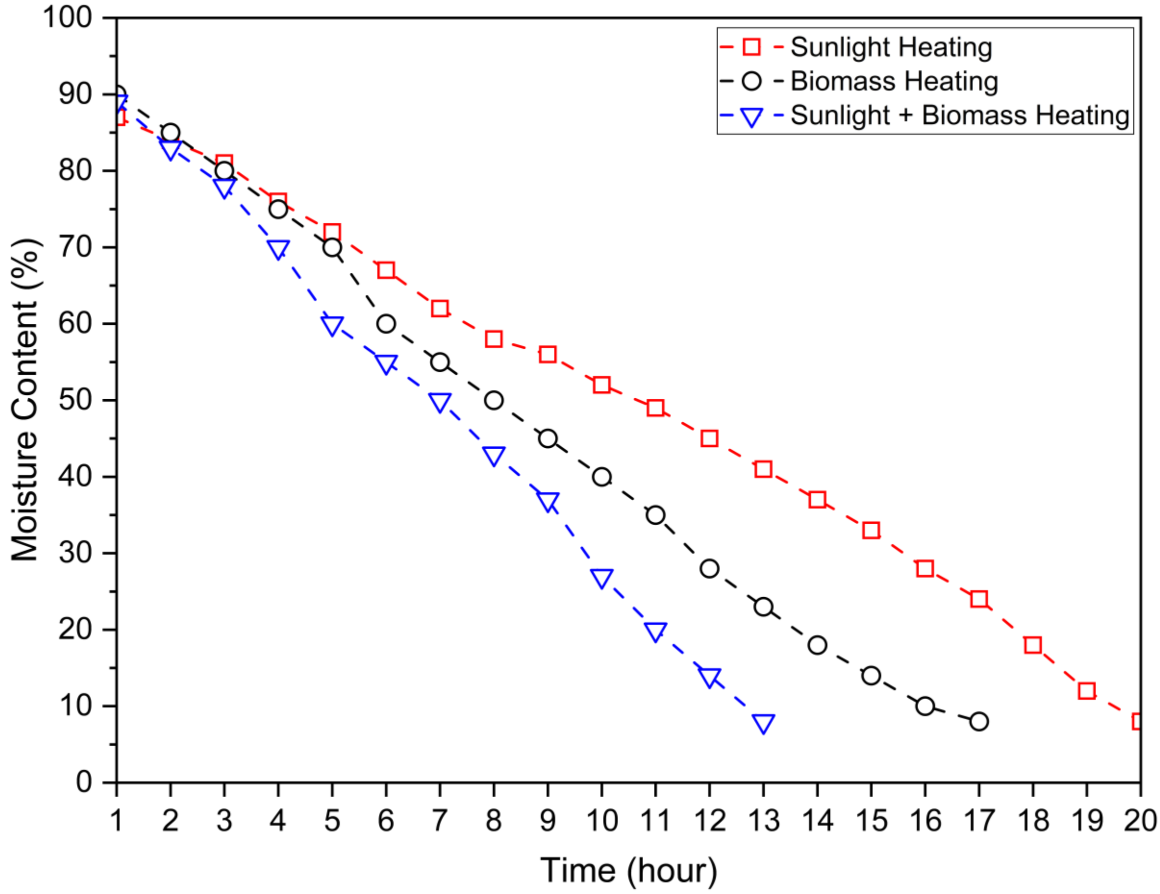


Figure 24: Moisture content reduction for 12 kg load upon sunlight, biomass and sunlight-biomass combined heating

5.2.6 Drying rate

For 4 kg load total removed about of water was around 3400 g and time required for sunlight heating, biomass heating and combined sunlight and biomass heating was about 13, 8 and 7 hours respectively. For the three process the drying rate was 261.53 g/h, 425 g/h and 485.71 g/h respectively.

Drying rate for 8 kg load were about 353.68 g/h, 523.2 g/h and 566.67 g/h respectively for sunlight, biomass heating and combination of sunlight and biomass heating respectively. Time required were 19, 13 and 11 hours respectively.

With increasing load condition, the time required for the food content to be dried up to the required property needed time increased. For 12 kg load, drying time required was about 20 hours, 17 hours and 13 hours respectively for sunlight, biomass and combination of sunlight and biomass heating. Drying rate found were 492 g/h, 600 g/h, and 766.15 g/h respectively for sunlight, biomass and combined heating.

Drying rate depends on many factors such as ambient air temperature and humidity, inlet hot air temperature and humidity. Less relative humidity means more water capturing capability for air. In different drying configuration inlet air humidity reduced significantly with increasing the air temperature. However, in sunlight heating the whole process was more dependent on sunlight intensity which often varies. As a result, this configuration took more time than biomass heating and combined heating. In all the process a suitable foot quality was maintained meaning not drying too much which could damage the food content itself.

5.2.7 Biomass consumption

For drying purpose local available wood was used as biomass energy source. Needed biomass for drying performance was recorded. In case of drying 4 kg sample required biomass was 33 kg and 25 kg respectively for biomass heating and combination of sunlight and biomass heating. 8 kg sample needed 46kg and 40 kg of biomass for biomass and combined biomass-sunlight heating whereas 12 kg load condition required 59 kg and 45 kg.

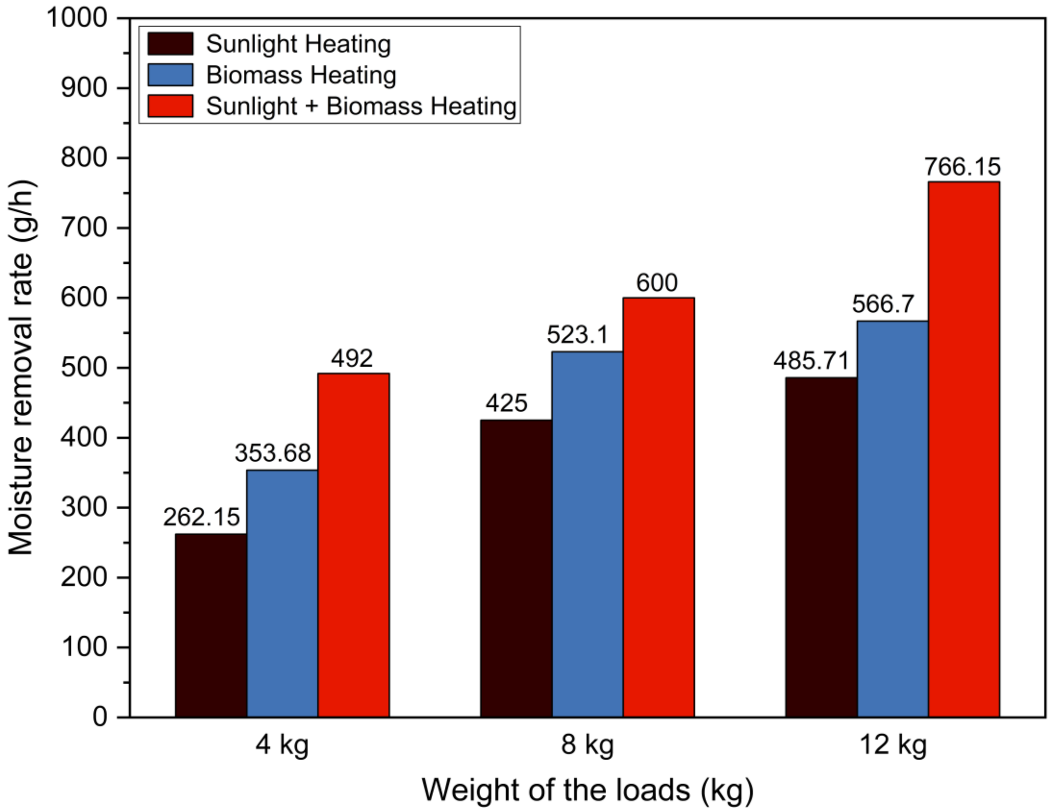


Figure 25: Drying rate of different load in three heating configurations

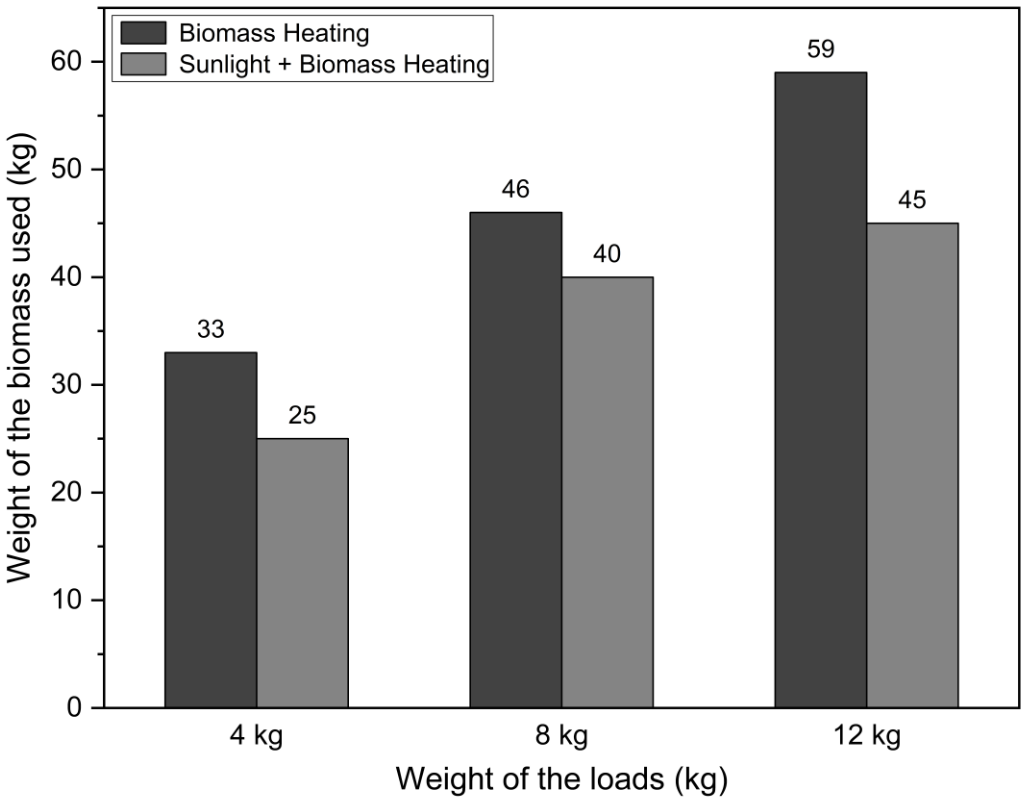


Figure 26: Biomass consumption in different loading condition and heating configuration

5.3 Discussion

In this study drying process for different loading condition in different operating configuration have been studied in order to understand the drying kinematic in sunlight drying, biomass heating drying and in combination of both the sunlight and biomass heating. Energy and exergy efficiency of three configuration have been studied and presented in the table. Also, exergy destroyed in three configurations have been presented in order to understand the effectiveness of heating process investigate the sector for optimization in order to make the overall dryer more efficient.

Drying model have been obtained for 8 kg load in all three-heating configuration which were in accordance with previous study. Obtained model can provide more information in drying kinematic of the drying process.

From the obtained result tables, it can be understood that sunlight exhibits substantially lower energy use and destruction, with an energy efficiency of 39% and an exergy efficiency of 37.7%. Drying process uses 20.238 MJ of energy while losing 33.917 MJ over the whole drying period. Two crucial factors are ambient temperature and sunlight intensity. Sunlight intensity increases the ambient air temperature which relates to faster temperature increase in the heating chamber. This can lead to faster drying rate. However, it’s very important to monitor the solar intensity in case of excess heating which can damage the product. The optimum storage condition has to be maintained. Surly higher sun intensity will increase the efficiency of the process. Therefore, optimal energy conversion from sunlight, it is therefore essential to optimize solar panel performance under a variety of environmental conditions.

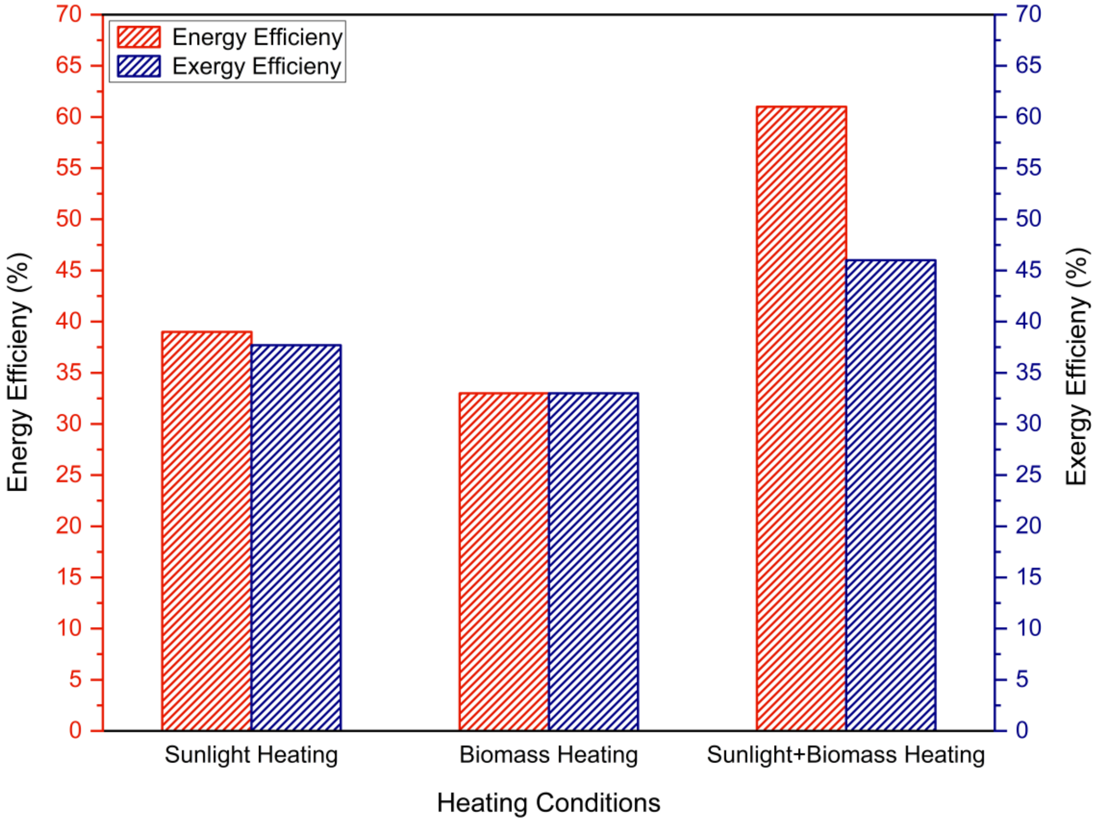


Figure 27: Energy and Exergy efficiency of different heating configuration

Biomass heating process took about 13 hours with an efficiency of 33% for both energy and exergy, exhibits significantly higher exergy utilization and destruction compared to sunlight. The biomass heating configuration utilizes 91.960 MJ of exergy while destroying 167.540 MJ. It can be easily understood that the total exergy expanded and destroyed were higher compared to sunlight heating. As process heat was generated by combustion, the quality of wood plays a vital role in the maximum heat generation and amount of time it takes. Different factors such as moisture of wood, type feed rate etc affect the heat generation. Study indicates the importance of optimizing the biomass heating in order to have more efficient combustion process and drying process in general. Controlling different factors such as ambient temperature, moisture content wood quality will play vital role in ensuring complete combustion and hence enhancing efficiency and reduce exergy destruction.

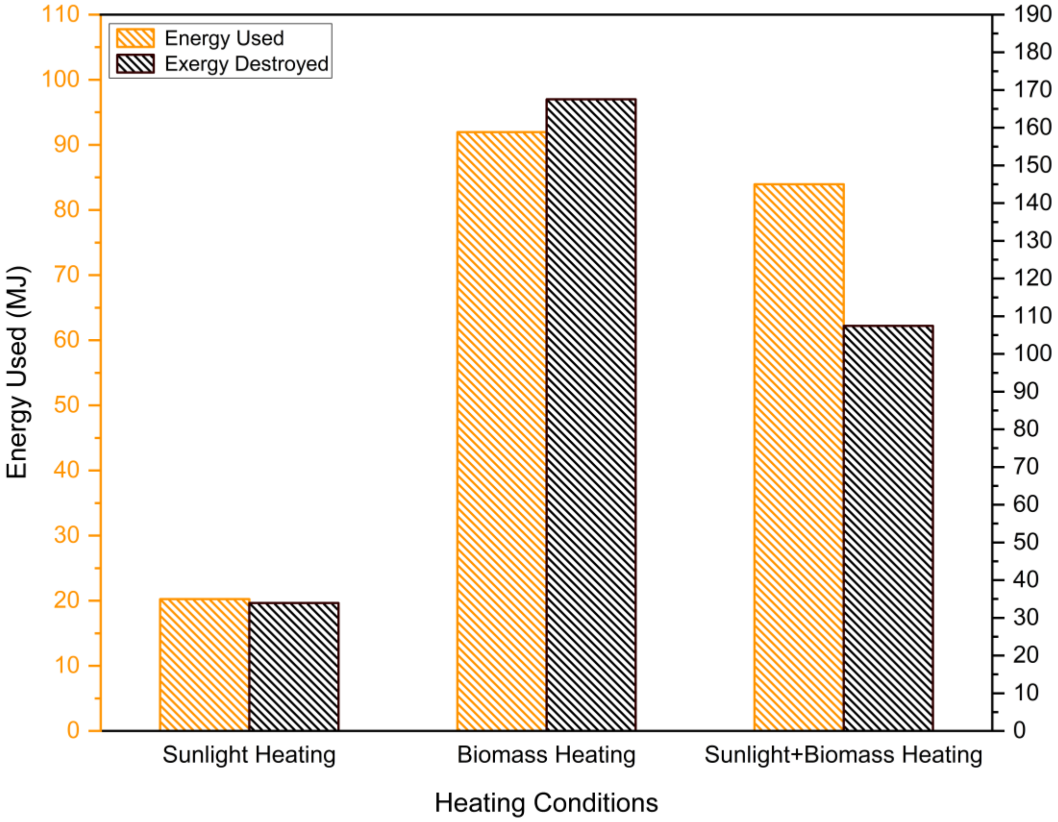


Figure 28: Energy used and Exergy destroyed in different configurations

Compared to other two drying process sunlight-biomass combined heating process have greater energy and exergy efficiency. This combined configuration utilizes 83.938 MJ of exergy while destroying 107.425 MJ with an energy efficiency of about 61% and exergy efficiency of about 46%. This hybrid technology has the capability of using intense solar intensity during daytime and using biomass heating as back up if required. The energy efficiency of this system was significantly higher compared to other two configuration because it can use both source of energy efficiently to increase the inlet air temperature at a shortest time. The magnitude of the higher temperature obtained in the combined heating process was also higher compared to other two configuration. This indicates better thermal energy usage capability thus making it an effective approach for maximizing overall system efficiency.

Chapter 6: Conclusion and future recommendations

6.1 Conclusion

The result tables, figures and discussions offer insightful information about the drying efficiency of a solar dryer; its energy use and total drying period when supplied with various energy sources.

As from the figure it can be seen that sunshine heating has a moderate level of energy and exergy efficiency, but there the overall drying process can be made more efficient by taking into account the ambient air temperature and sunlight intensity. If the ambient air can be preheated by any external exhaust air heating system it will increase the efficiency significantly.

while monitoring the sunlight intensity can increase the efficiency of sunlight heating, careful observation and quality check of biomass is required in case of biomass heating as it has less exergy utilization accompanied by more exergy destruction compared to sunlight heating. Factors such as wood quality, moisture content, wood species, wood density, wood age and condition of storage and handling can enhance the effectiveness of the drying process and reduce exergy wastage.

Sunlight-biomass hybrid heating is more promising as it maximizes the effective utilization of both energy source thus increases the efficiencies and reduces the exergy reduction.

By optimizing energy configurations, controlling environmental factors, and integrating complementary energy sources, it is possible to enhance sustainable energy generation and reduce exergy losses. Further research and technological advancements are essential to capitalize on these findings and drive the transition towards more efficient and sustainable energy systems.

Chapter 7: Appendix

7.1 Appendix A

Table 5: drying compartment and drying load specifications

Load, Kg	Length of tray (L)	Width of tray (W), m	Area of tray (LW), m^2	No of tray	Total drying area	Density (Load/total area), kg/m
4	0.45	0.3	0.135	12	1.62	2.5
8	0.45	0.3	0.135	16	2.16	3.7
12	0.45	0.3	0.135	20	2.7	4.44

I. 4 kg (2.5kg/m^2) loading

Table 6: 4 kg (2.5kg/$\boldsymbol{m^2}$)) load drying by sunlight heating

Time	T_a	T_1	T_2	T_3	RH_a	RH_i	%mc	%mc open	Moisture (Dryer), g	Moisture (Open),g
1	28.6	39.6	38.3	37.5	40	29	90	92	120	40
2	27.9	32	32.5	30.8	45	30	87	89	120	40
3	27.3	32	32.5	30.9	36	23	83	85	160	160
4	27.2	32.6	33	30.5	35	22	80	83	120	80
5	31.1	40.2	37.7	33.9	36	24	75	80	200	120
6	29.1	42.6	38.9	36.2	34	20	65	73	400	280
7	30.7	43.7	40.9	37.1	36	22	53	68	480	200
8	30.1	37.3	37.4	37.3	39	23	45	62	320	240
9	30.4	35.5	36.9	36.7	40	26	28	46	680	640
10	29.4	33.9	34.4	34.8	40	24	23	38	200	320
11	27.7	31.4	31.3	31.8	40	28	17	28	240	400
12	30.3	35.8	35.4	36.5	34	23	13	23	160	200
13	31.1	37.8	37.7	39.9	34	23	8	17	200	240

T_a	Ambient air temperature
T_1	Dryer inlet air temperature
T_2	Temperature at dryer mid-section
T_3	Outlet air temperature
RH_a	Relative humidity of ambient air
RH_i	Relative humidity of inlet air
$\%mc$	Moisture content percentage
Moisture	Moisture removed, gram water

Table 7: 4 kg (2.5kg/$\boldsymbol{m^2}$) load drying by biomass heating

Time	T_a	T_1	T_2	T_3	RH_a	RH_i	$\%mc$	Moisture removal (g)
1	33.7	61.1	56.2	61	45	20	87	240
2	34.4	56.3	51.2	57.4	35	20	80	280
3	33.3	66.5	64.5	67.2	36	20	67	520
4	30.6	72.2	65.5	72.9	48	20	55	480
5	26.8	59.2	55.9	58.5	40	20	40	600
6	31	53.9	52.3	55.5	43	20	28	480
7	33.5	65.6	62.2	64.4	36	20	15	520
8	31.4	67.9	60.5	63.8	38	20	8	280

Table 8: 4 kg (2.5kg/m^2) load drying by sunlight-biomass combined heating

Time	T_a	T_1	T_2	T_3	RH_a	RH_i	$\%mc$	Moisture removal (g)
1	29.9	62.2	63.9	61.8	36	22	78	600
2	32	67.5	60.2	65.3	30	20	65	520
3	31.3	74	67.7	72.3	28	20	53	480
4	28.2	64.7	59.1	60.7	32	20	40	520
5	28.6	55.2	52.7	54.4	46	22	30	400
6	32.5	63.3	61	58	39	20	17	520
7	33.1	50	45	48.8	36	20	8	360

II. kg (3.70 kg/m^2) loading

Table 9: 8 kg (3.70 kg/$\boldsymbol{m^2}$) load drying by sunlight heating

Time	T_a	T_1	T_2	T_3	RH_a	RH_i	%mc	%mc open	Moisture (Dryer), g	Moisture (Open), g
1	31.8	32.2	36.2	30.6	32	34	90	91	160	80
2	28.7	29.1	30.4	28.7	33	35	85	87	400	320
3	24.6	25.5	26.1	22.5	44	40	81	86	320	80
4	27.4	32.4	34	29.4	37	35	77	83	320	240
5	28	34.2	36.6	32.5	36	27	71	78	480	400
6	28.9	37.5	38.5	32.6	30	20	67	73	320	400
7	29.2	35.1	34.4	31.4	29	20	63	69	320	320
8	30.1	33.6	33.1	31.6	30	21	57	65	480	320
9	26.2	29.8	27.4	27.9	38	27	52	60	400	400
10	22.9	27.6	27.3	26.3	45	28	49	57	240	240
11	26.6	30.1	30.6	29.3	54	41	45	55	320	160
12	28.8	35.7	34.9	35.2	39	29	42	52	240	240
13	26.7	34.4	32.2	32.8	30	20	37	49	400	240
14	29.2	33.7	32.1	32.4	33	20	30	46	560	240
15	28.4	32.4	31.7	31.5	28	20	26	43	320	240
16	25.1	32.2	32	30.9	36	23	22	39	320	320
17	24.6	26.8	26.6	26.4	50	33	18	37	320	160
18	27.7	32.9	33.8	33.5	47	35	14	31	320	480
19	28.1	36	35.4	35.6	32	20	8	25	480	480

Table 10: 8 kg (3.70 kg/$\boldsymbol{m^2}$) load drying by biomass heating

Time	T_a	T_1	T_2	T_3	RH_a	RH_i	$\%mc$	Moisture removal (g)	
1	26.3	50.4	47.5	46.3	50	20	88	400	24.1
2	23	52.5	50.2	51	64	23	82	480	29.5
3	19.7	45.6	45.5	44.3	65	20	80	160	25.9
4	20.1	45.5	44.3	43.3	68	22	77	240	25.4
5	20.4	54.7	52	50.1	72	27	72	400	34.3
6	20.5	49.9	47.7	45.6	78	32	65	560	29.4
7	20.3	46.9	44.7	43.3	78	30	53	960	26.6
8	19.7	54.3	52.1	47.9	79	36	45	640	34.6
9	21	48.6	47.9	47.1	64	24	40	400	27.6
10	21.6	48.5	47.7	46	54	20	32	640	26.9
11	22.3	48.8	47.5	46.6	36	20	23	720	26.5
12	22.9	55.4	54.4	52.9	46	20	15	640	32.5
13	22.9	49.8	48.9	48.6	54	21	8	560	26.9

Table 11: 8 kg $(3.70\ \mathrm{kg}/\boldsymbol{m^2})$ load drying by sunlight-biomass combined heating

Time	T_a	T_1	T_2	T_3	RH_a	RH_i	$\%mc$	Moisture removal (g)
1	31.9	51.3	49.6	48.2	34	20	87	480
2	27.6	50.7	45.8	50.9	49	22	82	400
3	25.2	46.8	40.9	45.8	58	24	77	400
4	28.5	50.3	50.4	48.8	42	24	70	560
5	31.1	55.6	54.4	53.8	47	21	63	560
6	30.4	56.6	54.4	54.7	49	23	55	640
7	29.3	57.7	50.9	55.2	52	24	45	800
8	25.8	45.8	41.7	44.5	59	32	38	560
9	25.2	48.5	41.7	47	72	40	32	480
10	28.7	51.2	53.3	51.4	50	23	25	560
11	29.8	52.9	51.4	50.1	45	20	17	640

III. 12 kg loading

Table 12: 12 kg (4.44 kg/$\boldsymbol{m^2}$) load drying by sunlight heating

Time	T_a	T_1	T_2	T_3	RH_a	RH_i	%mc	%mc open	Moisture (Dryer)	Moisture (Open)
1	26.8	32.2	30.3	30.8	32	36	87	88	360	240
2	26.7	28.9	27.4	27.5	30	38	84	85	360	360
3	24.5	25.2	24.2	24.8	35	41	81	82	360	360
4	26.5	35.5	35.2	32.5	45	42	76	78	600	480
5	27	32	32.7	32.5	45	42	72	74	480	480
6	30.7	37.6	37.2	36.5	25	21	67	71	600	360
7	29.4	35.6	35.5	35.2	30	22	62	68	600	360
8	28.7	35	33.7	34.7	28	20	58	64	480	480
9	27.1	31.1	30	30.7	34	26	56	62	240	240
10	25	26.4	25.4	26.2	35	41	52	59	480	360
11	29.5	33.6	34.8	34.8	45	33	49	57	360	240
12	28.8	35.7	34.9	34.8	36	23	45	53	480	480
13	29.7	36.7	35.3	34.1	32	20	41	50	480	360
14	28.6	34.8	32.2	33.2	30	20	37	47	480	360
15	28.6	34.8	32.2	33.2	28	20	33	45	480	240
16	26.9	32.9	30.5	30.9	36	20	28	41	600	480
17	24.5	26.6	26.4	25.9	40	20	24	38	480	360
18	26.9	29.9	30.7	30.8	36	20	18	35	720	360
19	27.5	33.6	33.4	33.4	32	20	12	31	720	480
20	27.9	34.6	34.2	33.9	34	20	8	26	480	600

Table 13: 12 kg (4.44 kg/$\boldsymbol{m^2}$) load drying by biomass heating

Time	T_a	T_1	T_2	T_3	RH_a	RH_i	$\%mc$	Moisture removal (g)
1	22	50.3	46	46.1	57	23	90	360
2	20.8	47.8	43.3	42	62	36	85	600
3	20.1	46.4	41.1	42.1	64	35	80	600
4	21.5	55.5	46.2	46.1	56	23	75	600
5	20.7	57.1	50.3	49.8	59	24	70	600
6	21.2	56.1	52.3	50.9	61	26	60	1200
7	20.5	53.9	48.1	47.5	65	27	55	600
8	20.1	54.2	50.2	49.8	71	28	50	600
9	24.3	50.1	49.4	49.5	45	23	45	600
10	25	54.6	50.6	51.6	39	20	40	600
11	24.1	46.8	45.8	44.9	36	20	35	600
12	24.5	56.2	52.5	51.6	40	20	28	840
13	24	50	45.6	45.7	38	20	23	600
14	23.6	44.9	41.7	41.4	42	20	18	600
15	19.7	47.5	41.2	44	42	20	14	480
16	23.5	50.5	49.8	48.7	45	20	10	480
17	24.2	56.2	54.4	52.2	36	20	8	240

Table 14: 12 kg $(4.44\ \text{kg}/\boldsymbol{m^2})$ load drying by sunlight-biomass combined heating

Time	T_a	T_1	T_2	T_3	RH_a	RH_i	$\%mc$	Moisture removal (g)
1	30.8	52.7	54.4	50.7	29	20	89	240
2	29.9	55	52.7	49.7	26	20	83	720
3	23.2	47.6	42.8	42.5	45	20	78	600
4	25.1	51.5	48.6	44.9	30	20	70	960
5	28.1	60.2	57.7	54.2	31	20	60	1200
6	28.7	50	47.9	43.6	26	20	55	600
7	27	61.4	60.5	55.7	24	20	50	600
8	28.5	47.5	46.8	43.9	41	20	43	840
9	25.5	56.6	54.4	53.4	42	20	37	720
10	24.6	55	54.4	53.3	46	20	27	1200
11	24.4	41.7	42.3	40.2	46	20	20	840
12	28.8	42.2	41.5	39.4	35	20	14	720
13	28.7	44.3	44	41.8	29	20	8	720

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