

# Thermal Power Plant with 1 GW Capacity for Meeting Future National Electric Demands

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## Abstract

An analysis for a conceptual design of a thermal power plant (with a power capacity of 1 GW) is provided. This power plant can help in meeting the expected increase in the electric demand for Oman's dominant power system (2.4 GW between 2018 and 2025). A necessary fluid mass flow rate of 834.1 kg/s was predicted. The overall energy conversion efficiency (output useful electricity divided by input heat) was estimated to be 34.7%. The needed thermal energy is not restricted to a specific source, and solar heating is an option for supplying the needed heat. The power plant design is based on using a steam-turbine section, which may be composed of a single large steam turbine having a mechanical power output of 1115 MW; or composed of a group of smaller steam turbines. The analysis is based on applying energy balance equations under certain assumptions (such as neglecting changes in potential energy). The thermal analysis was aided by web-based tool for calculating needed properties of the working medium, which is water, at different stages in the power plant.

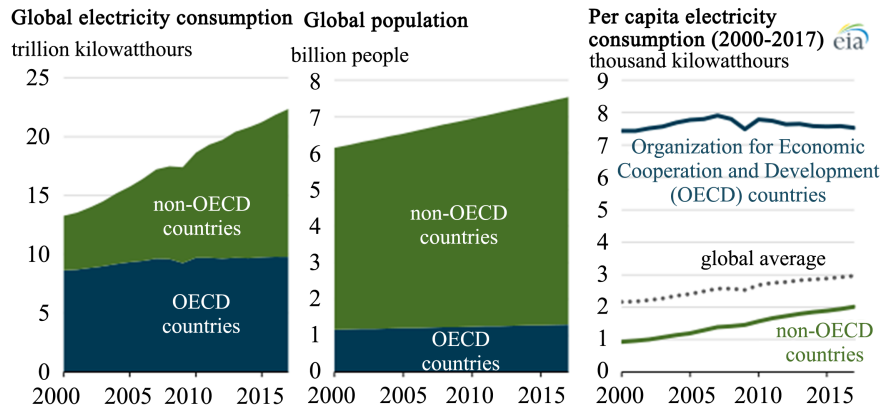
## Keywords

Power Plant, Power Station, Electricity, Energy, Thermal

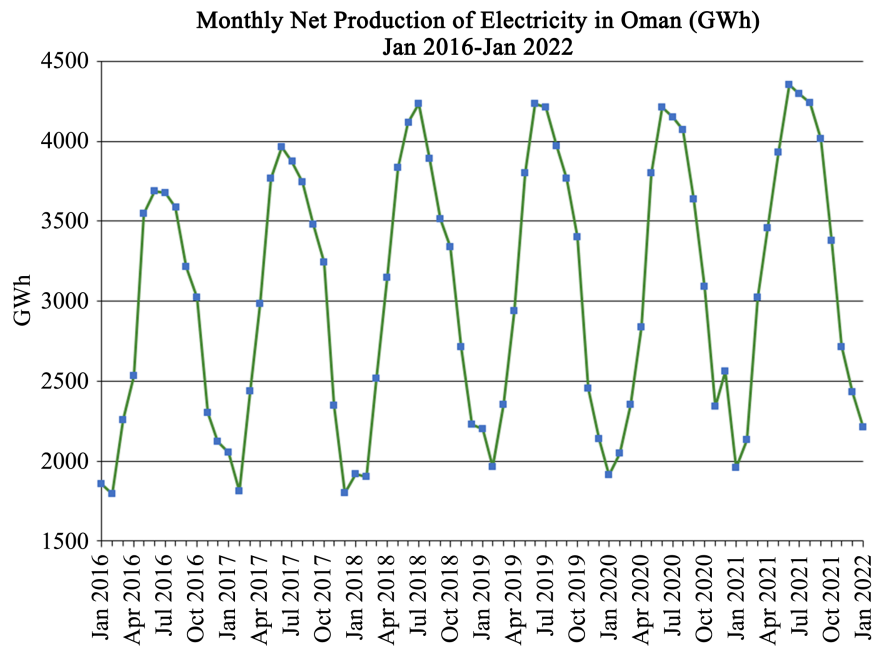
## 1. Introduction

There has been an observed increase in electricity generation or consumption in the Sultanate of Oman particularly and in the world generally [1] [2], as shown in **Figures 1-3**. Such growth in the electricity demand is strongly connected with this work.

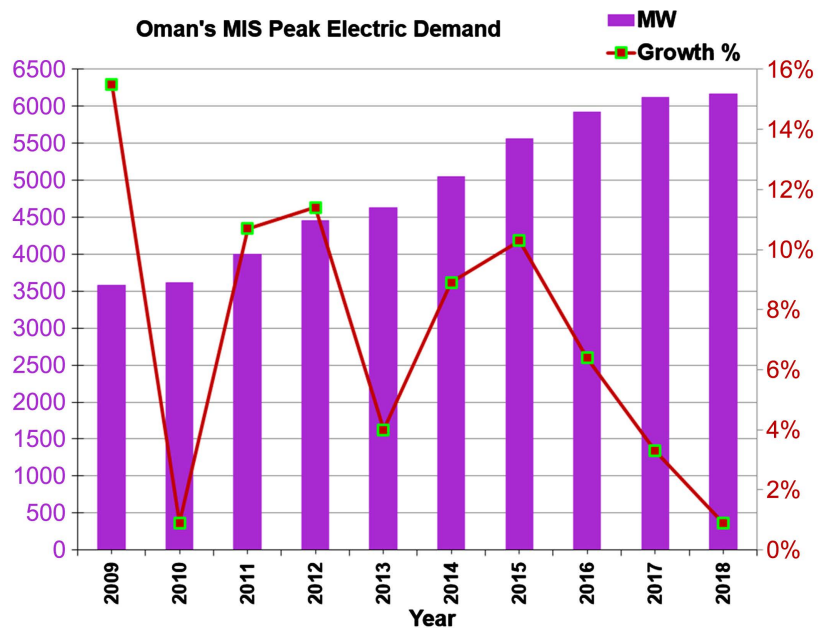
There are four main electric systems in Oman for commercial operations that supply electricity to customers, which are:



**Figure 1.** Historical data of electricity consumption compared with the population. OECD stands for: Organisation for Economic Cooperation and Development [3]. The figure is available publicly by the owner (U.S. EIA, United States Energy Information Administration—15 June 2020) in the public domain (not subject to copyright protection) at: <https://www.eia.gov/todayinenergy/images/2020.06.15/chart2.svg>. It can be reproduced and utilized freely, provided that an acknowledgment is made, which includes the publication date. A Copyrights and Reuse statement is available at: [https://www.eia.gov/about/copyrights\\_reuse.php](https://www.eia.gov/about/copyrights_reuse.php)



**Figure 2.** Monthly records of the net production of electricity, in the Sultanate of Oman covering the period from January 2016 to January 2022, in GWh (gigawatt-hours) [4]. The raw data were made available publicly online by the Data Portal of the Government of the Sultanate of Oman—National Center for Statistics and Information (NCSI): <https://data.gov.om/OMELCT2016/electricity>. The net production is calculated from the total production by subtracting the amount of electricity consumed locally by the power plants themselves. Considering all 73 months in the 6-year range of the data presented here, the average monthly ratio of net production of electricity to total production of electricity in Oman is 97.6%. The latest monthly data available in the data source as of the time of editing this text (11/April/2022) are for January 2022, which is included in the figure. Older data (since January 2014) are available but are not utilized here.



**Figure 3.** Annual records of peak demand at the level of the Main Interconnected System (MIS) of Oman during 2009-2018, in MW (megawatts), and their corresponding growth rates [5]. The raw data were made available publicly online by the Oman Power and Water Procurement Company (OPWP), in its 13<sup>th</sup> issue of the 7-Year Statement at:

<https://omanpwp.om/PDF/7%20Year%20Statement%202019-2025%20New.pdf>

The growth rate for any year is calculated from the peak power demand in that year ( $P_1$ ) and the peak power demand in the previous year ( $P_0$ ) as: growth rate =  $(P_1 - P_0)/P_0 \times 100\%$ . For example, the growth rate in 2018 is 0.9%, and it is calculated as:  $(6168 - 6116)/6116 \times 100\%$ , where 6168 is the peak power demand in 2018 (in MW) and 6116 is the peak power demand in 2017 (also in MW). The latest annual data available in the source document are for 2018, which are included in the figure. Older data (since 2005) are available but are not utilized here. As of the time of editing this text (11/April/2022), the issue of the source document (13<sup>th</sup> issue, for 201-2025) used here is the latest one.

1) The Main Interconnected System (MIS) is an electric grid consisting of a number of power plants (power stations) owned and operated by separate companies [6]. The Main Interconnected System zone includes the Governorates of Muscat, Buraimi, most of the Governorates of Al Batinah North, Al Batinah South, Ad Dakhiliyah, Ash Sharqiyah North, Ash Sharqiyah South, and Ad Dhahirah. Thus, it serves customers in 8 Governorates of Oman out of 11 total [7]. The three remaining Governorates are: Dhofar (southern part of Oman), Musandam (detached part from the Omani mainland, in the north), and Al Wusta (central part of Oman).

2) Dhofar Power System (DPS), which covers the city of Salalah on the south coast of Oman and its surrounding areas in the southern Governorate of Dhofar. The peak electricity demand for Dhofar Power System was 539 MW in 2018. This is about 8.7% of the 2018 peak electricity demand at the level of the Main Interconnected System (6168 MW).

3) Musandam Power System (MPS), where the northern Governorate Musandam is an Omani territory but separated from the main part of the country

by the United Arab Emirates, which is a neighbour country of Oman. The peak electric demand for the Musandam Power System is relatively small, being 83 MW only in 2018 (actual data). This is about 1.3% of the 2018 peak electric demand at the level of the Main Interconnected System (6168 MW).

4) Ad Duqm Power System (APS), where Ad Duqm is located on the eastern coastline of the large Omani Governorate called Al Wusta, approximately half-way between the Main Interconnected System (MIS) and the Dhofar Power System (DPS). The peak electric demand for the Ad Duqm Power System is the smallest among the four power systems, being about 41 MW only in 2018 (actual data). This is about 0.7% of the 2018 peak electric demand at the level of the Main Interconnected System (6168 MW).

Combining the four electric systems together, the 2018 peak electric demand of the Dhofar Power System (DPS), Musandam Power System (MPS), and the Ad Duqm Power System (APS) together was about 663 MW, which is approximately 11% of the peak demand of the Main Interconnected System (MIS) of that year (6168 MW). The 2018 MIS demand (6168 MW) was about 90.3% of the total 2018 peak demand of MIS, DPS, MPS, and APS together (6831 MW). This shows that the MIS grid is the dominant one among the four power systems.

There is also the Petroleum Development Oman (PDO) electric power system. PDO is a company responsible for the oil and gas exploration and production in the Sultanate of Oman. PDO system is connected with the Main Interconnected System (MIS) and the Dhofar Power System (DPS). The PDO electric power system is owned and operated by Petroleum Development Oman itself. PDO power system supplies electricity to the crude oil and natural gas fields of PDO.

As an additional remark, the areas in Oman that are located outside the service zones by the network of any of electric power systems get electricity from the Rural Area Electricity Company (RAEC or RAECO), which primarily utilize diesel generators [8]. The Rural Area Electricity Company later adopted a new brand name of “Tanweer” [9], which refers to an Arabic word that means “illuminating”.

According to the 13<sup>th</sup> issue of the 7-Year Statement of the Oman Power and Water Procurement Company (OPWP), the electricity at the level of Main Interconnected System (MIS) in Oman has been seeing a growing demand consistently between 2009 and 2018, with both the average power demand and the peak power demand in one year being always greater than their values in the previous year. Over that 10-year period (2009-2018), the annual growth rates for the average electric power demand and the peak electric power demand have never been zero or negative, despite an observed variation in their values. This is depicted in **Table 1**.

According to the 13<sup>th</sup> issue of the 7-Year Statement of the Oman Power and Water Procurement Company (OPWP), the peak electric power demand at the level of the Main Interconnected System (MIS) is expected to increase from 6168 MW in 2018 (actual value) to 8600 MW in 2025 (expected value). This means an increase of about 2400 MW (2.4 GW) of peak electric power demand is expected

**Table 1.** Annual electric power demand (average and peak) in the Main Interconnected System (MIS) of the Sultanate of Oman over 2009-2018.

Power Quantity	Year									
	2009	2010	2011	2012	2013	2014	2015	2016	2017	2018
average demand (MW)	1859	2028	2285	2599	2684	2845	3237	3364	3578	3748
Growth rate for the average (%)	12.9%	9.1%	12.7%	13.8%	3.3%	6.0%	13.8%	3.9%	6.4%	4.8%
Peak demand (MW)	3581	3613	4000	4455	4634	5047	5565	5920	6116	6168
Growth rate for the peak (%)	15.5%	0.9%	10.7%	11.4%	4.0%	8.9%	10.3%	6.4%	3.3%	0.9%

The data were made available publicly online by the Oman Power and Water Procurement Company (OPWP), in its 13<sup>th</sup> issue of the 7-Year Statement at: <https://omanpwp.om/PDF/7%20Year%20Statement%202019-2025%20New.pdf>. The latest annual data available in the source document are for 2018, which are included in the table. Older data (since 2005) are available but are not utilized here. As of the time of editing this text (11/April/2022), the issue of the source document (13<sup>th</sup> issue, for 201-2025) used here is the latest one.

in 2025 compared to 2018. For the MIS average electric power demand, it is expected to increase from 3748 MW in 2018 (actual value) to 5304 MW in 2025 (expected value). This means an increase of about 1600 MW (1.6 GW) of average electric power demand is expected in 2025 compared to 2018.

In relation to the above predictions of future electric power needs in Oman, this work considers a power plant with an ability to produce up to 1 GW of electric power. The working fluid is water, which should change between the liquid phase and the vapor phase repeatedly.

An electric power of 1 GW (which is proposed in the current work; and is equivalent to 1000 MW) may be enough to meet the needs of 66,000 homes in the Sultanate of Oman [10], with an estimate of about 15 kW power consumption per home.

An electric power of 1 GW is typical of a large power plant. For example, in the Sultanate of Oman, Al-Rusail Power Plant (located in Muscat, and uses natural gas as a fuel) has a power up to 665 MW or 0.665 GW [11]. The Barka II Power and Desalination Plant (located in the Governorate of Al Batinah South, and also uses natural gas as a fuel) has a power of 678 MW or 0.678 GW [12]. Sur Power Plant in Oman (located in the Governorate of Ash Sharqiyah North, and also uses natural gas as a fuel) has a power of 2000 MW or 2 GW [13].

In terms of originality and contribution to the scientific community; while this study does not introduce a hypothesis or a novel idea, it applies existing principles in thermal sciences and steam power plant operations to design a large-scale power plant with unique conditions. Also, this study may be utilized by undergraduate engineering students or by engineering instructors for explaining energy systems, such as turbines and boilers, with quantitative examples. The design provided here may also be extended by others, through implementing adjustments (such as reheat or elevated temperature of the superheated steam) that can improve the overall power plant efficiency. In this case, the study's contribution is providing an initial design with details about energy con-

version in its main components. Therefore, the additional effort is reduced by focusing on improving this existing design, rather than spending time and computational resources in making a new design.

## 2. Methodology

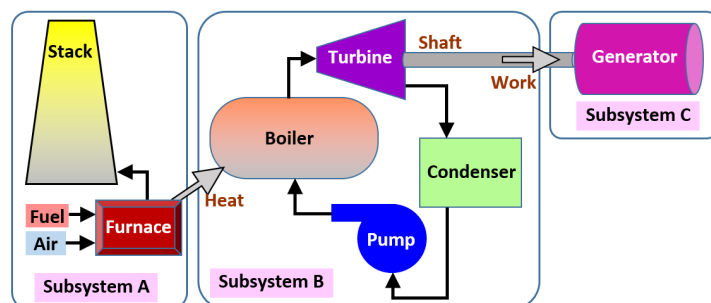
The work follows a quantitative design analysis, through applying principles of energy conversion [14] [15] [16] in each of the four sections in the conceptual power plant (water pump, boiler, steam turbine, and condenser).

**Figure 4** illustrates various elements of a typical thermal power plant, whose function is to convert heat into electricity. These components start with the source of the heat (thermal energy), which can be from burning a fossil fuel, from a nuclear reactor, or from concentrating the solar radiation [17]. The exact source is not specified in this work, and is left to the operator or owner to select. However, solar heating is recommended due to its clean renewable nature.

Regardless of the source of heat, it is received by a boiler that converts liquid saturated water (water that is ready for boiling if heat is absorbed) to superheated steam (water vapor that was heated beyond the boiling point). This superheated steam not only has a high thermal energy content, but also has a high pressure. The heat addition in the boiler takes place in pressurized vessels (like water tubes), where water is boils and steam is generated. The superheated steam is sent to a turbine, which extracts part of its thermal and pressure energy in the form of shaft rotation. The turbine shaft is coupled with the shaft of an electric generator, which is responsible of converting this mechanical power (shaft rotation) into electric power. Water leaves the turbine in the form of a two-phase flow like a mist, composed dominantly of steam but mixed with some carried liquid water droplets [18]. To allow reusing the exhaust water leaving the turbine, a condenser is needed to change the phase of any water vapor into saturated liquid, which can be sent to the pump. Thus, the working fluid (water) is used in a closed cycle.

The following list provides characteristics of some key components in the power plant that process the water in the closed cycle, known as the Rankine vapor power cycle:

- Pump: The specific entropy is constant;



**Figure 4.** Components of a thermal power plant (this sketch was produced directly rather than being taken from an external source).

- Boiler: The pressure is constant;
- Turbine: The specific entropy is constant;
- Condenser: The pressure and temperature are constant.

Requiring the specific entropy to be constant in the pump and turbine is equivalent to demanding very efficient pump and turbine, with no losses due to friction or heat loss.

A description of the analysis is provided next, including the equations used. The following energy balance equation applies to a pump, a boiler, a turbine, or a condenser:

$$\Pi = \dot{m}_{water} |\Delta h| \quad (1)$$

where ( $\Pi$ ) is a positive quantity that is equal to the power delivered to (in the case of pump or boiler) or extracted from (in the case of turbine or condenser) the water in the device, and this power can be thermal (in the case of boiler or condenser) or mechanical (in the case of pump or turbine), ( $|\Delta h|$ ) is the absolute value of the change in the specific enthalpy across the device, and ( $\dot{m}_{water}$ ) is the mass flow rate of water needed to operate the power plant.

Equation (1) implies two assumptions, which are neglecting the energy contributions from changes in the elevation (potential energy) and from the speed (kinetic energy) of the working fluid (water). However, both assumptions appear reasonable and can be justified. For example, an elevation change of the working fluid results in a change in the specific potential energy (potential energy per unit mass, pe) of

$$\Delta pe = gH \quad (2)$$

where the gravitational acceleration ( $g$ ) is approximately  $9.8 \text{ m/s}^2$ , and the elevation change ( $H$ ) is in meters. Thus, a change in the specific potential energy due to 1 m difference in the elevation is less than  $10 \text{ J/kg}$  ( $10^{-5} \text{ MJ/kg}$ ). This is very insignificant compared to changes in the specific enthalpies in any of the four devices analyzed.

In a similar manner, neglecting changes in kinetic energy can be justified. The speed of the working fluid (water) is related to its specific kinetic energy (kinetic energy per unit mass, ke) of

$$ke = 0.5c^2 \quad (3)$$

where the speed ( $c$ ) may be taken for saturated steam (water vapor formed by boiling liquid water, without additional heating beyond the boiling point) as  $30 \text{ m/s}$  [19]. Thus, the specific kinetic energy for this case is  $900 \text{ J/kg}$  ( $9 \times 10^{-4} \text{ MJ/kg}$ ). This is not a large value. The above discussion accompanied with numerical examples suggests that dropping the contribution from potential and kinetic energy is very reasonable.

The mass flow rate of water ( $\dot{m}_{water}$ ) needed to operate the power plant is obtained from:

$$\dot{m}_{water} = \Pi_{plant} / \left( 0.9 \left[ |\Delta h|_{turbine} - |\Delta h|_{pump} \right] \right) \quad (4)$$

where ( $\Pi_{plant}$ ) is the demanded electric power output from the power plant, which is 1 GW ( $10^9$  W), and the factor ( $0.9$ ) is suggested to account for power losses encountered during the various energy conversion processes (heat to mechanical energy to electricity) [20], such as those due to heat losses in steam pipes or friction in the moving parts of the turbine.

The overall efficiency of the power plant ( $h_{plant}$ ) to convert the received heat into electricity is expressed as:

$$h_{plant} = \Pi_{plant} / \Pi_{boiler} \quad (5)$$

It should be mentioned here that this study refers to a single device that represents a process carried out in that type of devices. However, there is a possibility to divide the process load over multiple units of the same device type instead of using a single unit. The decision of using one or multiple units may depend on factors like the price of the unit, the installation effort, and the maintenance cost; and how such factors change with the number of units. This aspect of the design problems is not considered here. As an example, a steam turbine for power plants may range in their output power from 275 MW (like the SST-3000 series of Siemens Energy) to 1900 MW or 1.9 GW (like the SST-9000 series of Siemens Energy) [21].

A number of fixed values were specified in order to reach a unique design. These are summarized below:

- Output electric power from the power plant:  $\Pi_{plant} = 1000$  MW;
- Condenser pressure:  $P_{condenser} = 12.5$  kPa;
- Pumping pressure:  $P_{after-pump} = 5000$  kPa;
- Turbine inlet temperature:  $T_{turbine-inlet} = 600^\circ\text{C}$ .

It should be noted that the pressure after the pump is also the pressure throughout the boiler and at the inlet of the turbine. The condenser pressure is also the pressure of the water leaving the turbine. The selected turbine inlet temperature ( $600^\circ\text{C}$ ) is consistent with the turbine models for power plants. The selected pumping pressure is not challenging for turbines offered in the market, which can operate at even higher pressures [22].

### 3. Results and Discussion

The properties of water were obtained using a digitized version of the water-properties tables [23]. A summary of the results is given below (the energy unit MJ is megajoule, and is equal to:  $1 \text{ MW} \times 1 \text{ s}$ ).

- Condenser temperature (from water-properties tables):

$$T_{condenser} = 50.2^\circ\text{C}$$

- Specific enthalpy before the pump (from water-properties tables):

$$h_{before-pump} = 0.209835 \text{ MJ/kg}$$

- Temperature after the pump (from water-properties tables):

$$T_{after-pump} = 50.4^\circ\text{C}$$

- Specific enthalpy after the pump (from water-properties tables):

$$h_{\text{after-pump}} = 0.214864 \text{ MJ/kg}$$

- Change in the specific enthalpy across the pump:

$$|\Delta h|_{\text{pump}} = 0.005029 \text{ MJ/kg}$$

(Calculated as:  $0.214864 \text{ MJ/kg} - 0.209835 \text{ MJ/kg}$ )

- Specific enthalpy after the boiler (from water-properties tables):

$$h_{\text{after-boiler}} = 3.666330 \text{ MJ/kg}$$

- Change in the specific enthalpy across the boiler:

$$|\Delta h|_{\text{boiler}} = 3.451466 \text{ MJ/kg}$$

(Calculated as:  $3.666330 \text{ MJ/kg} - 0.214864 \text{ MJ/kg}$ )

- Specific enthalpy after the turbine (from water-properties tables):

$$h_{\text{after-turbine}} = 2.329190 \text{ MJ/kg}$$

- Change in the specific enthalpy across the turbine:

$$|\Delta h|_{\text{turbine}} = 1.337140 \text{ MJ/kg}$$

(Calculated as:  $3.666330 \text{ MJ/kg} - 2.329190 \text{ MJ/kg}$ )

- Specific enthalpy after the condenser (same as before the pump):

$$h_{\text{after-condenser}} = 0.209835 \text{ MJ/kg}$$

- Change in the specific enthalpy across the condenser:

$$|\Delta h|_{\text{condenser}} = 2.119355 \text{ MJ/kg}$$

(Calculated as:  $2.329190 \text{ MJ/kg} - 0.209835 \text{ MJ/kg}$ )

- Net energy available for conversion as electricity, per kg of water:

$$0.9 \left[ |\Delta h|_{\text{turbine}} - |\Delta h|_{\text{pump}} \right] = 1.1988999 \text{ MJ/kg}$$

(Calculated as:  $0.9 [1.337140 \text{ MJ/kg} - 0.005029 \text{ MJ/kg}]$ )

- Mass flow rate of water:  $\dot{m}_{\text{water}} = 834.0980 \text{ kg/s}$

(Calculated as:  $1000 \text{ MW} \div 1.1988999 \text{ MJ/kg}$ )

- Pump power (mechanical) consumption:  $\Pi_{\text{pump}} = 4.194679 \text{ MW}$

(Calculated as:  $834.0980 \text{ kg/s} \times 0.005029 \text{ MJ/kg}$ )

- Boiler power (heat) consumption:  $\Pi_{\text{boiler}} = 2878.861 \text{ MW}$

(Calculated as:  $834.0980 \text{ kg/s} \times 3.451466 \text{ MJ/kg}$ )

- Turbine power (mechanical) release:  $\Pi_{\text{turbine}} = 1115.306 \text{ MW}$

(Calculated as:  $834.0980 \text{ kg/s} \times 1.337140 \text{ MJ/kg}$ )

- Condenser power (heat) release:  $\Pi_{\text{condenser}} = 1767.750 \text{ MW}$

(Calculated as:  $834.0980 \text{ kg/s} \times 2.119355 \text{ MJ/kg}$ )

- Overall efficiency of the power plant:  $h_{\text{plant}} = 34.7360\%$

(Calculated as:  $1000 \text{ MW} \div 2878.861 \text{ MW}$ )

It can be useful to add a remark about the predicted power plant efficiency of 34.7360%. This value is near the average efficiency of power plants in the United

States that operate by burning coal, which is 33% [24]. This agreement supports the validity of the analysis presented here.

#### 4. Conclusion

A preliminary design for a thermal power plant of up to 1 GW (1000 MW) electric power generation was provided. The theoretical power plant can operate with thermal energy from a variety of sources. The working fluid is water, which circulates in a pumping section, a boiler section, a turbine section, and a condenser section. The power consumed or released in each section guides in identifying the number of devices to be used in each section. For each unit of thermal energy delivered to the power plant, it produces 0.347 unit of electricity.

#### Conflicts of Interest

The authors declare no conflicts of interest regarding the publication of this paper.

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