Original Research Article

Evaluating the efficiency of renewable energy technologies through thermodynamic analyzes

Yasin Furkan Gorgulu

Department of Machinery and Metal Technologies, Keciborlu Vocational School, Isparta University of Applied Sciences, Isparta 32260, Turkey; yasingorgulu@isparta.edu.tr

Abstract: Renewable energy systems hold the key to a sustainable energy future, and at their core lies the pivotal influence of thermodynamics. This article comprehensively explores the fundamental thermodynamic principles that underpin renewable energy technologies, providing a robust foundation for understanding and optimizing their performance. In the context of renewable energy, temperature differentials drive energy flows, pressure and volume changes play crucial roles, and the conservation of energy is paramount. The Second Law of Thermodynamics, represented by entropy, guides the direction of natural processes within these systems. Exergy, a related concept, assesses the quality of energy within a system, facilitating efficiency evaluations. Renewable energy systems often operate on thermodynamic cycles, forming the basis for technologies like solar power plants and geothermal facilities. Heat transfer mechanisms, including conduction, convection, and radiation, are integral to these systems and influence their design and operation. This article summarizes these thermodynamic fundamentals in the context of renewable energy, offering insights into the principles that drive efficiency and sustainability. Understanding these principles is crucial for harnessing renewable energy's full potential and aligning with global efforts to transition toward cleaner and more sustainable energy sources.

Keywords: efficiency; energy transition; environmental impact; innovation; integration; renewable energy; sustainability; thermodynamics

1. Introduction

Thermodynamics, in its essence, is the science that deals with energy[1]. Despite an intuitive sense of what energy represents, a precise definition is found to be a challenging task. In essence, energy can be conceptualized as the capacity to bring about changes. The term "thermodynamics" finds its origins in Greek, where "therme" signifies heat and "dynamis" denotes power. This nomenclature initially reflected early endeavors to convert heat into usable power. However, in contemporary terms, thermodynamics encompasses a much broader spectrum, extending to encompass all facets of energy and its various transformations. This inclusive perspective embraces power generation, refrigeration, and the intricate relationships that govern the properties of matter[2].

Thermodynamics, initially focused on heat-to-work transformations, gradually evolved to recognize heat as a form of energy convertible into other types. Historically, scientists regarded heat as an immutable fluid, transferring it between bodies during heating processes. Remarkably, it was in 1824 that the limitations of converting heat into work were elucidated by Carnot based on this heat-fluid theory, laying the foundation for what is now known as the second law of thermodynamics. Only 18 years later, in 1842, Mayer's

groundbreaking discovery equating heat and mechanical work introduced the principle of energy conservation, the first law of thermodynamics.

Today, it is known that heat's equivalence with dynamic energy lies in the kinetic interpretation, attributing all thermal phenomena to the erratic motions of atoms and molecules. This viewpoint places the study of heat within a specialized realm of mechanics: statistical mechanics. This branch, shaped by Maxwell, Boltzmann, and Gibbs, provides a profound understanding of thermodynamic principles. In contrast, pure thermodynamics relies on experimental postulates, yielding conclusions without delving into kinetic mechanisms. This approach, while accurate, sometimes lacks a detailed understanding of processes. The first and second laws of thermodynamics are rooted in classical mechanics, while Nernst's third law, introduced in recent years, finds its statistical foundation in quantum mechanical concepts. The subsequent sections will explore the implications of the third law[3].

Renewable energy systems have emerged as a linchpin in the global pursuit of sustainable and environmentally responsible energy solutions. As the world grapples with the pressing challenges of climate change and energy security, renewable energy technologies offer a promising path forward. At the heart of these transformative technologies lies the profound influence of thermodynamics, a field of science that governs energy, heat transfer, and their transformations.

Thermodynamics, which encompasses a rich tapestry of principles and laws, plays a pivotal role in understanding, designing, and optimizing renewable energy systems. The marriage of thermodynamics and renewable energy represents a union between scientific theory and practical application, offering profound insights into the efficiency, viability, and sustainability of these systems.

In this article, the mutualist relationship between thermodynamics and renewable energy has been emphasized. The fundamental thermodynamic principles have shown that they underpin the operation of various renewable energy technologies, from solar and wind to geothermal and hydroelectric systems. Temperature gradients, pressure and volume changes, energy conservation, entropy considerations, and exergy assessments are among the key elements that shape the performance of these systems. While the valuable insights provided by previous reviews in this field are acknowledged, the study distinguishes itself by delving into the latest advancements in renewable energy technologies and their alignment with thermodynamic principles. Moreover, particular emphasis is placed on providing a holistic view of sustainability and environmental considerations, an aspect that, though touched upon by previous reviews, is explored in greater depth within this work. Recent developments and innovations in the renewable energy landscape are also taken into account, addressing pressing challenges and proposing innovative solutions for a future powered by nature's abundance. By doing so, a path forward is aimed at being illuminated that is not only informed by the lessons of the past but also adapted to the ever-evolving energy landscape of the present and the future.

2. Thermodynamics in renewable energy systems

Renewable energy, derived from natural sources, is commonly referred to as clean energy. This category encompasses resources that are perpetually replenished, including but not limited to sunlight, wind, rain, tides, waves, geothermal heat, and biomass. Within this spectrum, biomass also finds its place. Notably, carbon dioxide (CO_2) stands as the most prevalent greenhouse gas, but it's essential to recognize that other air pollutants, like methane, are emitted in substantial quantities and contribute significantly to global warming. The clean energy sector has undergone positive transformations, marked by substantial cost reductions, technological advancements, and increased efficiency. Simultaneously, there have been notable strides in developing solutions for seamlessly integrating renewable energy sources into electrical grids. Consequently,

the capacity of renewable energy within the power sector is poised for continued expansion over time. This study places a particular emphasis on the application of energy, entropy, and exergy analyses, which are fundamental concepts in thermodynamics. An in-depth exploration of these concepts is undertaken to provide a comprehensive comprehension of their principles. Additionally, the study delves into the foundational principles and real-world applications of thermodynamic cycles.

Energy is introduced into the system at its inception, representing the entirety of the input exergy, and subsequently departs from the system at various junctures within its course. **Figure 1** illustrates an exergy flow diagram corresponding to the Rankine cycle under specific operational conditions. This visual representation delineates the precise locations within the process where exergy losses transpire and elucidates the mechanisms through which exergy dissipates. This analytical approach holds paramount significance in the context of system design evaluation. Moreover, it furnishes valuable insights into avenues for enhancing system performance and provides strategic guidance for directing improvement endeavors.
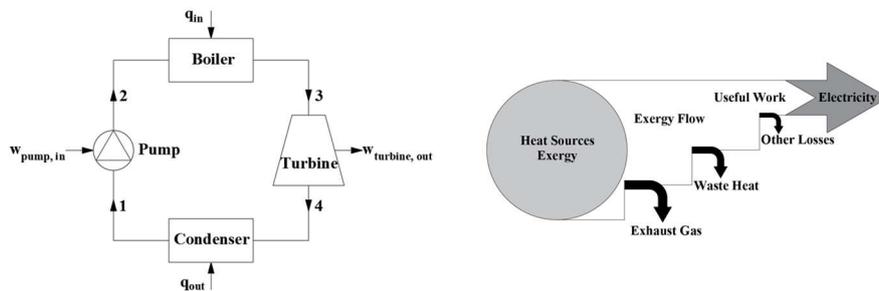

Figure 1. Schematic representation of the Rankine cycle and exergy distribution diagram[2,4].

The Rankine cycle operates with water as its working substance. It commences at state 1, where water enters the pump as saturated liquid and undergoes an isentropic compression to reach the desired pressure in the boiler. At state 2, this compressed liquid enters the boiler, where it transforms into superheated vapor, exiting as such at state 3. The heat supplied to the boiler is sourced from the energy or heat source and involves the conversion of water into steam through an isobaric process. Both the boiler and the superheater, where steam undergoes superheating, are collectively referred to as the steam generator. The superheated vapor then undergoes expansion from state 3 to state 4 across turbine stages. This process converts mechanical energy into electrical energy, generating useful work by rotating the shaft connected to an electric generator. Exiting the turbine at state 4, the steam is at a lower pressure and temperature, existing as a saturated liquid-vapor mixture with high quality (x). It proceeds into a large heat exchanger known as a condenser, where steam is condensed at constant pressure. This condensation is achieved by transferring heat from the steam to the surrounding environment, which can be the atmosphere, a body of water like a lake, or a river. Following condensation, saturated steam leaves the condenser and re-enters the pump, thus initiating a repetition of the cycle. Worth noting is that in these power plants, cooling is accomplished through air rather than water. This method of cooling, akin to what is employed in automobile engines, is termed "dry cooling". The Equations (1) and (2) below provide a means to quantify the thermal efficiency of power cycles[2]:

$$\eta_{th} = \frac{w_{net}}{q_{in}} = 1 - \frac{q_{out}}{q_{in}} \tag{1}$$

where

$$w_{net} = q_{in} - q_{out} = w_{turbine,out} - w_{pump,in} \tag{2}$$

2.1. Solar energy

This represents an innovative thermodynamic cycle with significant potential for enhancing energy conversion efficiency and markedly reducing global CO_2 emissions through the utilization of solar energy as its primary energy source. Solar radiation can be categorized into two distinct components: direct radiation and diffuse radiation. Direct radiation, often referred to as beam radiation, denotes the solar radiation that reaches the Earth's surface without undergoing scattering by cloud cover. Conversely, diffuse radiation, known as scattered radiation, is influenced by interactions with air molecules[4,5]. The collective solar radiation received, which encompasses the sum of both beam and diffuse radiation components, is termed global radiation. In this particular system, the engine harnesses a heat source, such as concentrated solar radiation, to supply energy to a fluid within a closed cycle. This energy, in turn, propels a turbine responsible for generating electricity. This operational cycle is commonly known as the solar Rankine cycle engine[4].

This innovative thermodynamic cycle holds significant promise for enhancing energy conversion efficiency and making substantial contributions to the global reduction of CO_2 emissions, all through the utilization of solar energy as its primary energy source. Solar radiation is classically categorized into two main components: direct radiation and diffuse radiation. Direct radiation, often referred to as beam radiation, represents solar energy that reaches the Earth's surface without undergoing scattering due to cloud cover. In contrast, diffuse radiation, recognized as scattered radiation, is altered as it interacts with air molecules[5]. The collective solar radiation received, which encompasses the sum of both beam and diffuse radiation components, is termed global radiation. Within this system, the engine harnesses a heat source, particularly concentrated solar radiation, as depicted in **Figure 2**, to supply energy to a fluid within a closed cycle. This energy, in turn, propels a turbine responsible for generating electricity. This operational cycle is commonly known as the solar Rankine cycle engine[4].
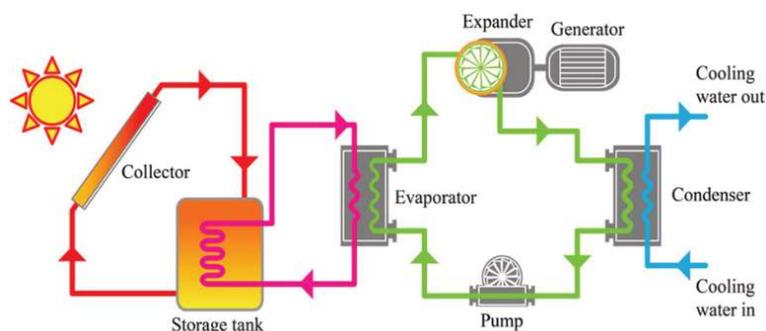

Figure 2. Diagram illustrating a compact solar organic Rankine cycle system[6,7].

The choice of working fluid in solar Rankine cycles is of paramount importance, particularly in low-temperature applications where it significantly impacts cycle efficiency. Recent developments have introduced nanofluids as potential working fluids for organic Rankine cycles due to their enhanced thermal properties, which offer advantages in designing Rankine cycle components and improving performance[8,9]. A nanofluid comprising pentane and silver nanoparticles has been employed as a working fluid in a solar Rankine cycle. The utilization of nanofluids as working fluids allows for the use of smaller heat exchangers and enhances efficiencies compared to traditional working fluids. It is worth noting that employing nanofluids presents several challenges that necessitate further research, including the investigation of nanofluid stability, nanoparticle migration to the gas phase, expander performance, and nanoparticle settling in heat exchangers. Despite these challenges, it is possible to assess the potential benefits that nanofluids can offer to the organic Rankine cycle[4].

In recent years, numerous correlations have been developed to predict the thermophysical properties (density, heat capacity C_p, thermal conductivity k, and dynamic viscosity) of nanofluids[10]. These correlations rely on the properties of the nanoparticles and volume concentration, providing satisfactory results, particularly at lower temperatures and volume concentrations. Nanofluids can be treated as pure fluids, allowing the application of dimensionless correlations for heat transfer in pure fluids by substituting nanofluid thermophysical properties. To compute the thermophysical and thermodynamic properties of nanofluids, including specific heat, thermal conductivity, viscosity, and density, the law of mixtures is employed, as represented by Equation (3)[11]:

$$\alpha_{total} = \alpha_{particles} + \alpha_{base\ fluid} \tag{3}$$

In this context, the symbol α represents a particular thermophysical attribute of the nanofluid. The interconnection between thermal conductivity, thermal diffusivity, and the density of the nanofluid can be delineated in Equation (4)[4]:

$$\lambda = \alpha . \rho . C_p \tag{4}$$

C_p denotes the specific heat, α represents the thermal diffusivity, while λ and ρ stand for thermal conductivity and density, respectively. The specific heat of nanofluids is computed as in Equation (5)[4]:

$$C_{p,nf} = \frac{(1-\phi).\left(\rho.C_p\right)_{bf} + \phi.\left(\rho.C_p\right)_p}{(1-\phi).\rho_{bf} + \phi.\rho_p} \tag{5}$$

The subscripts "nf" and "bf" denote the nanofluid and the base fluid, respectively. The symbol ϕ represents the concentration of nanofluid particles, and ρ signifies density. The calculation of nanofluid density is expressed in Equation (6)[4]:

$$\rho_{nf} = \phi_p.\rho_p + (1-\phi).\rho_{bf} \tag{6}$$

When conducting an energy analysis, two fundamental assumptions are taken into account: firstly, the system attains a state of equilibrium, and secondly, factors such as pressure drop in pipes and heat dissipation to the surroundings are disregarded. The equations utilized for carrying out the energy analysis are presented in Equations (7)–(11)[4]:

Evaporator:

$$\dot{Q}_E = \dot{m}_{ORC}.\left(h_{out,orc} - h_{in,orc}\right) \tag{7}$$

Turbine:

$$\dot{W}_T = \dot{m}_{ORC}.\left(h_{out,orc} - h_{in,orc}\right) \tag{8}$$

Condenser:

$$\dot{Q}_C = \dot{m}_{ORC}.\left(h_{out,orc} - h_{in,orc}\right) \tag{9}$$

Pump:

$$\dot{W}_P = \dot{m}_{ORC}.\left(h_{out,orc} - h_{in,orc}\right) \tag{10}$$

Thermal efficiency:

$$\eta_{ORC} = \frac{\dot{W}_T - \dot{W}_P}{\dot{Q}_H} \tag{11}$$

Shockley and Queisser provided an estimation of approximately 30% as the highest theoretically achievable efficiency for a crystalline silicon solar cell[12–14].

The energy balance equation primarily concerns the quantity of energy rather than its quality. In the realm of thermodynamics, the quality of a given amount of energy is delineated by its exergy, as the examination of exergy is an extension of energy analysis. Moreover, exergy analysis is a valuable tool due to its capacity to provide a precise and robust assessment of thermodynamic systems, taking into account the energy flow capable of performing work. This form of analysis can be applied to an entire system, its subsystems, or individual components, each offering distinct insights conducive to system enhancement[4].

The actual inefficiencies within a thermodynamic system manifest as exergy destruction at its boundaries, and the exergy transferred to the surrounding environment. Exergy loss occurs predominantly due to chemical reactions, fluid friction, flow throttling, the mixing of dissimilar flows, and heat transfer across finite temperature differentials. The overall exergy of a system comprises four main components: chemical, physical, potential, and kinetic exergy. This analysis employs a reference temperature of 298.15 K and a reference pressure of 1.013 bar. The subsequent equations, Equations (12)–(19), exemplify the exergy analysis employed to assess system performance based on the irreversibilities occurring within each component of the ORC (Organic Rankine Cycle) system, such as non-isentropic expansion and compression[4,15].

Fuel:

$$\phi_f = Q_H \left(1 - \frac{T_0}{T_H} \right) \tag{12}$$

Evaporator:

$$\phi_E = \dot{m}_{ORC} \cdot \left(h_{out,orc} - h_{in,orc} - T_0 \cdot \left(S_{out,ORC} - S_{in,ORC} \right) \right) \tag{13}$$

$$I_E = \phi_f - \phi_E = \dot{Q}_H \cdot \left(1 - \frac{T_0}{T_H} \right) - \dot{m}_{ORC} \cdot \left(\varphi_{out,ORC} - \varphi_{in,ORC} \right) \tag{14}$$

Turbine:

$$\phi_T = \dot{m}_{ORC} \cdot \left(h_{out,orc} - h_{in,orc} - T_0 \cdot \left(S_{out,ORC} - S_{in,ORC} \right) \right) \tag{15}$$

$$I_T = \dot{m}_{ORC} \cdot T_0 \cdot \left(S_{out,ORC} - S_{in,ORC} \right) \tag{16}$$

Condenser:

$$\varphi_C = \dot{m}_{ORC} \left(h_{out,orc} + h_{in,orc} - T_0 \cdot \left(S_{out,ORC} - S_{in,ORC} \right) \right) \tag{17}$$

Pump:

$$\phi_P = \dot{m}_{ORC} \cdot \left(h_{out,orc} - h_{in,orc} - T_0 \cdot \left(S_{out,ORC} - S_{in,ORC} \right) \right) \tag{18}$$

$$I_P = \dot{m}_{ORC} \cdot T_0 \cdot \left(S_{out,ORC} - S_{in,ORC} \right) \tag{19}$$

The exergy efficiency of the ORC system quantifies how efficiently the cycle operates concerning its performance in ideal reversible processes. It is determined using Equation (20)[4]:

$$\eta_{II,ORC} = \frac{\dot{W}_T - \dot{W}_P}{\phi} \tag{20}$$

The irreversibility ratio for each component of the solar-driven ORC system is expressed Equation (21)[4]:

$$\text{IR} = \frac{\text{I}_{\text{component}}}{\text{I}_{\text{total}}} \tag{21}$$

2.2. Geothermal energy

Geothermal energy, a renewable resource harnessed from the Earth's interior heat, offers diverse temperature ranges suitable for power generation. Geothermal heat sources span temperatures from 50 °C to 350 °C, making them an ideal heat source for the organic Rankine cycle[4,6,16]. However, it's important to note that in the case of low-temperature geothermal sources (typically below 100 °C), the cycle's efficiency is significantly influenced by the heat sink temperature, determined by ambient conditions. Hot springs, characterized by naturally flowing hot water or steam, are often utilized through extraction methods involving pumping or pressure differentials, typically employing dual wells. Geothermal wells tap into low- and medium-temperature geothermal energy sources, with temperatures reaching up to 150 °C. The volcanic heat source's electricity generation potential is contingent on prevailing temperatures, with effective utilization feasible when heat sources exceed 90 °C (see **Figure 3**).
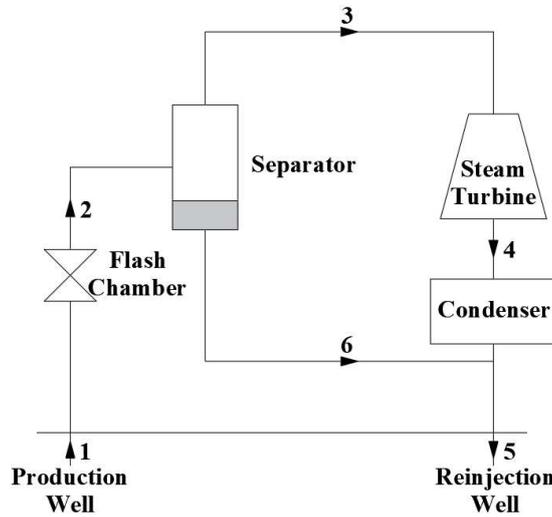

Figure 3. Schematic representation of a single-flash geothermal power plant[2].

The thermodynamic evaluation of a single-flash geothermal power plant closely resembles the analysis applied to the Rankine cycle. Disregarding alterations in kinetic and potential energy throughout the turbine, the power generated by the turbine can be ascertained through the following expression in Equation (22)[2]:

$$\dot{W}_{\text{out}} = \dot{m}_3 \cdot (h_3 - h_4) \tag{22}$$

The energy supplied to the facility can be determined by considering the difference in enthalpy between the state of the geothermal fluid at the facility's inlet and the enthalpy of liquid water at ambient conditions, multiplied by the mass flow rate of the geothermal fluid. This represents the energy content of the geothermal stream as it enters the facility relative to ambient conditions (state 0). Subsequently[2]:

$$\dot{E}_{\text{in}} = \dot{m}_1 \cdot (h_1 - h_0) \tag{23}$$

The thermal efficiency of the facility can be characterized as the proportion of the power produced to the energy supplied to the facility[2]:

$$\eta_{\text{th}} = \frac{\dot{W}_{\text{out}}}{\dot{E}_{\text{in}}} \tag{24}$$

There are also binary cycle power plants utilize geothermal brine from liquid-dominated resources with relatively low temperatures. For instance, it is stated a binary plant in Alaska that taps into a geothermal resource with a temperature of 57 °C[17]. These plants operate based on a Rankine cycle using a binary working fluid such as isobutane, pentane, and so on, which possess a low boiling point. The geothermal water vaporizes this binary fluid entirely and often superheats it through a network of heat exchangers. Subsequently, the binary vapor, after exiting the heat exchangers, undergoes expansion in a turbine and then condenses within an air-cooled condenser (dry cooling tower). Following condensation, it's pumped back to the heat exchanger, thus completing the cycle[2].

2.3. Biomass energy

Biomass, being a green energy source, does not contribute to increased CO_2 levels since it captures atmospheric CO_2 through photosynthesis. It is globally abundant and can be utilized for large-scale electricity generation, ranging from 1 MW to 15 MW. In the context of large-scale biomass power generation, one of the most efficient methods involves co-firing it with coal, achieving an impressive 45% efficiency rate. Conversely, in solid biomass-fired power plants, the typical approach involves combusting the fuel to generate steam, which is then used to drive a steam turbine (utilizing the Rankine cycle). The utilization of low working pressures in organic Rankine cycle power plants has mitigated the challenges associated with high-cost requirements like steam boilers. Another notable advantage is the extended operational lifespan of the engine due to the distinct characteristics of the working fluid, which, unlike steam, doesn't corrode turbine blades. The organic Rankine cycle effectively addresses the issue of limited input fuel availability in many regions, making it feasible for small-scale power plants to employ an efficient cycle[4].

One of the significant outputs derived from biomass is biofuels, which serve as a viable substitute for conventional petroleum-based fuels. Biofuels can exist in both liquid and gaseous forms and find prominent application in the realm of transportation as engine fuels. Additionally, they are utilized for purposes such as heating and electricity generation. Among the most prevalent biofuels are ethanol and biodiesel. The spectrum of biofuel products extends to encompass methanol, pyrolysis oil, biogas, producer gas, and synthesis gas. Biomass primarily serves as a source for the production of biofuels like ethanol and biodiesel. However, it's noteworthy that various other products typically derived from fossil fuels can also be synthesized from biomass. This range of products includes, but is not limited to, antifreeze, plastics, adhesives, artificial sweeteners, and toothpaste gel[2].

Ethanol production primarily relies on the utilization of starch found in corn grains. However, various sources serve as valuable contributors to ethanol production, including corn, sugar beets, sugar cane, and even cellulose-based materials like wood and paper. In the United States, corn stands out as the predominant source of ethanol production, whereas in Brazil, sugar beets take precedence. The selection of feedstock for ethanol production is contingent on its high sugar content. The initial step involves the conversion of the chosen feedstock into sugar, which subsequently undergoes fermentation into ethanol through the following chemical reaction[2]:

$$C_6H_{12}O_6 \rightarrow 2C_2H_5OH + 2CO_2 \tag{25}$$

Biodiesel, either ethyl or methyl ester, is manufactured through a process that involves the blending of organically-derived oils with ethanol or methanol, facilitated by a catalyst. The primary sources for biodiesel production encompass fresh and used vegetable oils, animal fats, and repurposed restaurant greases. Biodiesel possesses a higher heating value of approximately 40,700 kJ/kg, representing a roughly 9% reduction compared to petroleum diesel, which boasts a higher heating value of 44,800 kJ/kg[2].

Methanol, also known as methyl alcohol (CH_3OH), exhibits a higher heating value of 22,540 kJ/kg and a lower heating value of 20,050 kJ/kg. These values are notably less than half of those observed for gasoline. Extensive testing has been conducted on pure methanol and its blends with gasoline as potential alternatives to conventional gasoline. Among these blends, two common mixtures include 85% methanol and 15% gasoline and comprising 10% methanol and 90% gasoline[2].

Pyrolysis oil is generated through the thermal decomposition of biomass under elevated temperatures, typically in the absence of oxygen. One potential process involves rapidly heating cellulosic feedstock, often in granular form, to temperatures ranging from 400 °C to 600 °C for a brief duration, usually less than half a second, followed by rapid cooling or quenching[2].

Biogas, known by various names like swamp gas, landfill gas, or digester gas, typically comprises approximately 50–80% methane (CH_4) and 20–50% carbon dioxide (CO_2) when considering volume. In addition to these primary components, it contains minor proportions of hydrogen, carbon monoxide, and nitrogen. It's worth noting that methane has a higher heating value of 55,200 kJ/kg. Consequently, biogas containing 50% methane by volume has a higher heating value of 14,700 kJ/kg, while that with 80% methane reaches 32,700 kJ/kg[2].

Producer gas is generated through a thermal gasification process, involving the partial oxidation of solid biomass at elevated temperatures to produce a gaseous fuel. During this gasification process, steam and oxygen are introduced to solid biomass, like wood. In practical gasification systems, a substantial portion, typically ranging from 70–80%, of the biomass's heat is effectively converted into energy contained within the producer gas[2].

Synthesis gas, often referred to as biosynthesis gas or syngas, is generated through thermal gasification utilizing oxygen. It primarily consists of carbon monoxide (CO) and hydrogen (H_2). In the case where synthesis gas comprises 50% CO and 50% H_2 by volume, its heating value is calculated to be 19,000 kJ/kg. While synthesis gas can be derived from various sources such as natural gas, coal, and heavy diesel, our particular focus lies in its production from biomass feedstock[2].

2.4. Wind energy

A wind turbine functions by converting the kinetic energy present in the flow of air into electrical energy. This conversion process involves several components, including rotor blades, a drivetrain, a generator, electronic control systems, and various auxiliary elements. As the kinetic energy is harnessed, the air passing through the turbine rotor experiences a reduction in speed. To analyze the thermodynamics of horizontal-axis wind turbines, a common approach involves defining a boundary surface that encloses the affected air flow. This surface forms a long stream tube that extends from well upstream to well downstream of the turbine, with varying cross-sectional areas (as depicted in **Figure 4**)[18].

At the inlet of this stream tube, wind speed (v_1), pressure (P_1), and temperature (T_1) are found. Similarly, at the outlet, v_2, P_2, and T_2 are present, and at the rotor, v_o, P_o, and T_o are located. In this study, it is assumed a constant specific humidity ratio within the stream tube over a short time period. The following sections delve into the theory of wind turbine thermodynamics from two perspectives: energy analysis and exergy analysis. Both of these approaches incorporate meteorological variables such as wind speed, air density, atmospheric pressure, temperature, and humidity. By considering a comprehensive set of meteorological variables, the use of energy and exergy efficiencies allows us to accurately assess the performance efficiency of wind turbines.
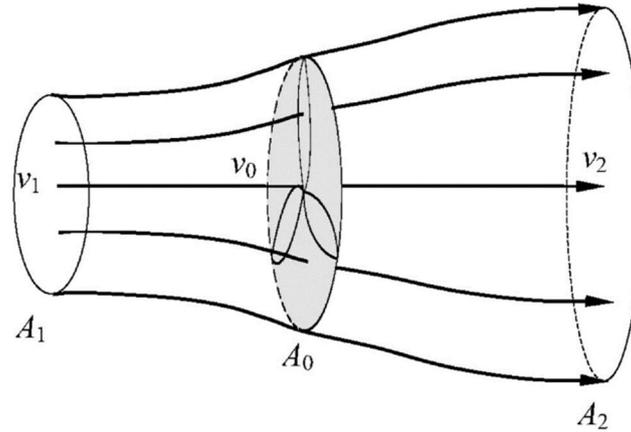
Figure 4. Diagram illustrating the concept of a stream tube surrounding a wind turbine[19].

Wind energy (E) represents the kinetic energy contained within a moving mass of air, characterized by its mass (m) and velocity (v). Determining the mass directly can be challenging, so it's often represented in terms of volume (V) by utilizing the air density (r), where r = m/v. This volume can further be described as the product of the cross-sectional area (A), which is perpendicular to the airflow, and the horizontal distance (L). In a physical sense, this horizontal distance (L) can be defined as "L = v.t", where "t" represents time. Thus, wind energy can be mathematically expressed in Equation (26)[20]:

$$E = \frac{1}{2} . \rho . A . t . v^3 \tag{26}$$

This equation encapsulates the concept of wind energy, taking into account air density, cross-sectional area, and wind velocity. Betz[21], applied a straightforward momentum theory to windmills, a concept initially introduced by Froude[22] in 1889 for ship propellers. This theory examines how the wind's speed changes as it interacts with a windmill rotor, considering two stages: before and after passing through the rotor. In this analysis, let's consider a mass "m" of air passing through the rotor per unit time. The change in momentum rate is represented as "m.$(v_1 - v_2)$", which equates to the resulting thrust produced by the rotor. Here, "v_1" and "v_2" refer to the wind speeds upwind and downwind, respectively, at a significant distance from the rotor. This allows us to express the power absorbed by the rotor, denoted as "P", through the Equation (27)[20]:

$$P = m . (v_1 - v_2) \bar{v} \tag{27}$$

Conversely, the rate at which kinetic energy changes in the wind can be formulated using Equation (28)[20]:

$$E_k = \frac{1}{2} m . (v_1^2 - v_2^2) . \tag{28}$$

The expressions presented in Equations (27) and (28) should equate, implying that the wind's deceleration, represented as $v_1 - \bar{v}$, before the rotor, equals the deceleration, indicated as $\bar{v} - v_2$, after it. This assumes a uniform and axial wind velocity direction through the rotor over the area A. In conclusion, the power harnessed by the rotor is denoted in Equation (29)[20]:

$$P = \rho . A . \bar{v} . (v_1 - v_2) . \bar{v} \tag{29}$$

Moreover Equation (29) can be arranged as Equation (30),

$$P = \rho . A . \bar{v}^2 . (v_1 - v_2) = \rho . A . \left(\frac{v_1 + v_2}{2}\right)^2 . (v_1 - v_2) \tag{30}$$

And Equation (30) can be arranged as Equation (31),

$$P = \rho.\frac{A.v_1^3}{4}.[(1 + \alpha).(1 - \alpha^2)] \text{ where } \alpha = \frac{v_2}{v_1} \tag{31}$$

Upon differentiation, it becomes evident that the power, denoted as "P", reaches its maximum point when "α" equals 1/3. This corresponds to a scenario where the final wind velocity, "v_2", matches one-third of the upwind velocity, v_1. Consequently, the maximum attainable power extraction is expressed as $\rho.A.v_1^3.(8/27)$. In comparison, the original wind contains $\rho.A.v_1^3.(1/2)$. In other words, an ideal windmill has the potential to harness 16/27 (approximately 0.593) of the wind's available power[20,23].

Efficiency in wind energy systems is elucidated through two key metrics: energy efficiency (η) and exergy efficiency (ψ). Energy efficiency, denoted as η (Equation (32)), is determined by dividing the useful energy generated by a wind turbine by the overall input wind energy. Conversely, exergy efficiency, labeled as ψ (Equation (33)), is defined as the ratio of the useful exergy produced by a wind turbine to the total exergy of the incoming air flow[18,20,24]:

$$\eta = \frac{E_{out}}{W_{wind}} \tag{32}$$

$$\psi = \frac{E_{out}}{Ex} \tag{33}$$

2.5. Hydro energy

For centuries, turbines have been employed to harness the readily available mechanical energy from rivers and water bodies, typically achieved through a rotating shaft, to perform valuable mechanical work. The component responsible for this rotation in a hydroturbine is known as the runner. When water serves as the working fluid, these machines are referred to as hydraulic turbines or hydroturbines. To accumulate water with potential energy, substantial dams are constructed along the course of rivers. The water, rich in potential energy, is then directed through turbines to generate electricity, constituting a hydroelectric power plant. Some dams also serve purposes like agricultural irrigation and flood control. The construction of large dams is a time-consuming and capital-intensive endeavor; however, the cost of electricity production through hydropower is considerably lower than that of fossil fuels. Many extensive hydroelectric power plants incorporate multiple turbines arranged in parallel, providing utility companies the flexibility to deactivate certain turbines during periods of low power demand or for maintenance purposes[2].

The mechanical energy contained within a moving fluid can be quantified when considering a per-unit-mass perspective in Equation (34):

$$e_{Mechanical} = \frac{P}{\rho} + \frac{v^2}{2} + g.z \tag{34}$$

This is a representation where "P/ρ" signifies the flow energy, "$V^2/2$" represents the kinetic energy, and "gz" indicates the potential energy of the fluid, all expressed on a per unit mass basis. Consequently, the alteration in mechanical energy within a fluid during incompressible flow can be described in Equation (35):

$$\Delta e_{Mechanical} = \frac{P_2 - P_1}{\rho} + \frac{v_2^2 - v_1^2}{2} + g.(z_2 - z_1) \tag{35}$$

Within fluid systems, our focus often lies in the procedure of harnessing mechanical energy from a fluid through a turbine, resulting in mechanical power in the shape of a rotating shaft, which can be utilized to operate a generator or other rotary apparatus. The efficacy of this conversion process, specifically the extent to which mechanical work is efficiently extracted relative to the change in mechanical energy of the fluid, is

quantified by what is referred to as the turbine efficiency. In a rate-based depiction, this efficiency can be defined by Equation (36):

$$\eta_{Turbine} = \frac{\dot{W}_{Shaft}}{\Delta\dot{E}_{Mechanical,fluid}} = \frac{\dot{W}_{Shaft}}{\dot{m}.\Delta e_{Mechanical}} = \frac{\dot{W}_{Shaft}}{\dot{m}.g.h} = \frac{\dot{W}_{Shaft}}{\dot{W}_{Max}} \qquad (36)$$

Here, represents the power output through the shaft generated by the turbine, and $\dot{m}.\Delta e_{Mechanical}$ denotes the rate of mechanical energy reduction in the fluid. It's equivalent to the maximum achievable:

In this context, $\dot{W}_{Shaft}$ represents the power output generated by the turbine's shaft, while $\dot{m}.\Delta e_{Mechanical}$ signifies the rate at which mechanical energy decreases in the fluid. This rate is equal to the maximum power achievable, denoted as $\dot{W}_{Max}$, and is calculated using the expression $\dot{W}_{Max} = \dot{m}.g.h$, as per the notation. To ensure positive efficiency values and avoid negatives, we consider the absolute value of the change in mechanical energy. A turbine efficiency of 100% signifies perfect conversion between the fluid's mechanical energy and shaft work, although reaching this value is practically unattainable due to frictional effects. It's important to note that turbine efficiency should not be confused with generator efficiency, which is defined as a separate parameter also shown in Equation (37):

$$\eta_{Generator} = \frac{\dot{W}_{Electric}}{\dot{W}_{Shaft}} \qquad (37)$$

The electrical power generated by the generator is represented as $\dot{W}_{Electric}$. Typically, a turbine and its accompanying generator are assembled as a single unit. Consequently, our primary concern lies in evaluating the combined efficiency of this turbine-generator combination. This combined efficiency is defined by Equation (38):

$$\eta_{Turbine} - \eta_{Generator} = \eta_{Turbine}.\eta_{Generator} = \frac{\dot{W}_{Shaft}}{\dot{W}_{Max}}.\frac{\dot{W}_{Electric}}{\dot{W}_{Shaft}} = \frac{\dot{W}_{Electric}}{\dot{W}_{Max}} \qquad (38)$$

3. Results and discussion

The study focused on the thermodynamic assessment of various renewable energy technologies, including solar, wind, hydroelectric, geothermal, and biomass systems. The results of our comprehensive analysis shed light on the efficiency, sustainability, and potential for further enhancements in each system. An energy source earns the "renewable" label when it can be continually replenished without significant environmental impact. It's also referred to as alternative, sustainable, or green energy. In contrast, fossil fuels like coal, oil, and natural gas are non-renewable, diminishing upon consumption while also releasing detrimental pollutants and greenhouse gases[2].

Solar energy stands as one of the most well-known renewable sources. Despite the planet receiving abundant solar energy, its full utilization remains economically challenging due to the relatively low energy concentration on Earth and the substantial upfront costs associated with its harnessing[2]. The analysis of PV cells revealed a wide range of efficiencies, influenced by factors such as temperature, irradiance, and material properties. Thermodynamic principles were pivotal in understanding energy conversion mechanisms and optimizing PV cell performance. For solar thermal system efficiency was observed in solar thermal systems, where the thermodynamic principles of heat transfer, entropy, and exergy were instrumental. Advanced materials and innovative design played significant roles in enhancing overall system efficiency.

Wind energy involves the conversion of kinetic wind energy into electricity via wind turbines. It's the swiftest growing renewable energy source, with wind turbines being deployed worldwide[2]. The efficiency of

wind turbines was assessed through the application of thermodynamic analyses. Factors such as blade design, generator efficiency, and wind speed were found to impact energy extraction significantly. Strategies for improving wind energy efficiency, guided by thermodynamic insights, were discussed.

Hydropower, reliant on amassing river water in elevated dams and directing it through hydraulic turbines, contributes significantly to electricity generation. In certain countries, it fulfills the majority of electricity demands[2].The thermodynamic evaluation of hydropower generation considered dam systems, turbine efficiency, and reservoir management. Sustainable practices, incorporating thermodynamic efficiency metrics, were proposed to mitigate environmental impacts.

Geothermal energy taps into the Earth's heat. In regions with high-temperature underground geothermal fluids, this resource is extracted and then converted into electricity or heat. Geothermal energy conversion represents one of the most established renewable technologies. It's chiefly used for electricity generation and district heating[2]. Our analysis of geothermal systems focused on resource assessment and heat exchange processes. Thermodynamic efficiency metrics were used to optimize energy extraction, ensuring sustainability and reducing environmental effects.

Biomass, considered organic renewable energy, encompasses various sources such as agricultural and forest residues, crops, etc. Biomass energy is gaining traction thanks to its diverse available sources[2]. Thermodynamic analysis of biomass conversion pathways highlighted the role of exothermic reactions and entropy changes. Efficiency metrics specific to biomass conversion informed discussions on process optimization and technology improvements

All renewable energy sources can yield valuable energy in the form of electricity, with some also generating thermal energy for heating and cooling applications. Wind and hydropower exclusively produce electricity, while solar, biomass, and geothermal can be harnessed for both electricity and heat.

4. Conclusion

In this comprehensive exploration of the intersection between thermodynamics and renewable energy, a thorough examination has been undertaken regarding the essential principles, applications, and implications that underpin the transition towards a more sustainable and renewable-dependent energy landscape. Through the lens of thermodynamics, the fundamental mechanisms and efficiencies governing renewable energy systems across a diverse spectrum of sources, from solar and wind to hydroelectric, geothermal, biomass, and energy storage, have been unveiled.

There are several critical takeaways emerge:

(1). Thermodynamics as the guiding science: Thermodynamics, with its laws and principles, emerges as the guiding science that underlines the efficiency, performance, and sustainability of renewable energy systems. From the conversion of sunlight into electricity to the harnessing of wind power and the extraction of geothermal heat, thermodynamic principles serve as the compass guiding engineers and researchers towards the optimal design and operation of these systems.

(2). Renewable Energy's vast potential: The manuscript has showcased the immense potential of renewable energy sources, not only in addressing the looming challenges of climate change and resource depletion but also in reshaping the global energy landscape. Renewable energy is no longer a niche technology; it is a cornerstone of a sustainable energy future.

(3). Efficiency is key: Efficiency, as a core thermodynamic concept, is highlighted as the linchpin in realizing the full potential of renewable energy. The pursuit of higher efficiency across all aspects of renewable

energy systems, from energy capture and conversion to storage and grid integration, is paramount in achieving sustainability goals.

(4). Sustainability and environmental considerations: The importance of sustainable practices and environmental considerations in renewable energy development has also been underscored. Essential components, such as life cycle assessments, biodiversity preservation, and responsible resource management, are emphasized in ensuring that the benefits of renewable energy are realized without compromising our ecosystems.

(5). Ongoing challenges and future directions: While the achievements and advancements in renewable energy are celebrated, the persistent challenges that lie ahead are acknowledged. Pressing concerns, such as energy storage scalability, intermittency management, and the need for robust grid infrastructure, remain. These issues must be grappled with by future research directions while continuing to innovate and optimize renewable energy technologies.

In closing, the marriage of thermodynamics and renewable energy is represented as a beacon of hope in the fight against climate change, environmental degradation, and energy insecurity. It stands as a testament to human ingenuity and innovation. As we look to the future, the lessons learned here must be drawn upon to continue the journey towards a sustainable, clean, and equitable energy future—a future where thermodynamics guides us towards a world powered by nature's abundance, where energy is harnessed efficiently and responsibly, and where the well-being of both humanity and the planet is secured for generations to come.

Acknowledgments

Conflict of interest

The author declares that there is no conflict of interest.

References

1. Kamran M. Thermodynamics for renewable energy systems. In: Kamran M, Faza MR (editors). *Renewable Energy Conversion Systems*. Acedemic Press; 2021. pp. 21–51.
2. Çengel YA, Boles MA. *Thermodynamics: An Engineering Approach*, 8th ed. McGraw-Hill Education; 2015.
3. Fermi E. *Thermodynamics*. Dover Publications; 1956. 176p.
4. Subramanian KRV, George R. *Thermodynamic Cycles for Renewable Energy Technologies*. IOP Publishing Ltd; 2022.
5. Wang R, Jiang L, Ma Z, et al. Comparative analysis of small-scale organic Rankine cycle systems for solar energy utilisation. *Energies* 2019; 12(5): 829. doi: 10.3390/en12050829
6. Baral S, Kim D, Yun E, Kim KC. Experimental and thermoeconomic analysis of small-scale solar organic Rankine cycle (SORC) system. *Entropy* 2015; 17(4): 2039–2061. doi: 10.3390/e17042039
7. Belgasim B, Aldali Y. Review on solar thermal electricity in Libya. *Solar Energy and Sustainable Development* 2018; 7: 49–61. doi: 10.51646/jsesd.v7iSI.74
8. Mondejar ME, Andreasen JG, Regidor M, et al. Prospects of the use of nanofluids as working fluids for organic Rankine cycle power systems. *Energy Procedia* 2017; 129: 160–167. doi: 10.1016/j.egypro.2017.09.098
9. Saadatfar B, Fakhrai R, Fransson T. Conceptual modeling of nano fluid ORC for solar thermal polygeneration. *Energy Procedia* 2014; 57: 2696–2705. doi: 10.1016/j.egypro.2014.10.301
10. Sharma KV, Suleiman A, Hassan HSB, Hegde G. Considerations on the thermophysical properties of nanofluids. In: Korada VS, Hamid NHB (editors). *Engineering Applications of Nanotechnology: From Energy to Drug Delivery*. Springer; 2017. pp. 33–70.
11. Sami S. Impact of magnetic field on the enhancement of performance of thermal solar collectors using nanofluids.

International Journal of Ambient Energy 2019; 40(8): 875–884. doi: 10.1080/01430750.2018.1437561

12. Zanatta AR. The *Shockley-Queisser* limit and the conversion efficiency of silicon-based solar cells. *Results in Optics* 2022; 9: 100320. doi: 10.1016/j.rio.2022.100320

13. Shockley W, Queisser HJ. Detailed balance limit of efficiency of p-n junction solar cells. *Journal of Applied Physics* 1961; 32(3): 510–519. doi: 10.1063/1.1736034

14. Gutowski TG. Manufacturing, renewable energy and thermodynamics. Available online: https://lmp.mit.edu/sites/default/files/documents/Gutowski.pdf (accessed on 30 October 2023).

15. Marin A, Dobrovicescu A, Grosu L, Gheoeghian A. Energy and exergy analysis of an organic rankine cycle. *UPB Scientific Bulletin, Series D* 2014; 76(4): 127–136.

16. Samsuri NB. *A Simulation Study on Performance Enhancement of Technoeconomic Efficiency of Ocean Thermal Energy Conversion Cycle Using Different Working Fluids* [Master's thesis]. Malaysia-Japan International Institute of Technology; 2017.

17. Erkan K, Holdmann G, Benoit W, Blackwell D. Understanding the Chena Hot Springs, Alaska, geothermal system using temperature and pressure data from exploration boreholes. *Geothermics* 2008; 37(6): 565–585. doi: 10.1016/j.geothermics.2008.09.001

18. Hu W, Liu Z, Tan J. Thermodynamic analysis of wind energy systems. In: Okedu KE, Tahour A, Aissaoui AG (editors). *Wind Solar Hybrid Renewable Energy System*. IntechOpen; 2020. pp. 1–19.

19. Coelho P. The Betz limit and the corresponding thermodynamic limit. *Wind Engineering* 2023; 47(2): 491–496. doi: 10.1177/0309524X221130109

20. Şahin AD, Dincer I, Rosen MA. Thermodynamic analysis of wind energy. *International Journal of Energy Research* 2006; 30(8): 553–566. doi: 10.1002/er.1163

21. Betz A. In: Randall DG (translator). *Introduction to the Theory of Flow Machines* (German). Pergamon Press; 1966. 282p.

22. Froude RE. On the part played in propulsion by difference in pressure. In: *Transactions of the Institution of Naval Architects*. Royal Institution of Naval Architects; 1889. pp. 1–423.

23. Golding EW. *Generation of Electricity by Wind Power*. Routledge; 1987. 368p.

24. Redha AM, Dincer I, Gadalla M. Thermodynamic performance assessment of wind energy systems: An application. *Energy* 2011; 36(7): 4002–4010. doi: 10.1016/j.energy.2011.05.001