Palestine Polytechnic University
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Case study of 5 MW Parabolic Trough Power Plant in Palestine

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Abstract

Electrical power generation can be quite a challenge, but it's essential, there are many ways to produce power and some of them have side effects on the environment (non-clean power plant) such as coal thermal plants, in this project, the power plant will be using renewable sources (clean power plant) for generating power, concentrated solar power system is selected for this project, in particular parabolic trough collectors thermal plant.

The system is planned to be located in Palestine, and it's expected to be able to generate (2-3) % of Hebron's total power consumption and a case study of the system will be analyzed, with different scenarios, such as open loop system without speed drop control, closed loop, variable and constant load effect on the system and its frequency, and maintaining a constant frequency for a safe operation of the grid.

The major challenge in designing power plants, is the variation of sciences used in it, Chemical, Mechanical, Electrical, and more types of engineering are involved in this, thus there is a big challenge in connecting everything together to finally be able to produce power safely.

The system is modeled in Matlab Simulink, and all the scenarios are studied within the software alongside the speed drop control (governor) system, a speed control system is designed and tested using the Matlab Simulink software.

الملخص

يعد إنتاج الطاقة تحدياً، و لكنه مهم، هنالك عدة طرق لإنتاج الطاقة، بعض منها لديه تأثيرات جانبية على البيئة (محطاق الطاقة الغير نظيفة)، و تعتمد على مصادر محدودة، مثل محطات الفحم الحرارية، في هذا المشروع، محطة الطاقة ستستخدم مصادر طاقة متجددة (محطة طاقة نظيفة) لتوليد الطاقة، تم إختيار نظام الطاقة الشمسية المركزة في هذا المشروع، على وجه الخصوص محطة طاقة حرارية من نوع "**Parabolic Trough**".

خطط لأن يكون النظام في فلسطين، و من المتوقع أن يغطي (2-3)% من الإستهلاك الكلي للخليل، و سيتم تحليل حالات دراسية لهذا النظام، مع سيناريوهات مختلفة، مثل الحمل الثابت أو المتغير، و تأثيرات كل منها على التردد و النظام ككل و تصميم نظام تحكم للمحافظة على ثبات التردد لأجل تشغيل سليم مع الشبكة.

التحدي الأكبر في تصميم محطات الطاقة هو التنوع في العلوم المستخدمة بها, الكيمياء و الميكانيك و الكهرباء و عدة أنواع أخرى من الهندسة تشارك في هذا العمل, بالتالي التحدي الكبير هو في ربط تلك العلوم معاً من أجل إنتاج الطاقة بشكل آمن و سليم.

صمم النظام بإستخدام برنامج ماتلاب سيميولنك، و تم دراسة جميع الحالات في البرنامج مع نظام الجوفيرنر و التحكم في السرعة و التردد للنظام، سيتم تصميم نظام تحكم بسرعة المولد و تنفيذه و إختباره بإستخدام برنامج الماتلاب سيميولنك.

DEDICATED

To our families

To our parents

To our Homeland

To everyone gave us the support we asked

And to everyone who appreciate the value of science.

ACKNOWLEDGEMENT

We would like to give our grateful to the whole educational staff in Palestine Polytechnic University that we grew up with, and especially to our project supervisor PhD. Abdelkarim Daud for giving us his time when we asked and helping us to go through this project.

And it’s our pleasure to give thanks to our families for the support and encouragement that they gave to us all those studying years.

To all of you, Thanks!

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Chapter 1

Introduction

1.1 Introduction :

Electrical power became one of the life essentials nowadays, Palestine isn’t excluded, since it doesn’t own any source of power because it’s under occupation, that mean owning an independent source of power is essentially, building a power plant is needed in Palestine, but also the sources to run a traditional power plant are not available all the time or limited in Palestine, therefore the best choice is to go green and harvest the power that exist around us and no one has control over it, therefore the choice landed on the Concentrated Solar Power(CSP) technology and in particular Parabolic-Trough type.

Concentrated power plant is a type of thermal power generation, and therefore the main component is the heat source, and in this case, it’s the sun, thus the area will play a great role of deciding how the efficiency of the plant will be, Palestine has an average **direct normal radiation (DNI)**[5] of 2300kWh/m2 which is a high value considering for example Spain, as it has the highest total CSP plants capacity[12] in the world with 2300MW of total plants, it has a DNI[29] average of 2100kWh/m2, giving those information, Palestine is a suitable area for using CSP.

Thermal power plants, In general, are all similar in the power block, since all of them uses thermal power to create mechanical power and the mechanical power then are converted into electrical power, but the main difference is the way thermal power is produced, some are using natural gas and some are using nuclear reaction to create the heat their seeking for, but all of the traditional methods of thermal power generation have side effects either on the environment or the people that live near them and are all limited sources of power, for that, Concentrated Solar Power is combining the advantages of generating electricity from generators and the environment-friendly aspect.

Hebron city in Palestine is consuming 368 GWh yearly[14], and in our project we are scoping to study a 5MW plant that can provide 2-3% of Hebron’s yearly consumption.

1.2 Literature review :

Using CSP Plant(CSPP) to generate power isn't a new thing, it's been used since 1912 which is actually the first time CSP plant saw the light and it was in Egypt near Cairo[1], and to be more exact, it was Parabolic Trough type, and since then the development in CSP technologies never stopped.

M. Al-Soud, E. Hrayshat[2] from Jordan designed a prototype of 50 MW CSPP in Jordan the analysis of their data showed that Jordan has a positive potential of using CSPP.

Pedro Á. Gómez Showed in his book[3] a detailed analysis of steam generators for CSPP and dived deeply in improving the efficiency and matching it well with the economical part.

E. Bellos, C. Tzivanidis and K. Antonopoulos[4] published a detailed working fluid investigation for Euro Trough(ET) collector were their research focusing the light on the performance of CSPP under different Heat Transfer Fluids(HTF), such as Therminol VP1 and Molten salts and other fluids.

E. Ajlouni, H. Alsamamra did **a review of Solar Energy Prospective in Palestine**[5] which opened out eyes on the possibility of having CSPP in Palestine.

1.3 Scope of Project

The plant will provide the power needed at the peak demand, this will reduce the marginal price of the electricity at the peak demand, new opportunities for power engineers is raised, the engineers staff is needed to operate and maintain the power plant, and the educational opportunities are not excluded since it will be a very appreciated place to develop practical skills for engineers in Palestine.

1.4 Objectives

For this project, the main goal is to design a 5 MW capacity power plant in Hebron in Palestine, this capacity shall be responsible of providing Hebron of 2-3% of its yearly consumption, and to achieve this, it needed to:

1). Select and analyze a suitable collector.
2). Analyze and select a proper power conversion system.
3). Select a suitable generation unit.
4). Model and simulate and test a speed drop control system to control the generator's speed to maintain a constant frequency on the grid.
5). Design a Matlab model to test the proposed design with case studies proposed.

1.5 Estimated Cost and Revenue

Such project is very costly but in the other hand can be profitable, either economically or in other terms, and to estimate the cost of this project, another projects close in to this project in its properties are investigated.

National Renewable Energy Laboratory (NREL) published a cost analysis research [13], and for this project's specs, the cost of kWe in dollar is equal to = 4600 $/kWe in 2012, and given the reduction in the prices in 2018 the estimated cost of kWe is around 3500 $/kWe, given those information, the costs are decreasing furthermore, and using NREL software (SAM), the estimated cost of this plant is around **17.5 Million $**, but is it worthy?

To answer this, we need to estimate the revenue and the payback period of the plant, according to Hebron Municipality's annual report[14], Hebron city consumes **369 GWh** yearly and that costs them 206 Million NIS which is **59 Million $ yearly**.

For this project we can estimate the output yearly generation using the following equation (1.2)[15]

$$\boldsymbol{E = \varepsilon \cdot P \cdot 365\, day \cdot 24h} \tag{1.2}$$

E : Annual Energy (Generated Electricity) in Wh/year

$\boldsymbol{\varepsilon}$: Capacity Factor

P : Net Capacity

So the estimated yearly generation can be calculated, thus the estimated payback period is also known, the average capacity factor of such system is 22% based on a report from NREL[13], The annual energy generated is :

$$\boldsymbol{E = 0.22 \cdot 5(MW) \cdot 365\ day \cdot 24h}$$

E = 9.63 GWh/year

Which is **2.61%** of Hebron's yearly consumption, and thus this costs **1.54 Million $ yearly**, which In turn gives us a simple payback period of:

$$\boldsymbol{PB = \frac{17.5}{1.54} = 11.4\ years}$$

Steam generator based power plant has up to **20 years** lifespan (check appendix F), so the plant is predicted to be profitable for about **9 years** of operation.

2

Chapter 2

Concentrated Solar Power Plants

2.1 Types of Thermal Power Plants(TPP)

Thermal Power plants are the most commonly used type of plants in the world, so basically any plant that required converting thermal power into electrical power is considered a Thermal Power Plant no matter how the thermal power is collected or generated, some famous examples of those plants are the Natural Gas Plants(NGP), Nuclear Power Plant(NPP) and the Concentrated Solar Power Plant(CSPP), every type has its own way to get the thermal power required for the plant, NGP plants burn gas to generate heat then convert it into electrical power, NGP and CSPP are using nuclear reaction to generate heat and collecting solar heat, respectively, therefore the way of getting the thermal power is the most important point to describe which type of TPP it is, and for environmental-friendly plant it’s better to use the renewable sources as a source of thermal power, such as geothermal and sun, therefore CSPP are considered in this project.

2.2 Types of Concentrated Solar Power Plants(CSPP)

All CSPP are common in one aspect which is using the sun irradiation (direct) to generate electrical power, but the way heat is collected is deciding which type of CSPP[7] it is, there are three commonly known types of CSPP which are:

- Solar Power Tower
- Parabolic Trough
- Dish Stirling

And there are more types such as Fresnel Reflector, but the first three mentioned types are the most common.

Figure (2.1) shows those types:

Figure (2.1) From Left to right, Parabolic, Tower, Dish Stirling

Tower type concentrate solar heat (solar radiation which turn into heat) to one point, and dish type is typically same as tower but instead of many mirrors reflecting into one point here each individual mirror reflect heat into individual point, in parabolic trough, linear mirrors are reflecting heat into receiver tube.

2.3 Parabolic Trough Solar Power Plant

2.3.1 Introduction:

Parabolic Trough plants are the most commonly used topology of CSPP despite it has lower efficiency than Solar Tower[6] , that's because of its high efficiency to value ratio, which means, it's more economical efficient to use Parabolic Trough Collectors(PTC), and for that particular reason we picked the PTC type.

PTC concentrate sunlight on a liquid inside a tube that runs parallel to the mirror as shown in figure (2.2) below. The liquid heat is generally used to produce steam that drives a steam turbine[7], which in turn used as a prime-mover to drive a generator that produces electrical power.

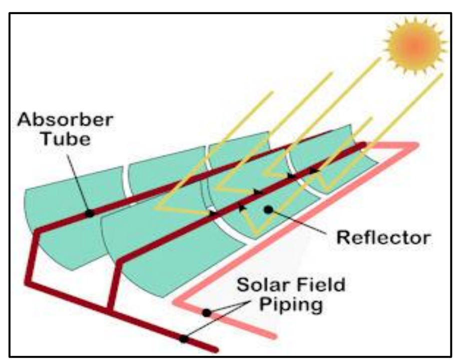

Figure (2.2) Heating illustration

This hot liquid will be transferred via pipes to the steam generator which in turn is going to heat up water until steam with produced, that steam has also high pressure that make it possible to turn a turbine, the steam then goes back to be condense again to water and then reused back again in the steam generator, and the cycle goes on.

2.3.2 Power Conversion Cycle

Power conversion is where the thermal power is converted into mechanical power that drives a generator's prime mover to generate electricity, this flow is known as the Power Cycle, and the most common used and efficient cycle in steam generation is Rankine Cycle [3], Figure (2.3) will show the schematic diagram of the Rankine cycle used in this project.

Simple Rankine Cycle can be expressed [3] as follow:

1). compressing pure feed water to high pressure (usually in MPa)
2). boiling and superheating water into steam in a boiler
3). expanding high pressure steam into low pressure steam using turbines(which in turn gives mechanical rotation)
4). Condensing the low pressure steam to liquid and reuse it in the cycle again.

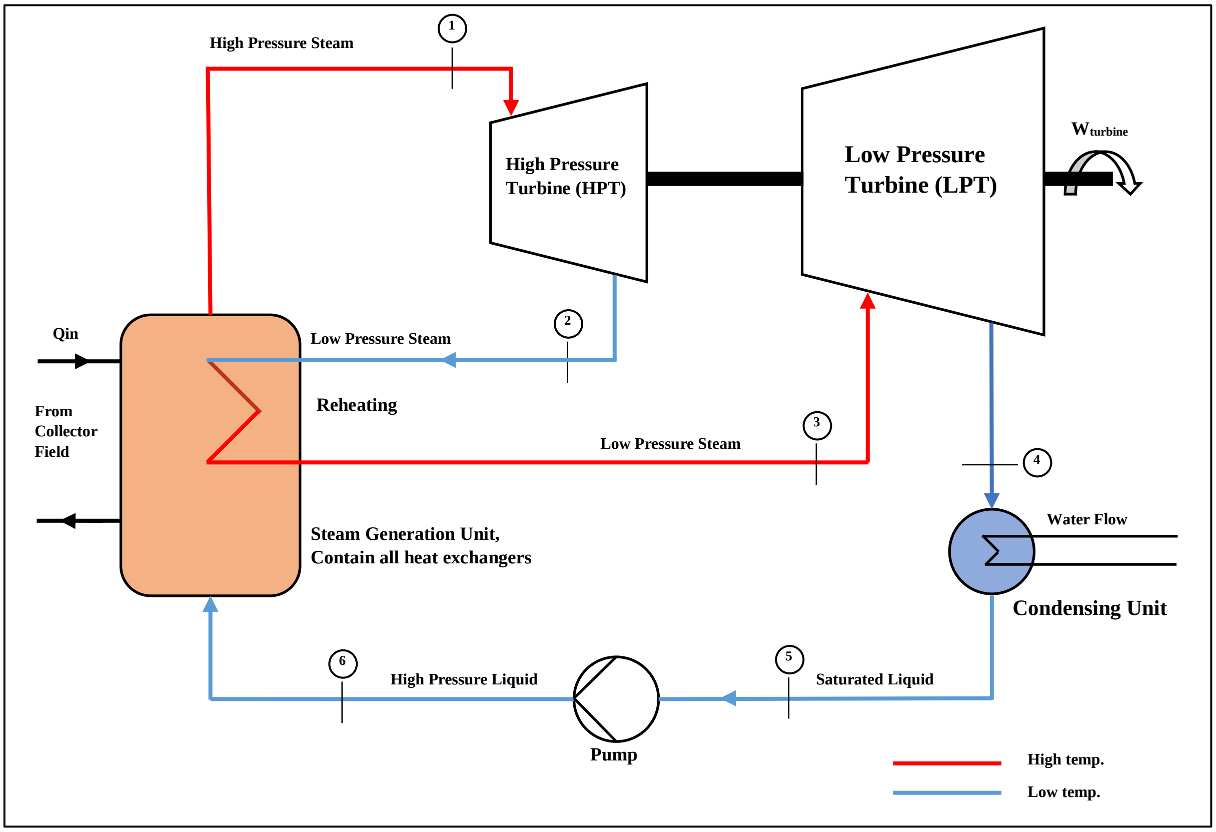

Figure (2.3), Rankine cycle approach, follow steps from (1 to 6)

The connection of two turbines (High Pressure and Low Pressure) is because it's not practically logical to jump from very high pressure in (MPa) to (KPa) directly, and this might damage the turbine and reduce its efficiency, for that two turbines are used to make it more practical and more efficient [11].

In Rankine cycle, to increase the efficiency you need to increase the temperature and the pressure [3], so it can be expressed as follow in equation (2.1):

$$\boldsymbol{P}\uparrow \quad \boldsymbol{T}\uparrow \rightarrow \quad \eta\% \uparrow \tag{2.1}$$

For that reason, in step 2, the output wasn't connected directly to the low pressure turbine, but rather, connected to a re-heater that rises up the temperature of the steam again since its temperature decreased because it's converted into mechanical power inside the high pressure turbine.

2.4 Concentrated Solar Power Plants

This section will focus on the main component of the Parabolic Trough Solar Power Plant (PTSPP), the design approach is to divide the plant into several parts, and then work on each part individually, and then connect them all together and make the necessary adjustments, to finally get a one piece plant, the plant is broke-down into 4 main parts which are:

1). Solar Field Block
2). Power Conversion Block
3). Power Block

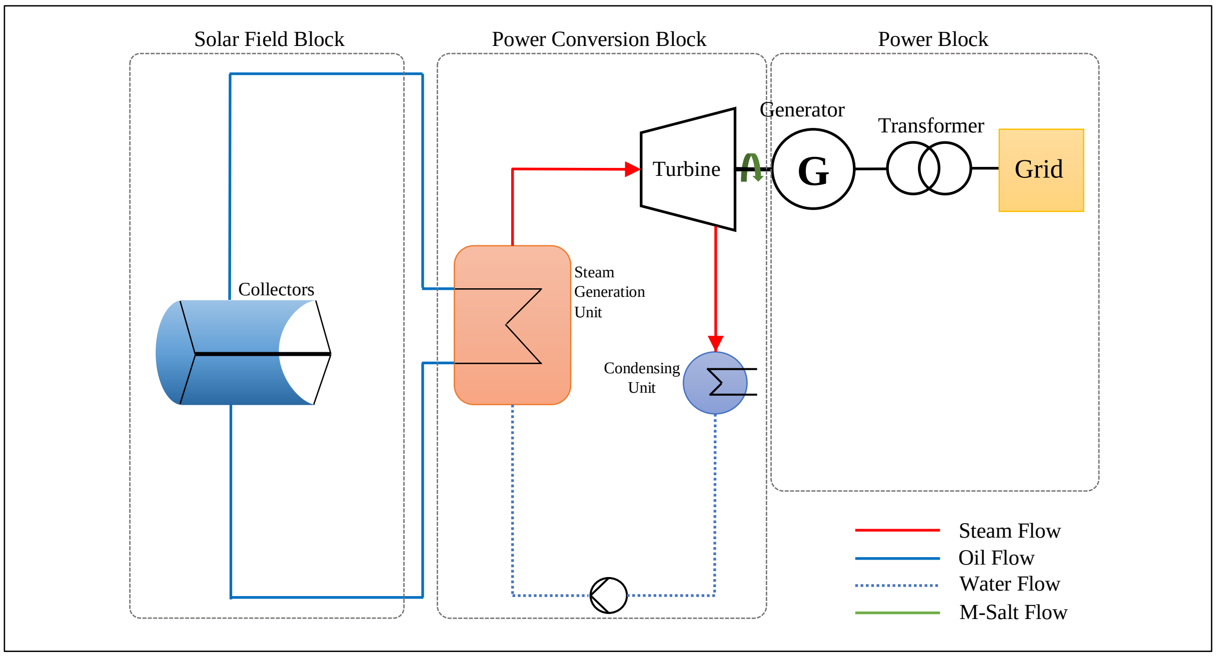

Figure (2.4) Plant Diagram

2.5 Plant Flow

Solar field block is the one responsible of collecting heat from the sun and concentrate it in a receiver that contains a specific Heat Transfer Fluid (HTF), HTF's main purpose is to transfer the heat through the TES to the power conversion block, where the steam generator will use this heat to convert the water into high pressure steam that's responsible of driving a Generator in the Power Block to finally generate electrical power which will be stepped up to high voltage using generator step up transformer, this High Voltage(HV) electrical power will be ready to be transmitted to the grid.

The total conversion ratio of this process is depending on many factors, most importantly the power conversion cycle, table (2.1) [3] shows the estimated efficiency (ŋ) in different pressure and temperature levels for Rankine Cycle:

Table (2.1) Estimated Efficiency of Rankine Cycle

Temperature	Conversion ŋ at 15Mpa	Conversion ŋ at 5Mpa	Real Net Conversion ŋ
700	48%	44.6%	40-45%
400	43.4%	40.2%	35-40%
300	31.5%	39%	25-30%

But this is not the total efficiency of the plant, the total efficiency will be less than the conversion efficiency, due to the losses and the auxiliary equipment in the plant.

2.6 Solar Field Block

This is the block that's responsible of the heat collection, this is done using a Parabolic Collector with a receiver tube connected to it, as figure (2.5) shows.

Figure (2.5) Parabolic Collector

2.6.1 Parabolic Collectors

Parabola-shaped mirrors produce a linear focus on a evacuated receiver tube along the parabola's focal line. The complete assembly of mirrors plus receiver is mounted on a frame that tracks the daily movement of the sun on one axis, figure (2.6) shows the structural diagram of a parabolic trough solar collector.

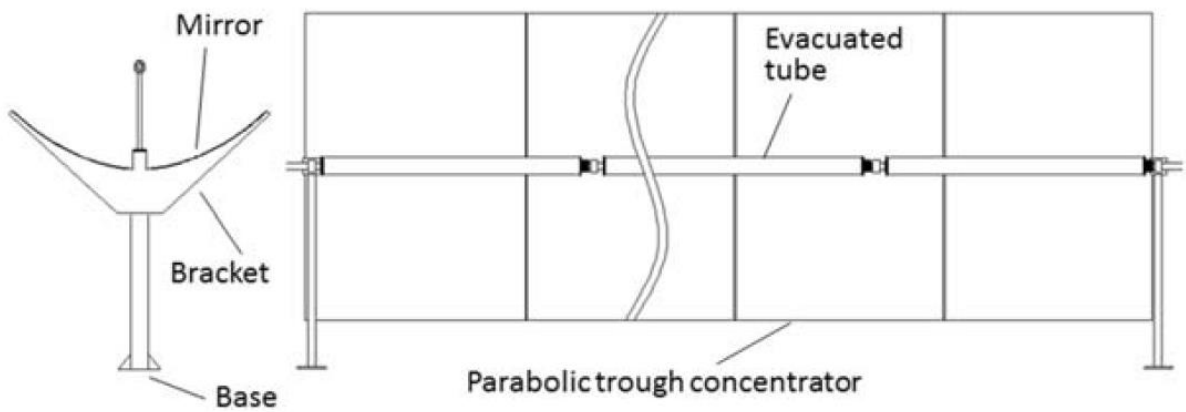

Figure (2.6) Structural diagram of parabolic trough solar collector

2.6.2 Receiver tube

The evacuated receiver is responsible of conserving the heat of the HTF and prevent it from losing its heat, therefore a special type of receiver tubes are used, figure (2.7) shows the schematic diagram of a receiver tube.

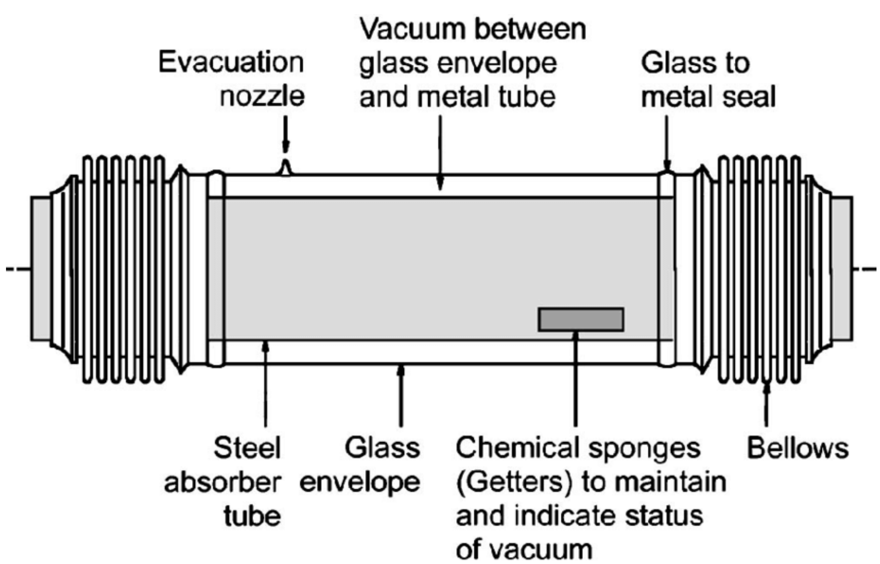

Figure (2.7) Schematic diagram of a parabolic receiver tube

2.6.3 Thermal analysis of parabolic collector

Thermal calculation aims to know the thermal power production of a specific collector, using the following equation [16] it will be possible to calculate the thermal power of a parabolic trough collector.

$$Q_u = F_R[SA_a - A_r U_L(T_i - T_a)] \tag{2.2}$$

Qu = useful power
Aa = Aperture collector area
Ar=Receiver area
S = mean solar radiation
FR = Heat removal factor
Ti = Inlet fluid temperature
Ta = Ambient temperature
UL = Overall collector heat loss coefficient.

2.7 Power Conversion Block

In this block the thermal power will be converted into mechanical power using the Rankine cycle, the Rankine cycle contains several important parts which are:

1). Steam generation unit
2). Turbines
3). Condensing unit
4). Pump

2.7.1 Steam Generation Unit(SGU)

To convert water into high pressure steam efficiently, steam generators has different components, figure (2.8) is showing those components which are in facts, different types of Heat Exchangers.

There is 4 main component in the SGU, which are:

1). Super Heater
2). Reheater
3). Evaporator
4). Economizer

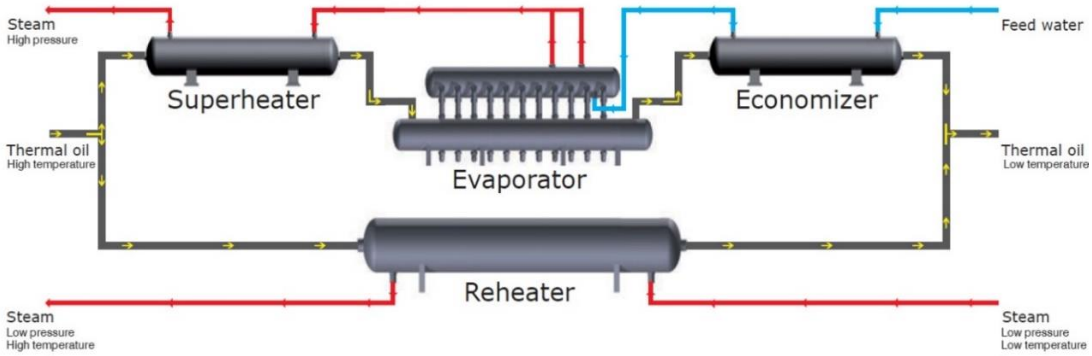

Figure (2.8) Steam Generator Unit components

- **Super heater:** it's used to heat up the saturated steam until high pressure turbine inlet condition is achieved.
- **Evaporator:** it's used to provide heat to generate steam from hot water.
- **Economizer:** often called "Preheater", it's used to heat up the steam generator feed-water until achieve the saturation conditions.
- **Reheater:** it's used to heat up the steam that came out from the high pressure turbine until achieve low pressure turbine inlet temperature condition.

2.7.2 Turbines

Turbine are used to convert thermal power into mechanical power by expanding the higher pressure steam through the turbine blades into lower pressure steam which rotate the turbine shaft[11], two turbines are used, one is a High Pressure Turbine(HPT) and the other is a Low Pressure Turbine(LPT), using two turbines is to increase the efficiency and protect the turbine from a potential damage due to the reduction from very high pressure(in MPa) to very low pressure(in kPa), figure (2.9) is showing the principle working of a simple steam turbine.

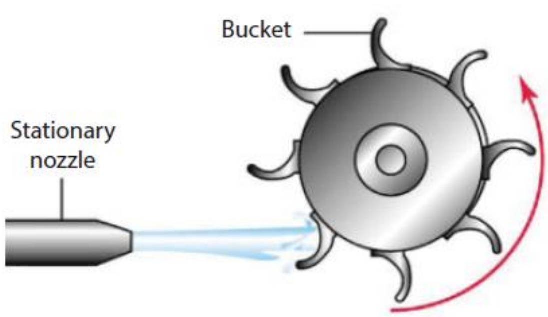

Figure (2.9), simple steam turbine

2.7.3 Analysis

Thermal and dynamic analysis are the main parts of power conversion analysis, and to be able to calculate the output power of this cycle, a simple and graphical approach is chosen and taken from I. Urieli in his book (Engineering Thermodynamics)[11], this approach isn't very accurate because it ignores the losses and the auxiliary consumption, but it makes analyzing complicated thermal plants a simple task, then the actual values can be calculated from knowing the tolerance value in the calculation, and this is achieved from the same book as it analyze a real known plant with known specifications, so the real results can be compared with the analytical one, thus the accurate calculation can be achieved.

For the power conversion cycle, the most common equations are used to for this analysis are descried as follow in equations (2.2) and (2.3), which gives the output power of the turbine and the enthalpy of the turbine, respectively.

$$\boldsymbol{W_{turbine} = \dot{m} \cdot w} \tag{2.3}$$

Where $\dot{m}$ the mass flow, and **w** is the total enthalpy of the turbine

$$\boldsymbol{w = h_1 - h_2} \tag{2.4}$$

Where h1 and h2 are the inlet and the outlet enthalpy [11], respectively, of the turbine as shown in figure (2.10), and they are related to the pressure and the temperature in each step.

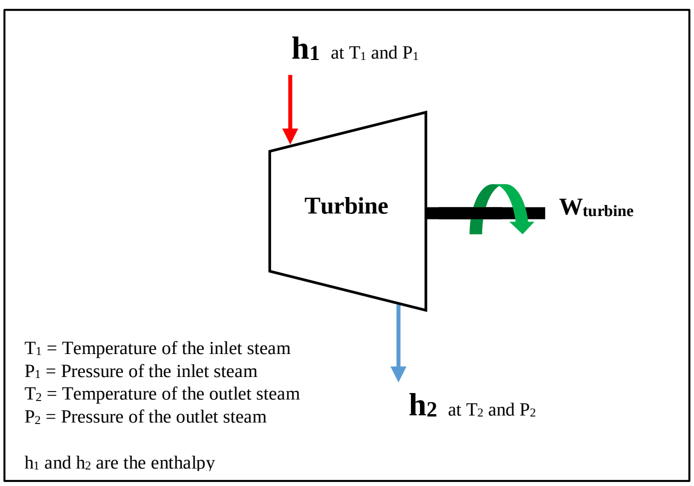

Figure (2.10), simple analysis of one turbine

2.8 Power Block

The power block is the final block in this project, and it's the most important one, since the electrical power is finally generated here, so it consist of two main components, which are the generator and the transformer, the generator's function is to convert mechanical rotation of the turbine into electrical power, and the transformer is used to step up the output voltage of the generator, to prepare it to the transmission part, which is happening outside the plant.

Those important components are expensive, and any damage in them will not be financially costly only!, but will stop the plant from functioning too, which might lead to blacking out[18] the system which is something unwanted, and for that, an enhanced protection system is designed to protect the generator and the transformer from any expected faults.

2.8.1 Generator

Generators convert mechanical power into electrical power, the generator is the main part of any power generation project, and there are many types of generators, each with special properties.

The most common used generators are the Induction Generator(IG) and the Synchronous Generator(SG), for this plant, SG is selected, because the speed delivered from the turbine is constant and thus the prime mover of the generator will run in a constant speed, the IG is used In case of the alternating speed such as wind turbine.

2.8.2 Transformer

Transformers most common function is to either step up or step down the voltage or the current, in the power plants, there are many types of transformers are used:

1). Generator transformer
2). Station transformer
3). Auxiliary transformer
4). Instrument transformers

The Generator Transformer is used to step up the output voltage of the generator so it can be transmitted using the transmission lines, since it's known from ohm's law that in case of constant power, if the voltage increases the current decreases to match the power, and reason of decreasing the current is to reduce the cost of the transmission equipment and to reduce the losses [19].

The Station Transformer is used to provide the generation unit with the starting power needed when the plant is newly constructed, or in case of a shutdown happens for some reason, and the generation units need to start up again, and it receives its power from the grid.

The Auxiliary Transformer is used to deliver power to the low voltage loads (below 1kV) inside the plant.

The Instrument transformers are used for metering and protection.

2.9 Speed Drop Control of Synchronous Generator

The Synchronous Generator (SG) can rotate in a constant speed called the "synchronous speed", which is what distinguish it from the induction machine, the speed of the generator is related directly to the frequency and the number of poles of the generator as shown in equation (2.5)[24]

$$\boldsymbol{N_m = \frac{120 \cdot f}{P}} \qquad (2.5)$$

Where

Nm = synchronous speed (rpm)

f = Frequency

P = number of poles

Usually the load at the grid is not stable, and from figure (2.8) [24], the change in the load can cause a slightly change in the frequency, thus, the speed of the SG will be changed due to the change in the frequency as equation (4.3) shows.

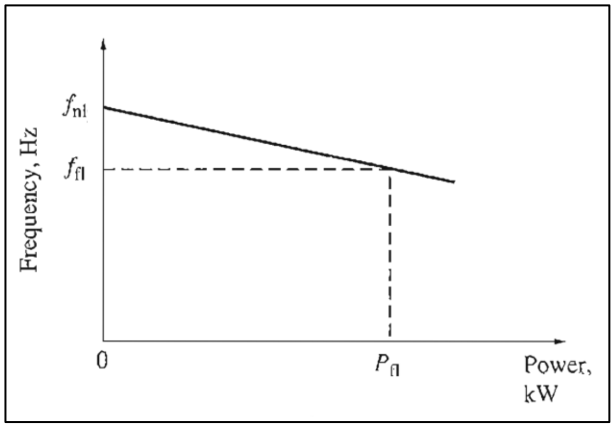

Figure (2.8), Frequency vs Power curve for a generator

Furthermore, any change in the frequency will cause an unwanted damage to the devices that's connected to the grid, therefore it's important to maintain a constant frequency within a very small acceptable deviation[25] (±0.1Hz), and to be able to control the frequency.

The most common method for speed control for steam generators, is the Speed Drop Control (SDC) method, in this method, a reference speed is used in a closed loop system that will identify any change in the speed, resulting in a speed drop value, which is used to determine a valve opening of a turbine, thus, the speed of the turbine is changed due to this, and since the turbine is the prime-mover of the SG, the speed of the SG will change too, furthermore, the frequency will change too, figure (2.9) shows the schematic diagram of this control method.

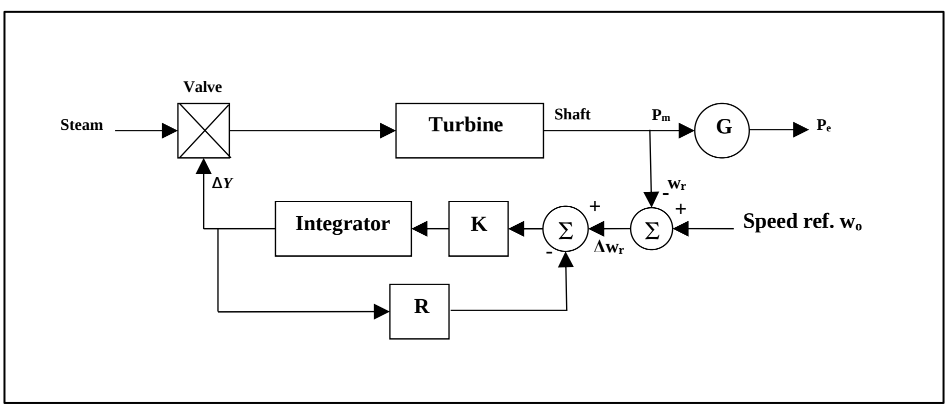

Figure (2.9), Speed Drop Control (Governor with steady-state feedback)

For derivation check appendix G.

3

Chapter 3

Design and calculations

3.1 Introduction

In this chapter, the main parameters of this plant is calculated precisely, the number of collectors needed, the area needed for them and the power conversion cycle calculation, which will decide the output power of the turbines, thus the total electrical power generated and the total efficiency of the cycle and the plant.

The total Thermal power of the plant is a critical part in the calculation process, and to be able to find the total thermal power needed to generate 5 MWe, the total conversion efficiency must be known.

One of the major contributor of the total conversion efficiency of the plant, is the power conversion block efficiency, which is the Rankine cycle efficiency, since the temperature and the inlet pressure of the cycle is assigned, the approximation of the power conversion efficiency can be known using Table (2.1), which shows by approximation that the efficiency of the Rankine cycle for 400^{o} C and 12.5 MPa is ranged from 40%-50%.

Using simple calculation method for the power conversion efficiency and the turbines mechanical power and enthalpy, the total thermal power of the plant is calculated after calculating the efficiency.

3.2 Power Conversion efficiency (Rankine Cycle)

Israel Urieli showed a simplified method of calculating the ideal Rankine cycle in his book (Engineering Thermodynamics)[11], from figure (3.5), which is showing the cycle used in this plant, the step by step analysis can be found by separating each components, as figure (4.1) shows.

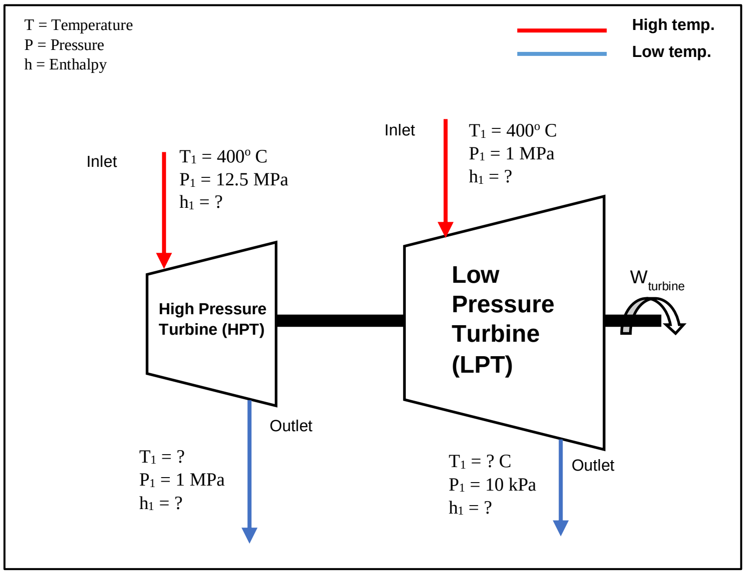

Figure (3.1), Turbines Analysis

where "h" is the enthalpy, which a property that identify how much energy is stored inside a specific material (which is here the Steam), this value can be known from specific tables [11], and the value of "h" can be found using the pressure and the temperature at a given point, thus, the calculation can be made, and the final analysis of the turbines is given at figure (4.2).

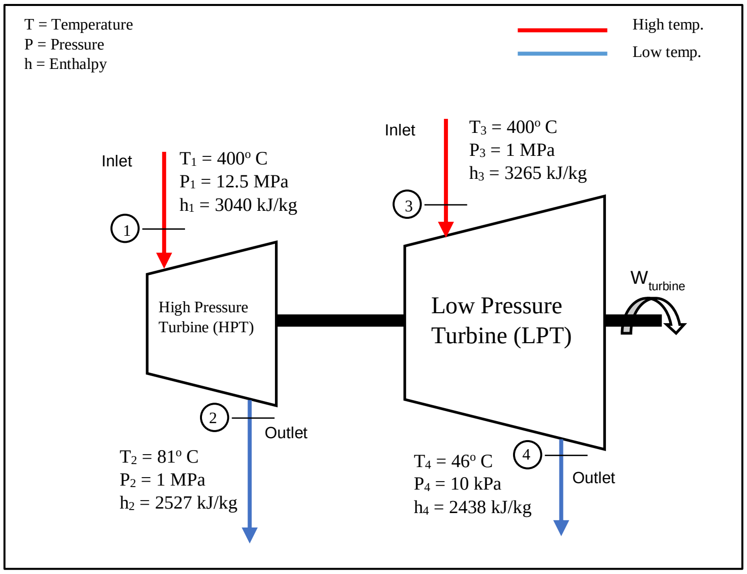

Figure (3.2), enthalpy values of the turbines

The total enthalpy of the turbine can now be found using the following equation [11]

$$W_{turbine} = h_{inlet} - h_{outlet} \tag{3.1}$$

The total enthalpy of the high pressure turbine is equal to:

$$W_{HP\_turbine} = h_1 - h_2$$

$$W_{HP\_turbine} = 3040 - 2527 = 513 \text{ kJ/kg}$$

The total enthalpy of the low pressure turbine is equal to:

$$W_{LP\_turbine} = h_3 - h_4$$

$$W_{LP\_turbine} = 3265 - 2438 = 827 \text{ kJ/kg}$$

The total enthalpy of both turbines is

$$W_{total} = W_{HP\_turbine} + W_{LP\_turbine}$$

$$W_{total} = 513 + 827 = 1340 \text{ kJ/kg}$$

The total power can be calculated when the mass flow value is known using equation (3.2)[11]

$$P_{turbine} = W_{total} \cdot \dot{m} \tag{3.2}$$

The mass flow ($\dot{m}$) will be calculated at the final step.

Now to complete the cycle, two parts left to go, which are the condensing unit and the steam generation unit, figure (3.3) show both parts.

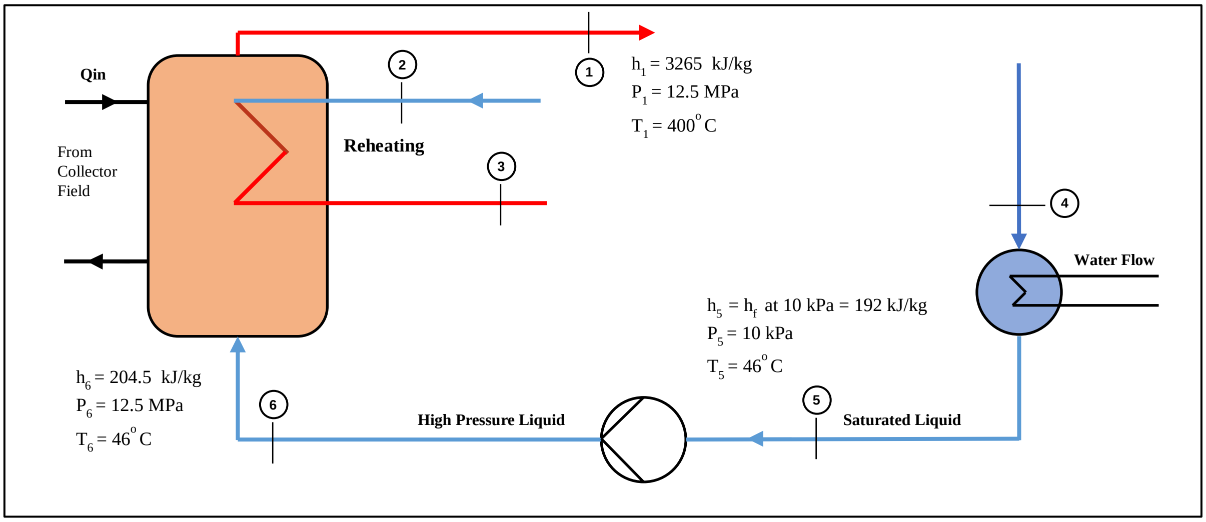

Figure (3.3), condensing unit and steam generation unit analysis

Since the steam turned back into a liquid and reaches the saturation at step 5, the temperature of the saturated water can be known from its pressure, and the enthalpy of it is known from the saturation property table of the water at any given pressure and temperature[11].

At step 6, the enthalpy is equal to previous enthalpy with the addition of the enthalpy provided taken from the pump, and it can be calculated as follow [11]:

$$\boldsymbol{h_{pump} = v \cdot \Delta P} \tag{3.3}$$

$$\boldsymbol{h_{pump} = 0.001 * (12500 - 10) = 12.49\ \text{kJ/kg}}$$

And thus,
h6 = 192 + 12.49 = **204.49 kJ/kg**

Since h1 and h6 are known, the total needed Qin can be calculated:

Qin = h1 – h6
Qin = 3265 – 204.49 = **3060.5 kJ/kg**

Thus the total efficiency of the conversion cycle can be calculated as follow:

$$\boldsymbol{\mu_{conversion} = \frac{W_{total} - h_{pump}}{Q_{in}} = \frac{1340 - 12.49}{3060.5} = 43\%}$$

And this value is inside the range that was assumed from Table (2.1), thus, it’s correct.

The thermal power required to energize the power conversion cycle and the mass flow of the steam generation unit can be calculated, and therefore the output power of each turbine can be identify, using equation (4.1):

$$\boldsymbol{P_{th} = \frac{P_e}{\eta_{overall}} = \frac{5 \cdot 10^6}{0.43} = 11.62\ MW_{th}}$$

$$\boldsymbol{P_{th} = Q_{in} \cdot \dot{m}}$$

$$\boldsymbol{\dot{m} = \frac{P_{th}}{Q_{in}} = \frac{11.62 \cdot 10^6 \cdot 10^{-3}}{3060.5} = 3.79\ kg/s}$$

Therefore the output power of each turbine is:

$$P_{HP\_turbine} = W_{HP\_turbine} \cdot \dot{m}$$

$$P_{HP\_turbine} = 513 \cdot 3.79 = 1.94\ MWe$$

$$P_{LP\_turbine} = W_{LP\_turbine} \cdot \dot{m}$$

$$P_{LP\_turbine} = 827 \cdot 3.79 = 3.134\ MWe$$

And the total output power is:

$$P_{turbine} = 1.94 + 3.134 = 5.1MWe$$

4.3 Number of Collectors Needed

To be able to calculate the number of collectors needed, first the Thermal production of one single collector must be known, and to calculate that, equation (2.2) [16] is used.

$$Q_u = F_R[SA_a - A_r U_L(T_i - T_a)]$$

Where,

Aa = Aperture collector area = 552 m^2

$$\mathbf{A_r = Receiver\ area = \pi D_o L = \pi * 0.07m * 99.5m = 21.88\ m^2}$$

Do = receiver outer diameter = 0.07 m

S = mean solar radiation in Palestine = 800 W/m2 [6]

FR = 0.8 [23] Heat removal factor

Ti = Inlet fluid temperature = 300 C^o

Ta = Ambient temperature = 25 C^o

UL = Overall collector heat loss coefficient, UL = 17.64 W/m^2 K – check appendix B

After knowing all of those parameter, the useful power gained by the collector can be calculated as follow:

$$Q_u = 0.8[800 \cdot 552 - 21.88 \cdot 17.64 \cdot (300 - 25)]$$

$$Q_u = 0.8[441,600 - 106,140]$$

$$Q_u = 268.37\ kW$$

So, the selected collector gains 268.37 kW of thermal power at 25° C ambient temperature, and from this we can identify the number of needed collectors to supply 11.62 MWth:

$$\# \, \boldsymbol{of\ collectors} = \frac{\mathbf{11.62 \times 10^6}}{\mathbf{268\,370}} = \mathbf{44}\ \boldsymbol{collectors}$$

The mass flow now can be calculated to achieve the 400° C outlet temperature (Practically it's 393°C outlet and 293°C, which gives the same difference), using equation (3.4) [16]

$$\boldsymbol{Q_u} = \dot{\boldsymbol{m}}\boldsymbol{c_p}(\boldsymbol{T_o} - \boldsymbol{T_i}) \tag{3.4}$$

$$\dot{\boldsymbol{m}} = \frac{\boldsymbol{Q_u}}{\boldsymbol{c_p}(\boldsymbol{T_o} - \boldsymbol{T_i})} = \frac{\mathbf{268.37}\boldsymbol{k}}{\mathbf{1577(400 - 300)}} = \mathbf{1.7}\ \boldsymbol{kg/s}$$

3.4 Plant Layout

The Final Plant layout with the most important parameter is shown in figure (3.4).

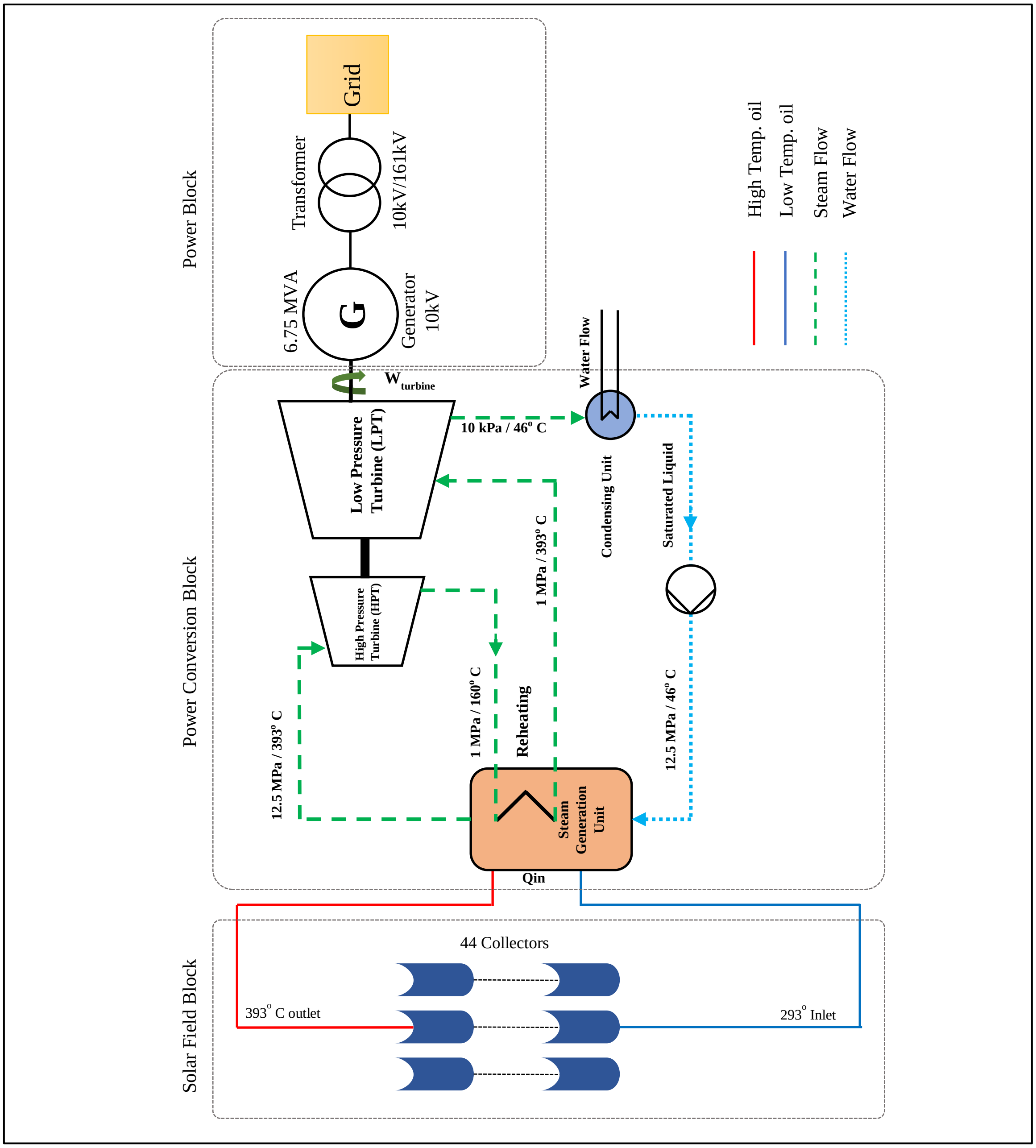

Figure (3.4) Plant Layout

4

Chapter 4

Component Selection

4.1 Introduction

The selection of components is a key factor to make the analysis and calculation possible, in this chapter, the needed component for each part of the plant will be selected depending on specific factors for each part, to maintain the highest possible efficiency and the best economical value.

4.2 Collectors

Collectors are used to harvest and collect the heat that's coming from the sun's radiation, and therefore, several factors are investigated to gain the highest possible efficiency with respect to the financial value too.

The reflectivity of the collector's mirror is one of the most important factors for selecting a collector, since it decide the amount of reflected radiation that would be absorbed by the receiver tube, and the price is also considered.

For that, the best choice landed on the Euro Trough (ET) Collector, which has a 94% [20] of mirror reflectivity and a competitive price in the industry.

Table (3.1) is showing the ET-100 parabolic collector specifications [20]:

Table (4.1) ET-100 specifications

ET-100 Specifications	
Focal Length	1.71 m
Absorber radius	35 mm
Aperture width	5.76 m2
Aperture area	552 m2
Collector length	99.5 m
Number of modules per drive	8
Number of glass facets	244
Number of absorber tube	24
Mirror reflectivity	94%

And Figure (4.1) is showing the elements of the ET-100 collector:

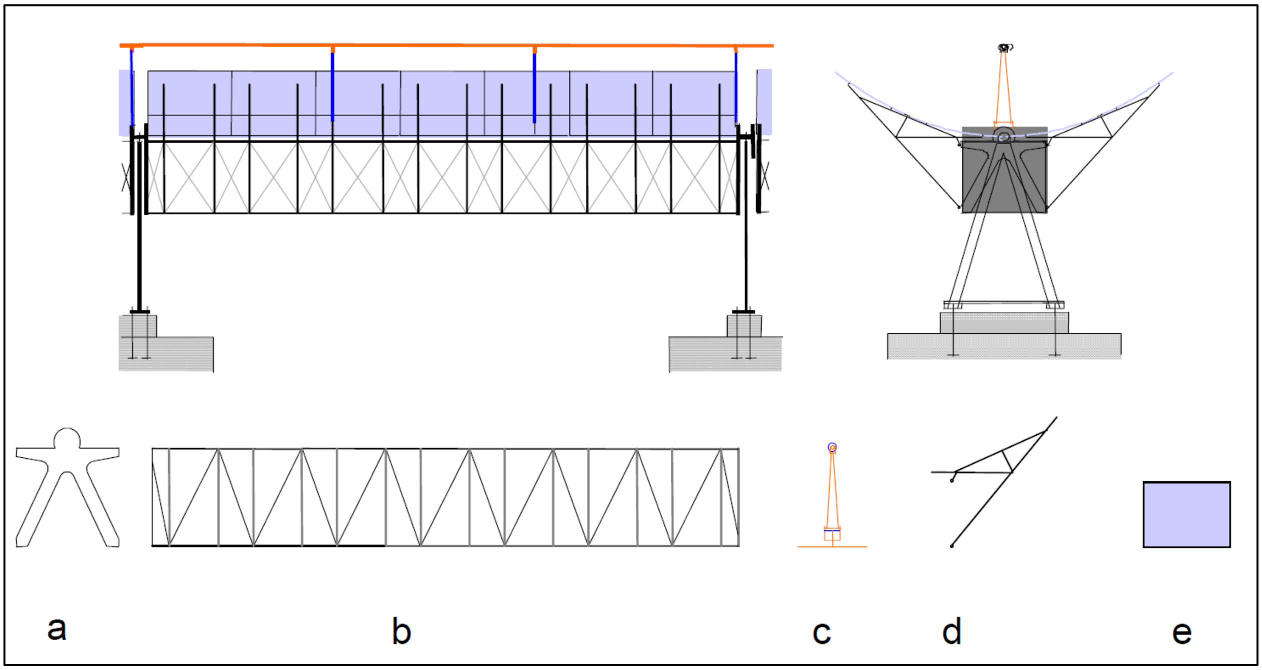

Figure (4.1) ET-100 Elements

Where, (a) is the endplate, (b) is the steel frame, (c) is the absorber tube support, (d) is the cantilever arm and (e) is the mirror facet.

The ET-100 is capable of handling 24 receiver tube to it, furthermore the selection of the receiver tube is not less important than the collector, since they function as a one piece.

To select a receiver tube, factors such as solar absorptance and transmittance are taken into consideration, those indicate how much of solar radiation is absorbed and the amount of light that passes through the glass [21], respectively.

SCHOTT PTR®70 Receiver is selected, which has a high end specifications, such as 97% of transmittance and 96% of solar absorptance, Table (4.2) will show the specifications of this receiver.

Table (4.2) PTR 70 receiver tube specifications

PTR 70 Specifications	
Length	4060 mm
Outer diameter	70 mm
Solar absorptance	≥ 96%
Solar Transmittance	≥ 97%
Glass outer diameter	125 mm
Aperture length	> 96.7% of total length

Figure (4.2) shows PTR 70 receiver tube.

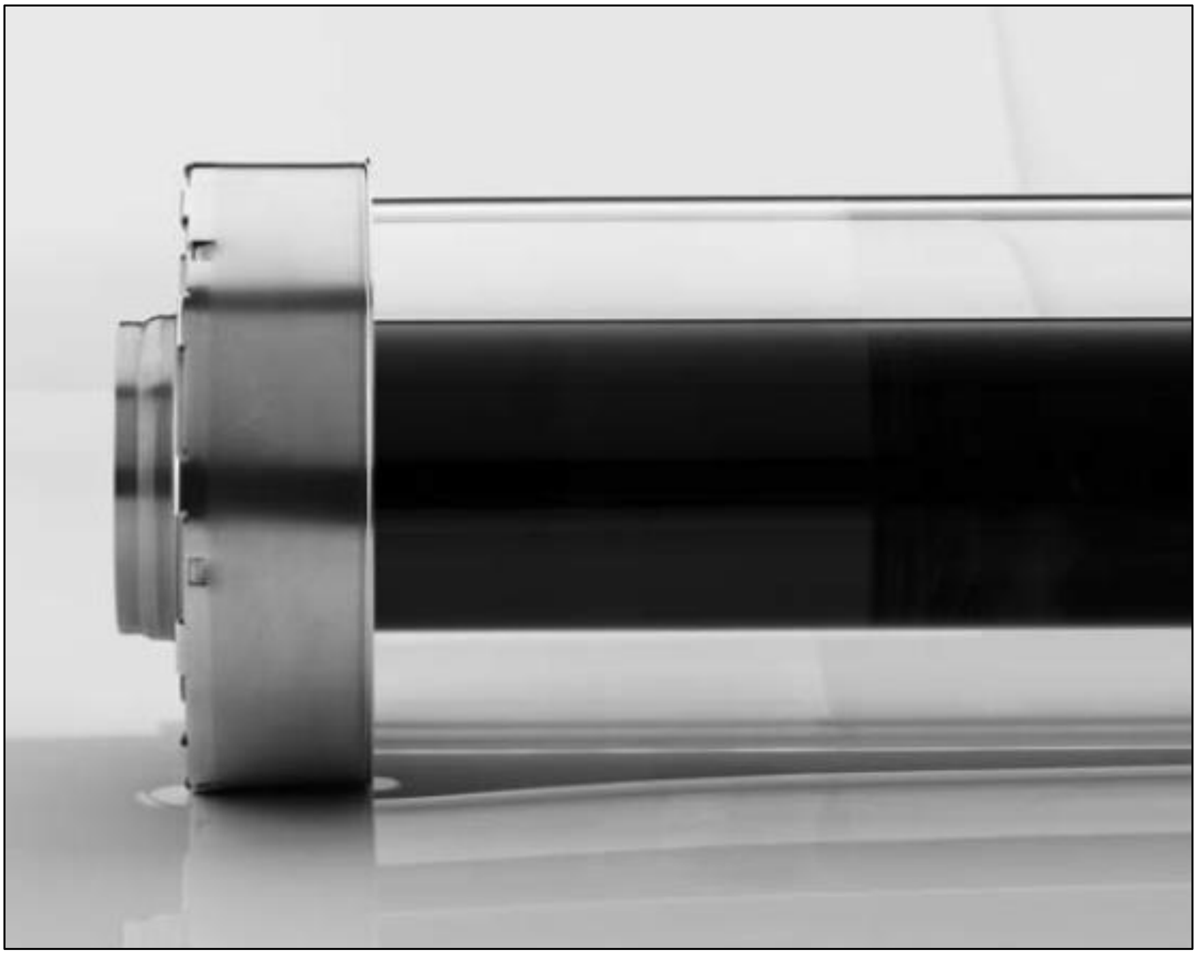

Figure (4.2) PTR 70 receiver tube

4.3 Heat Transfer Fluid (HTF)

"Heat transfer fluids carry the heat to the storage tank and then to the steam generator. As a result, it is important for good fluids to have a low viscosity and high thermal capacity"[22], water, oil and molten salts can be used as HTF, for years, special type of oils are developed for this specific operation, Therminol™ is an oil family, which is developed specially for thermal transfer operations by Eastman® company.

Therminol VP-1 is a very capable transfer fluid for medium temperatures (300-500^o C), it's the most common transfer oil used in the CSPP over the world, and it's selected for this project too, since the inlet temperature is selected to be 300^o C and the outlet is 400^o C.

Table (4.3) shows the specifications of the Therminol VP-1 at different temperatures.

Table (4.3) Therminol VP-1 specs. [4]

Property	At 300^o C	At 400^o C
Circulating fluid (cp)	1577 J/kg K	1860 J/kg K
Density (ρ)	1046 Kg/m3	964 Kg/m3
Thermal conductivity (k)	0.135 W/m K	0.124 W/m K
Viscosity (μ)	3.2 x 10^{-3} Pa. sec.	6.6 x 10^{-4} Pa. sec.

4.4 Power Conversion

The most important parts in the power conversion block are the Turbines and the Steam Generation Unit (SGU), the SGU is used mainly to generate steam, and the Turbines are driven by this steam, thus a mechanical power is generated, and the Turbine then is used as a prime mover for a synchronous generator to generate electrical power later.

The efficiency of the power cycle is the major contributor to the overall efficiency of the plant, therefore, selecting the proper and the most efficient tools in this block is essential.

4.4.1 Steam Generation Unit (SGU)

The steam generation unit is responsible of several important objectives in the power conversion block, all described in chapter **2**, section **2.7.1** previously, all those element are build-in within one unit, which is called the Steam Generation Unit.

AALBORG CSP® is a known company concern in SGUs building, and they offer a high end and premium quality SGUs, and their SGUs are commonly used all over the world, and thus, it's selected for this project, figure (4.3) is showing the AALBORG CSP's steam generation unit schematic diagram with real values taken from a 25MW project.

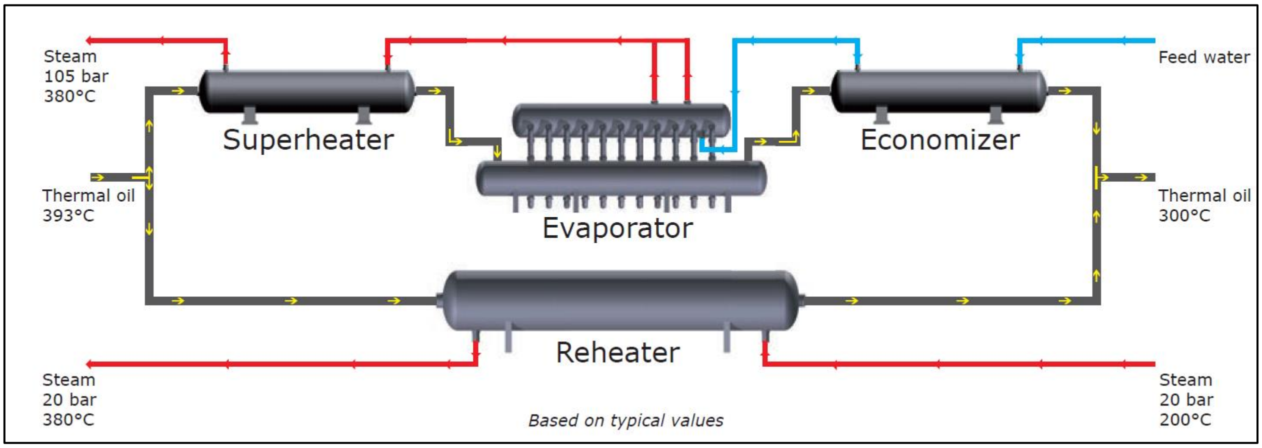

Figure (4.3), Schematic Diagram of a 25MW SGU from AALBORG CSP®

AALBORG's SGU can provide different mass flow capacities (28, 56, 75) kg/s, and that's more than enough for this project, it will be described in details later in the calculation chapter.

4.4.2 Turbines

In chapter 1, the Rankine cycle is described, and figure (1.5), is showing that to increase the efficiency we used two turbines, one is a HP turbine and the other is a LP turbine.

To maintain the highest possible efficiency, the pressure and the temperature must be increased, as equation (2.2) illustrate, for that, the selection of the turbines depends heavily on their maximum pressure and temperature capability, thus, the highest pressure and temperature with respect to the value of money were found to be 12.5 MPa and 500^{o} C, and the two turbines selected for that are described in the Table (4.4).

The turbines are provided from Siemens® and Mitsubishi® heavy industries, Respectively, D-R AVTTW/GTW is selected as a high pressure turbine, and AT52C is selected as a low pressure turbine.

Table (4.4) Selected Turbines and their characteristics.

Parameter	D-R AVTTW / GTW	AT52C
Max power output	**4.5 MW**	**6.5 MW**
Max inlet pressure	**12.5 MPa**	**12.3 MPa**
Max inlet temperature	**550^{o} C**	**540^{o} C**

The above turbines satisfies the pressure and temperature required, and thus, they are selected, a detailed calculation of the turbines power generation is provided in the calculation chapter.

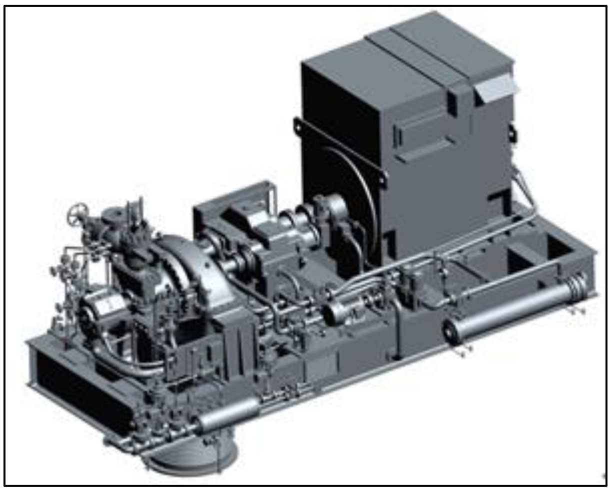

Figure (4.4) AT-type Mitsubishi® steam turbine connected to a generator

4.5 Power Block

The power block contains the most important devices, which are the generator and the transformer, to make the suitable selection of both devices, set of parameters must be investigated.

The selected generator must be able to provide 5 MW of electrical power, also for the project's region, the frequency is 50 Hz.

ABB®, has a large set of Synchronous Generators (SG), and a Generator with the needed specification is selected, C418 is a 6.75 MVA which is 125% of the rated capacity. SG introduced by ABB®, and table (4.5) is showing its specifications.

Table (4.5) C418 SG specifications

Output Power	5.4 MW at 0.8 PF
Model Type	AMG0630DU04 DAP
Frequency	50 Hz
Number of Poles	4 Poles
Speed	1500 RPM
Output Voltage	10 kV

The output voltage of the generator is 10 kV, and this value will be stepped up by a Generator Step-Up (GSU) Transformer, to make it more practical and efficient for transmission, in Palestine the transmission system is divided into two types [27]:

A) 161 kV Transmission system.

B) 400 kV Transmission system.

And at the region, where the plant is decided to be build (Hebron/Bani Na'im), the system used is 161kV, for that, a transformer with the capability of stepping up the voltage from 10kV to 161kV is needed, with capacity of 125% of rated capacity, which is at least 6.5 MVA.

Table (4.6) the 161 kV system detailed [27].

Height of pylon (m)	33
Width of corridor (m)	40
Number of pylons per km	3-4
Width of the base of the pylon (m)	1.5 - 4

5

Chapter 5

Plant Simulation

5.1 Software used

For this project, two software are used, first, Matlab Simulink is used to model the system and study the effect of the types of loads on the system and the generator's frequency and the case studies, and it will include a speed drop control method to stabilize the frequency, second, SAM (System Advisor Model) from NREL for the steady state annual analysis of the thermal plant with respect to the weather data all over the year.

5.2 Matlab Simulink

The plant is modeled using Matlab Simulink software to study the load effect on the plant, different scenarios are studied and simulated, such as variable load (Load Profile) and constant load etc…

5.2.1 Overall Plant model

Figure (5.1) shows the plant overall view using Matlab Simulink.

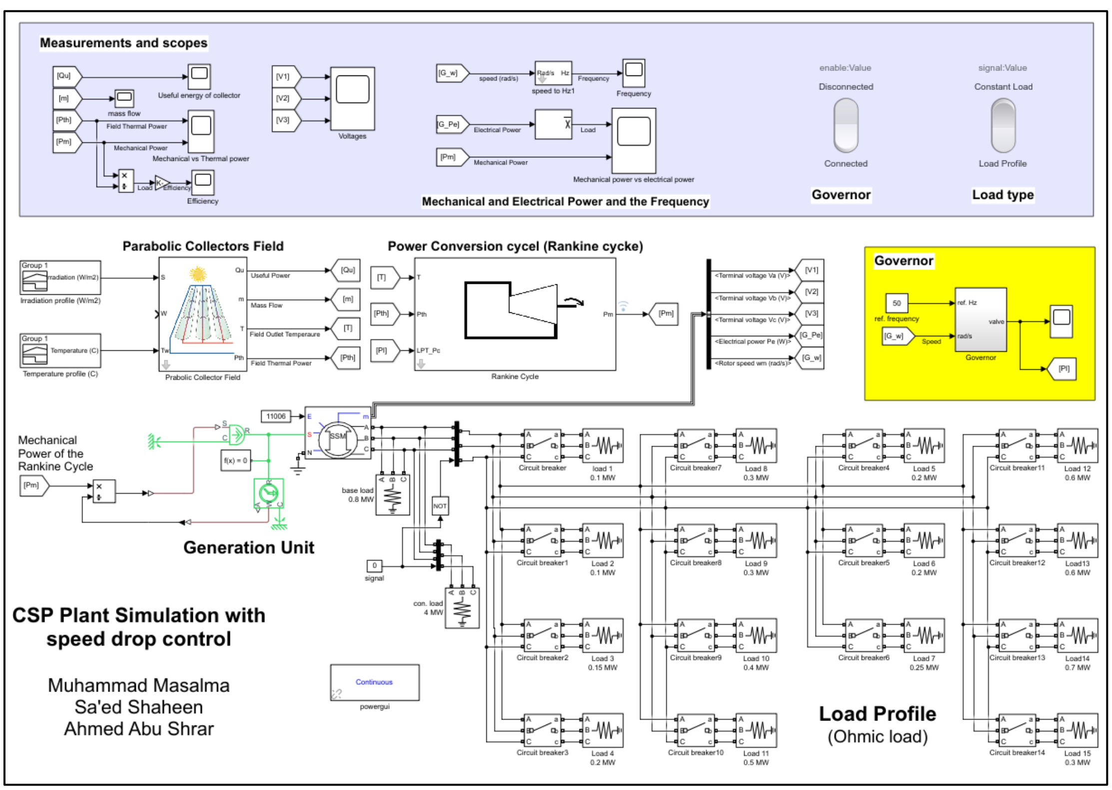

Figure (5.1) CSP Plant Simulation using Matlab Simulink

5.2.2 Collector Field Mask

Equation (2.2) represents the mathematical model of a Parabolic Collector, the useful energy of the collector is determined by this equation.

The main mask of the collector field is shown in figure (5.2).

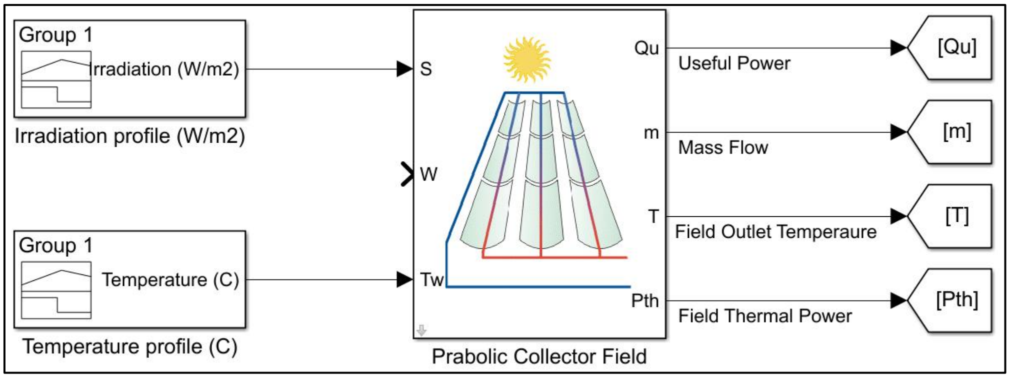

Figure (5.2) Collectors Field Mask

Some main parameters can be changed from the mask's properties as seen in figure (5.3), the user can choose if the source of the irradiation, temperature or the wind are constant values or a predefined profiles.

Figure (5.4) represents the mathematical model of the collector.

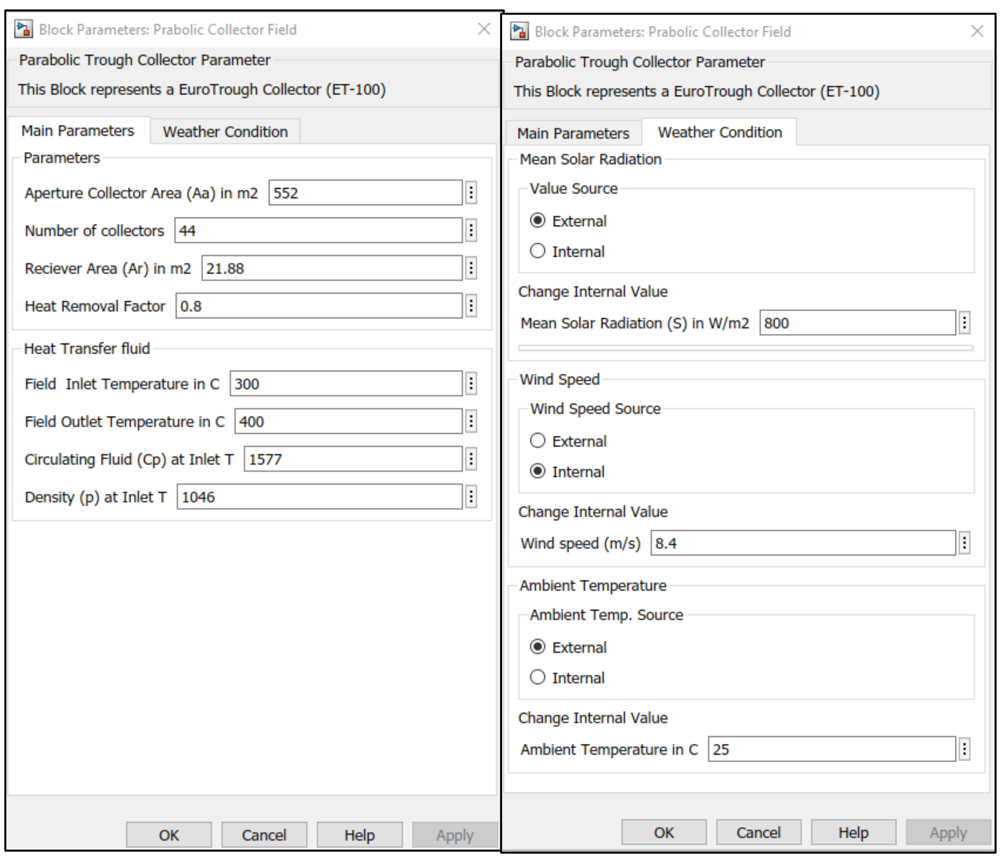

Figure (5.3) the parameters of the collector field mask.

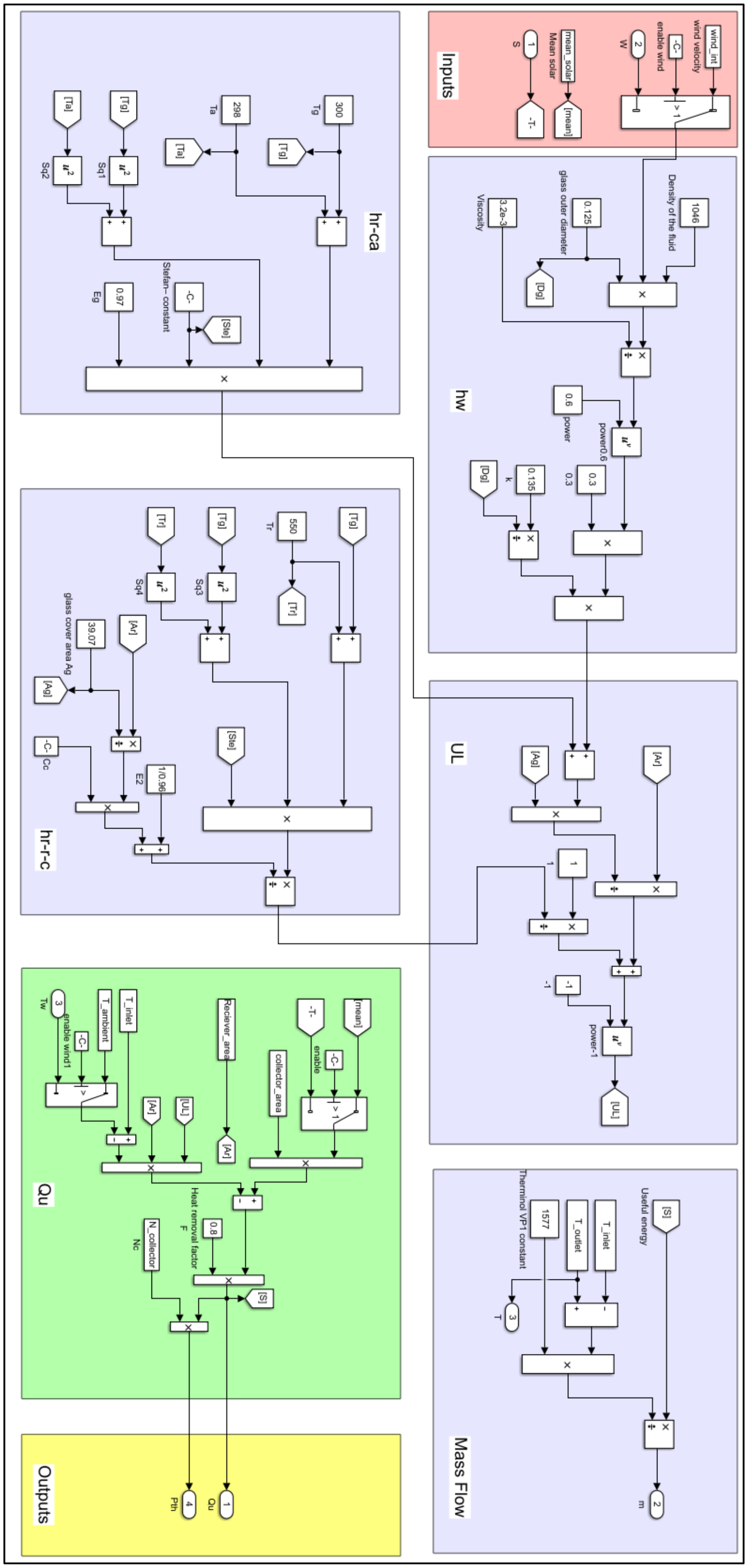

Figure (5.4) Collector field under mask mathematical model

The Inputs of this model are the Direct Normal Irradiation (DNI), the wind speed and the temperature, and the outputs are the useful energy produced by one collector and the total thermal energy of the field of N collectors.

This model represents equation (2.2):

$$\boldsymbol{Q_u = F_R[SA_a - A_rU_L(T_i - T_a)]} \tag{2.2}$$

5.2.3 Power conversion cycle (Rankine Cycle)

This model represents the Rankine cycle with the turbines, the input of this cycle is thermal power, and the output is mechanical power produced by the turbines.

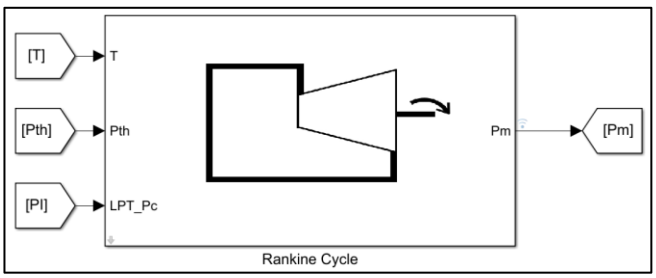

Figure (5.5) Rankine Cycle Model

T as an input represents the outlet temperature of the field which is energizing the steam generator of the Rankine cycle, P_{th} is the total thermal power produced by the field collector, and P is the control signal of the governor, this signal controls a valve on the low pressure turbine that can adjust the outlet pressure of the turbine within a specific range, in which will be used for the speed drop control of the system.

The output of the cycle is P_m, which represent the mechanical power of the turbine which is used as a prime mover for the synchronous generator of the plant.

Figure (5.6) is the shows under mask model.

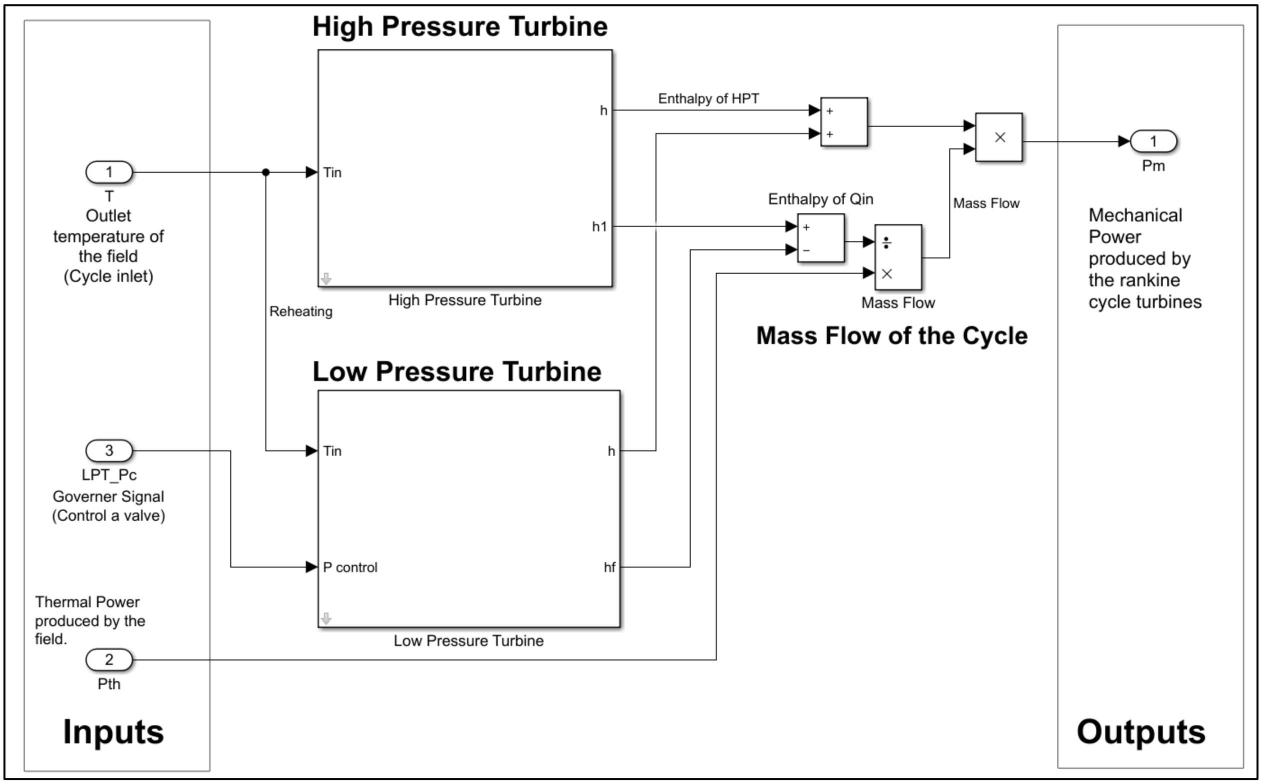

Figure (5.6) under mask of the Rankine Cycle model

Both the high pressure turbine and low pressure turbine are using look-up table to determine the appropriate value of the enthalpy of each turbine, those tables are dedicated to steam, refer to appendix A for steam properties tables used in this model.

Figure (5.7) and (5.8) shows under mask model of each turbine.

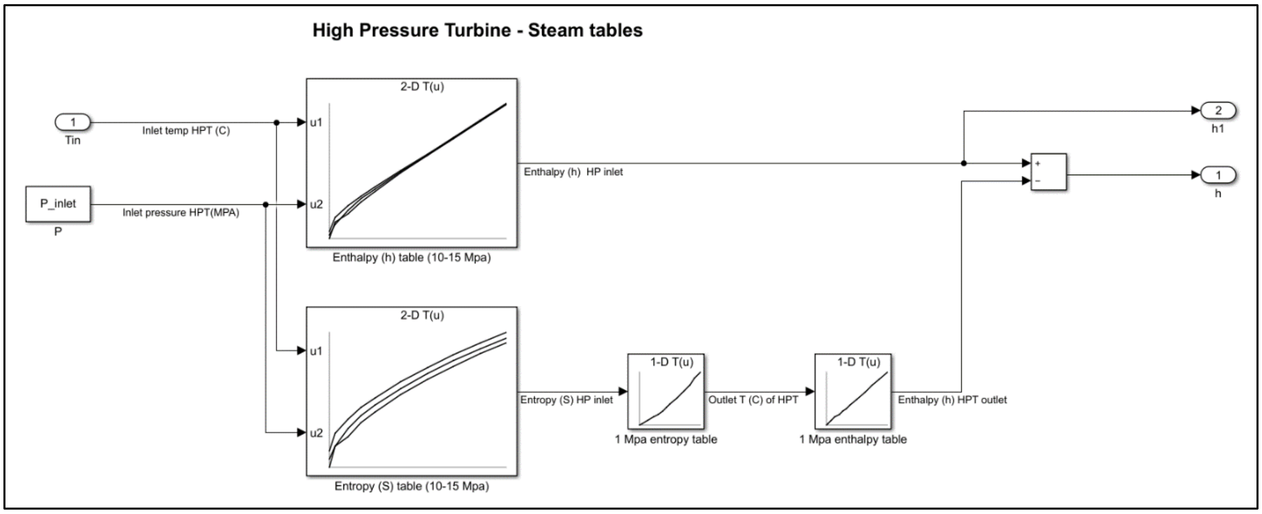

Figure (5.7) High pressure turbine model

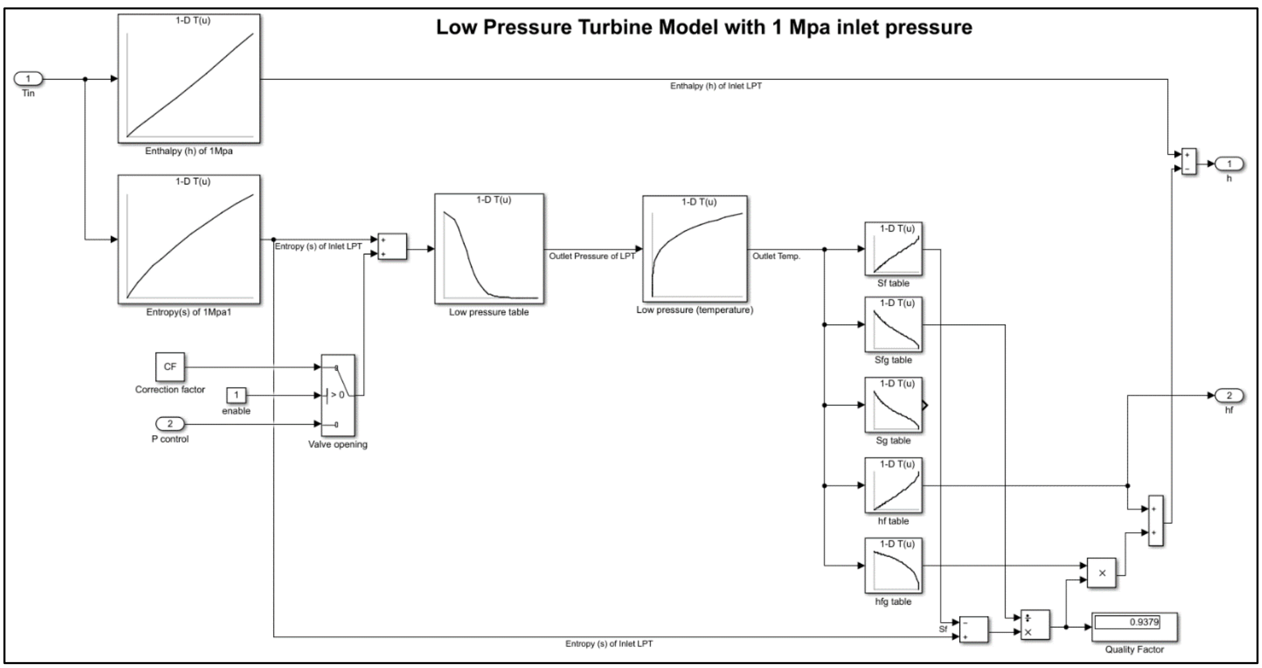

Figure (5.8) Low pressure turbine model

The output of both turbines are two values, one represents the enthalpy at the inlet side of the turbine, and the other value represents the enthalpy at the outlet side of the turbine, which are used to calculate the mechanical power of the turbine.

5.2.4 Generation unit

The generation unit contain the synchronous generator, which convert the mechanical rotational power into electrical power.

Figure (5.9) shows the synchronous machine connected as a generator with the mechanical power received from the steam turbines.

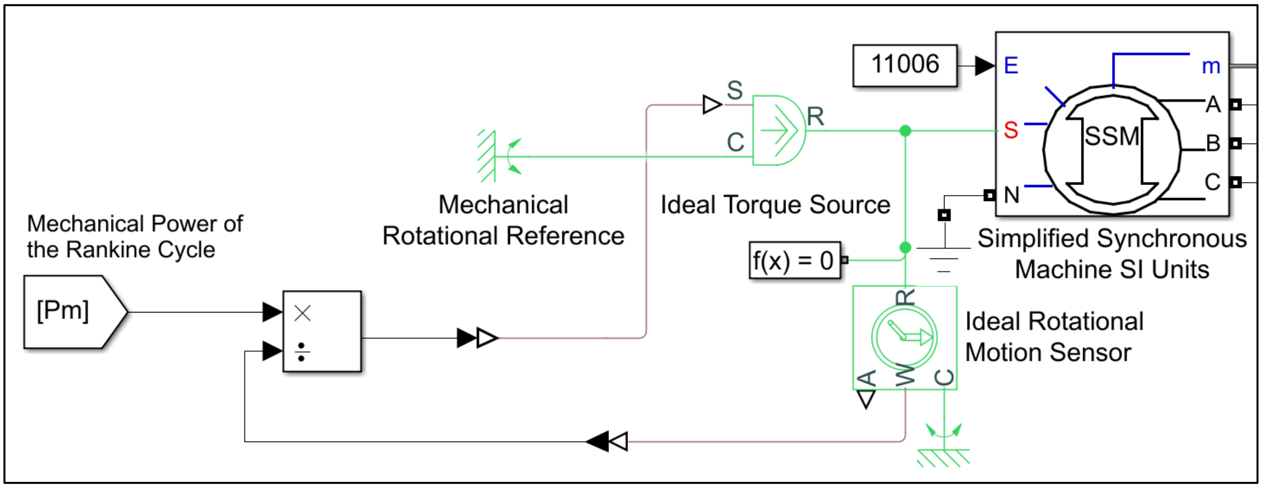

Figure (5.9) Generation unit

Load profile is connected to the generator as shown in figure (5.10).

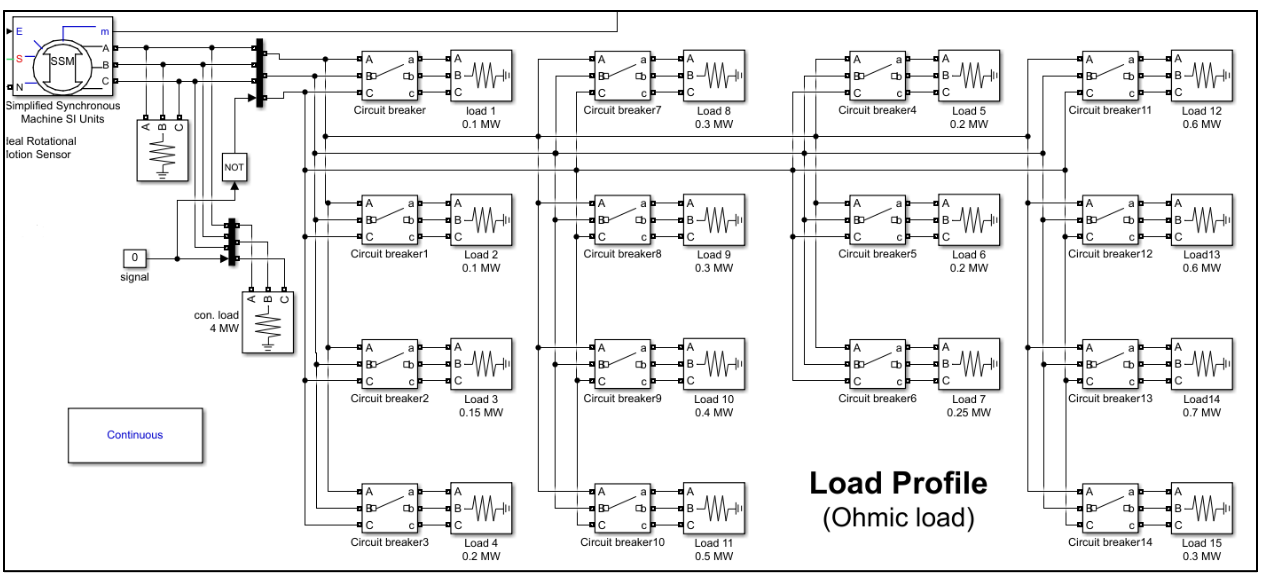

Figure (5.10) Load profile connected to the generator

5.3 SAM software

This software will provide the steady state output power of the plant with dynamic weather data, the data for the weather and the location is selected to be Jerusalem, which will give the most accurate data for our case.

The data given to the design are:

- Header Data (Latitude, Longitude etc.…)
- Average wind speed
- Average temperature
- Direct normal beam (DNI)
- Other data

The calculated data of the plant are enrolled to the software, such as the number of collectors, the type of collector with their parameters, the receiver tube parameters, the HTF and all other needed parameters. (Check appendix E)

5.4 Case study results and discussion

The steady state output power of the plant will be taken from SAM software, and the effect of the load on the frequency and the load profile case study will be taken from Matlab Simulink model.

Figure (5.11) shows the steady state output electrical power of the plant annually as average for each month, and figure (5.12) shows the thermal power produced by the field an entering the cycle both using SAM software.

It's noticed that at sunny days the output is higher, which is due to the higher DNI, the best months are June, July, August and September which is the summer season.

The annual net electrical energy production of the plant is **10.4 GWh/year** (check appendix E)

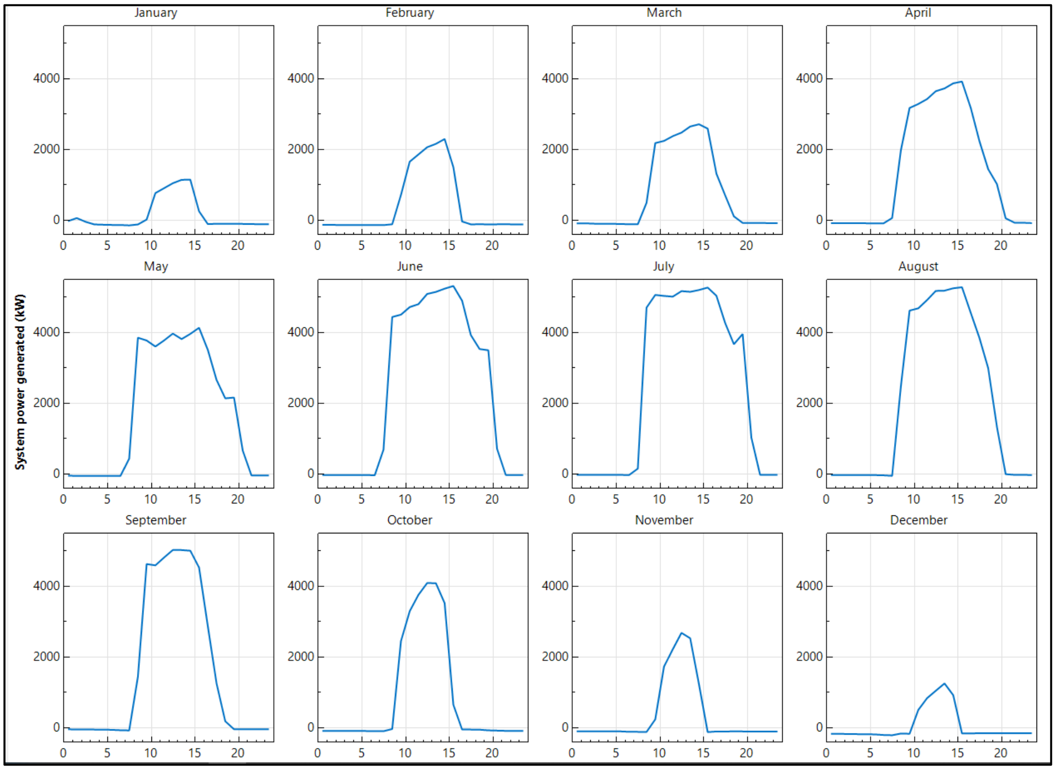

Figure (5.11) Steady state output electrical power of the plant.

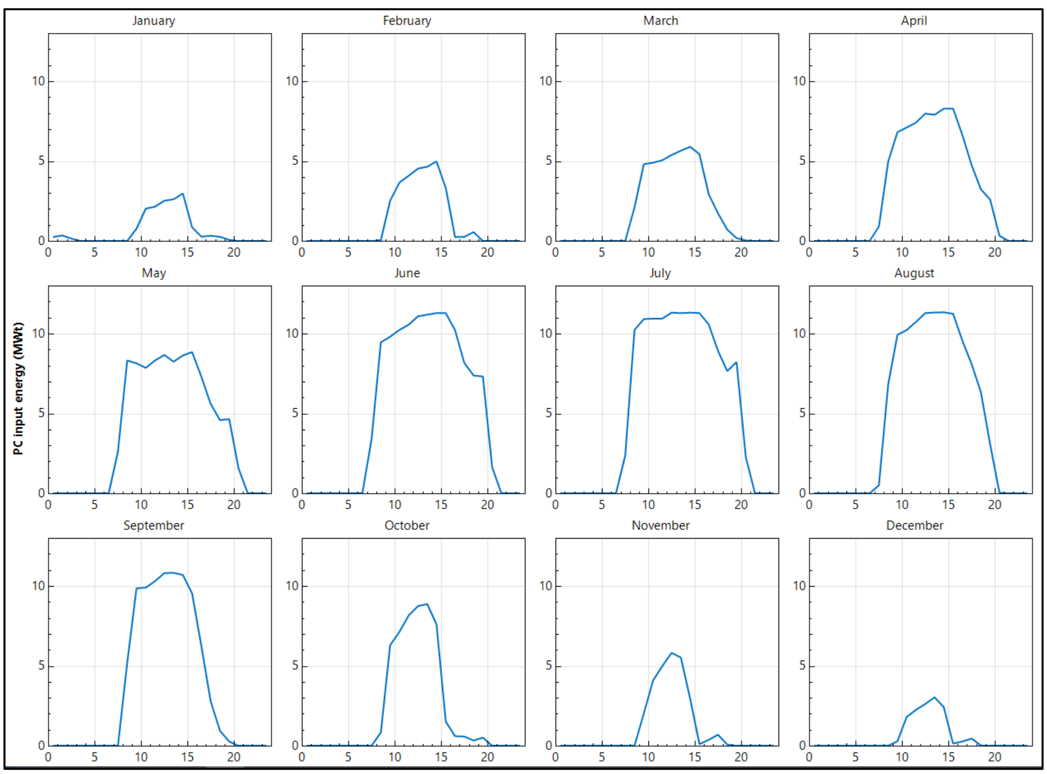

Figure (5.12) Inlet thermal power of the Rankine cycle

5.4.1 Open loop case study

The Input of this case study is an experimental DNI and temperature profile representing an average location in Palestine.

Figure (5.13) and (5.14) shows the DNI and the temperature profiles used, respectively.

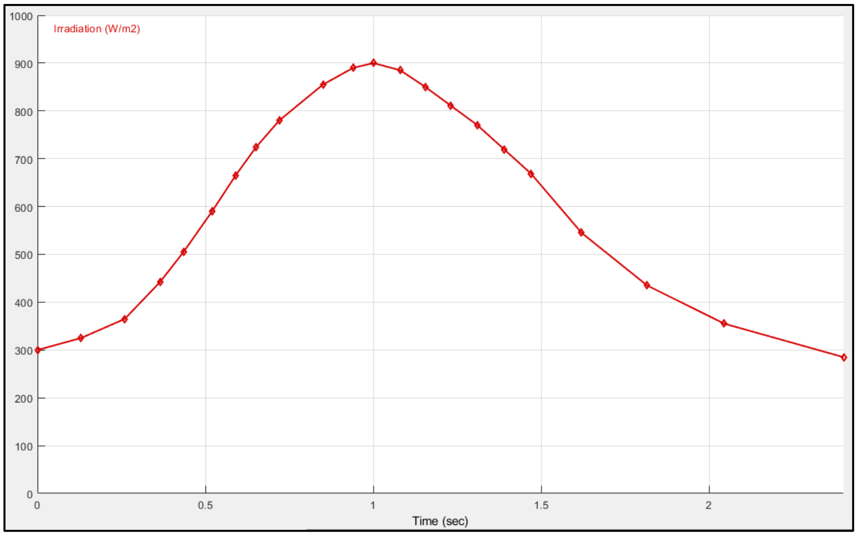

Figure (5.13) DNI profile

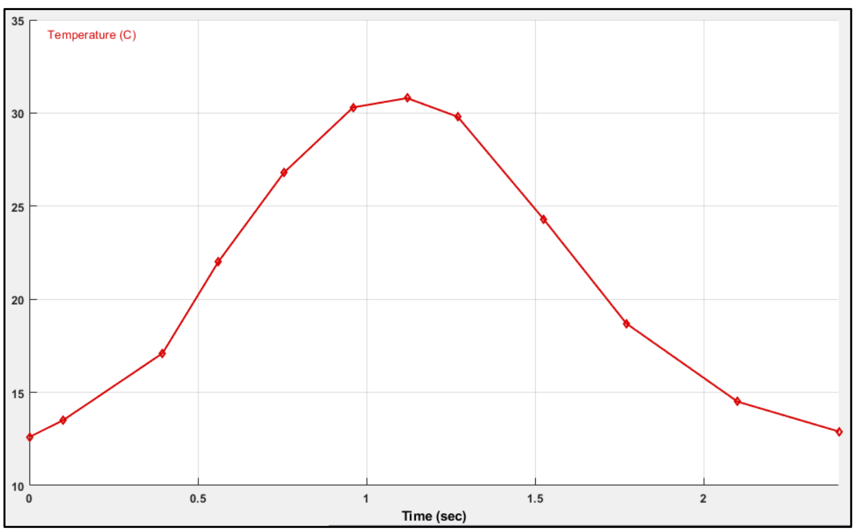

Figure (5.14) Temperature profile

Different cases are analyzed, the changing in valve is for the LPT outlet valve which will result in a change of the outlet pressure, and thus changing the enthalpy of the turbine and the mechanical power of the turbines, which is needed for the speed drop control.

Case 1: Constant pressure (20kPa) and constant load

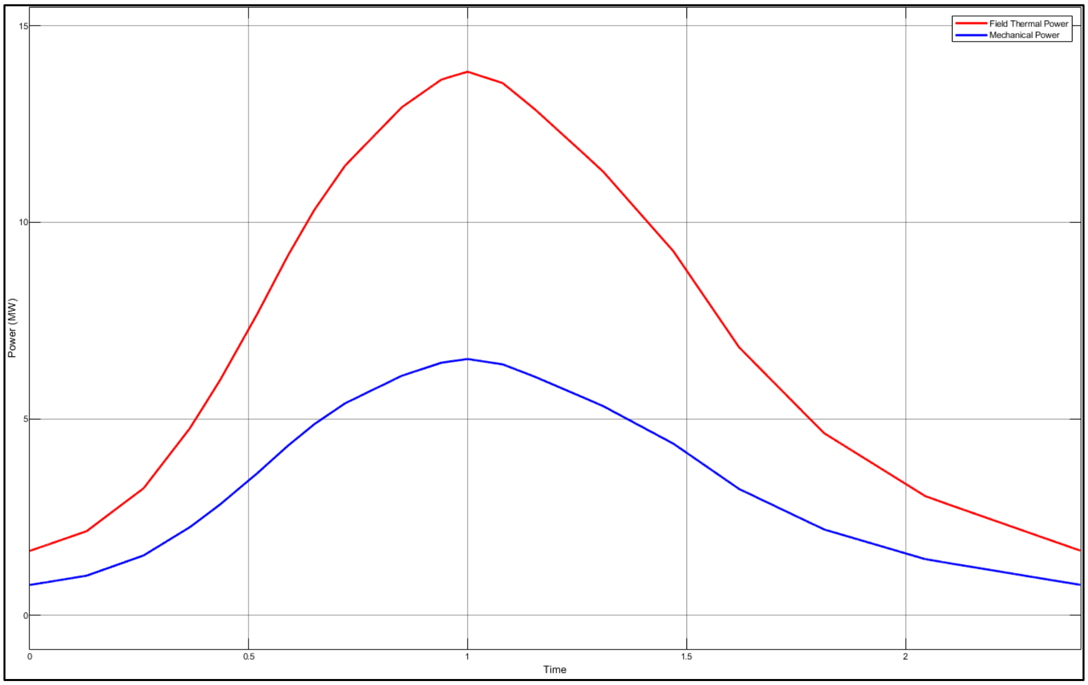

Figure (5.15) Thermal power vs mechanical power.

Thermal power and mechanical power are shown in figure (5.15) for case 1, since the governor is disconnected, there is no control of the speed, thus the frequency.

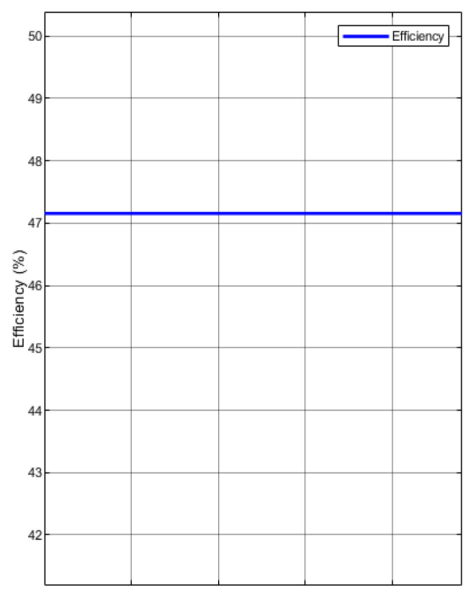

Figure (5.16) efficiency

The efficiency of this case is shown in figure (5.16) and the frequency of the system at this case is shown in figure (5.18).

It's noticed that the frequency is not constant, which is not acceptable for the system.

The change is the frequency is cause by overloading and under loading the generator as shown in figure (5.17).

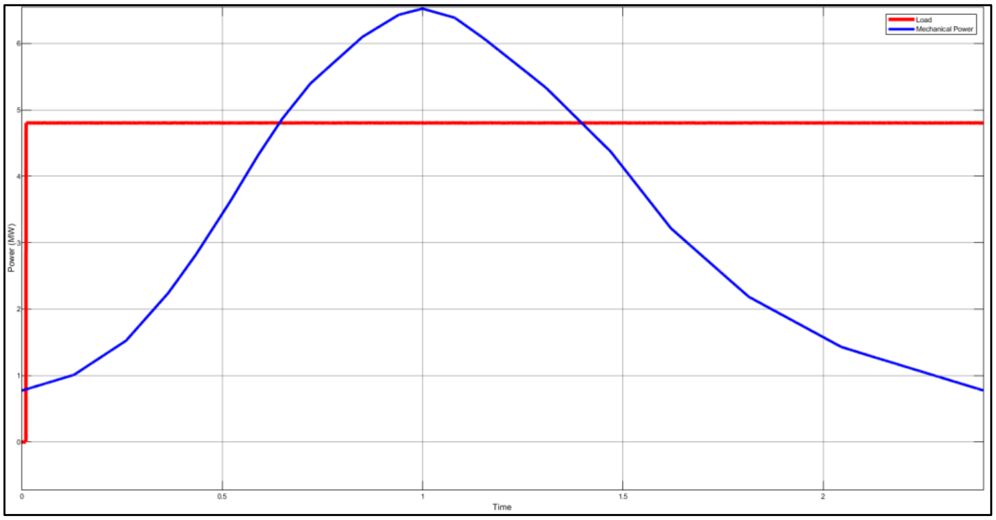

Figure (5.17) Mechanical power with load (electrical power)

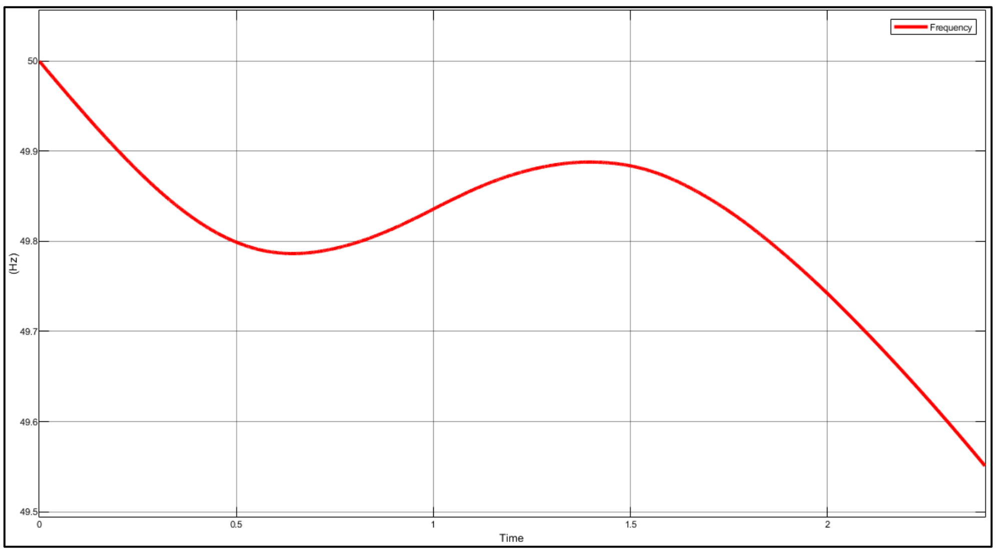

Figure (5.18) Frequency of the system

Case 2: Constant pressure (20kPa) and variable load (load profile)

Thermal power and mechanical power are the same as shown in figure (5.15), thus the efficiency of the power conversion is the same as shown in figure (5.16).

The frequency of the system in this case is shown in figure (5.19), and it’s noticed that the frequency change is little than the previous case, because the load power is closer to the mechanical power produced.

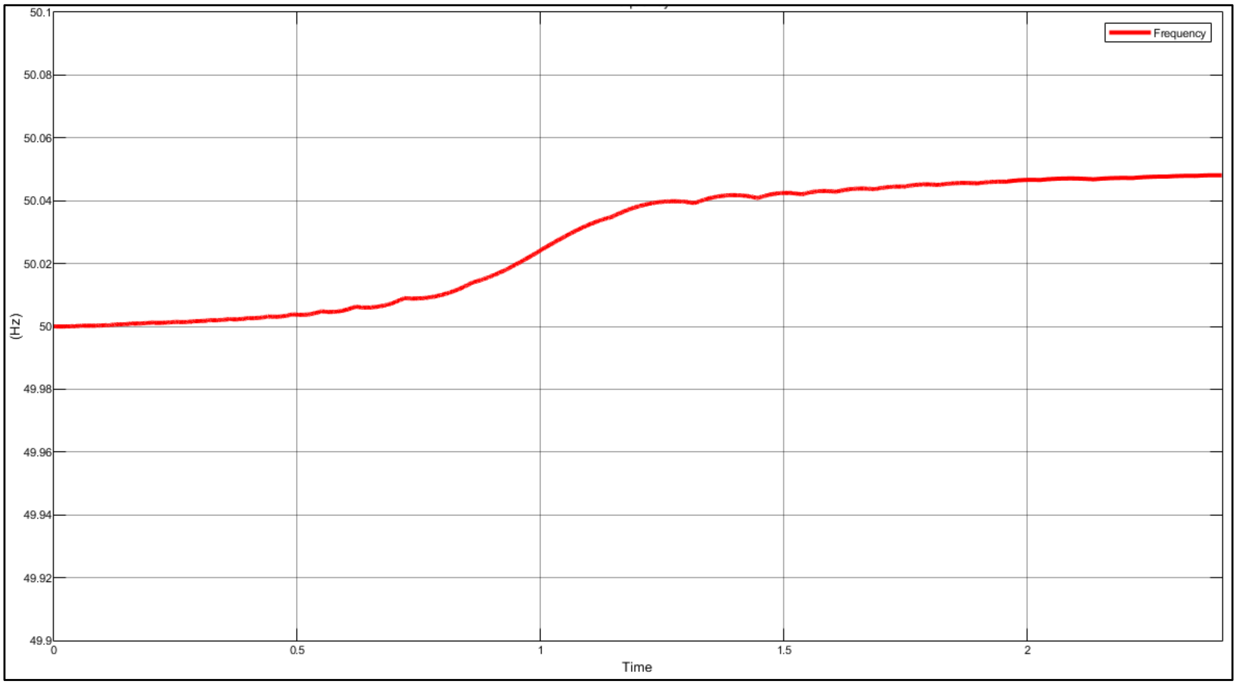

Figure (5.19) Frequency of the system at case 2

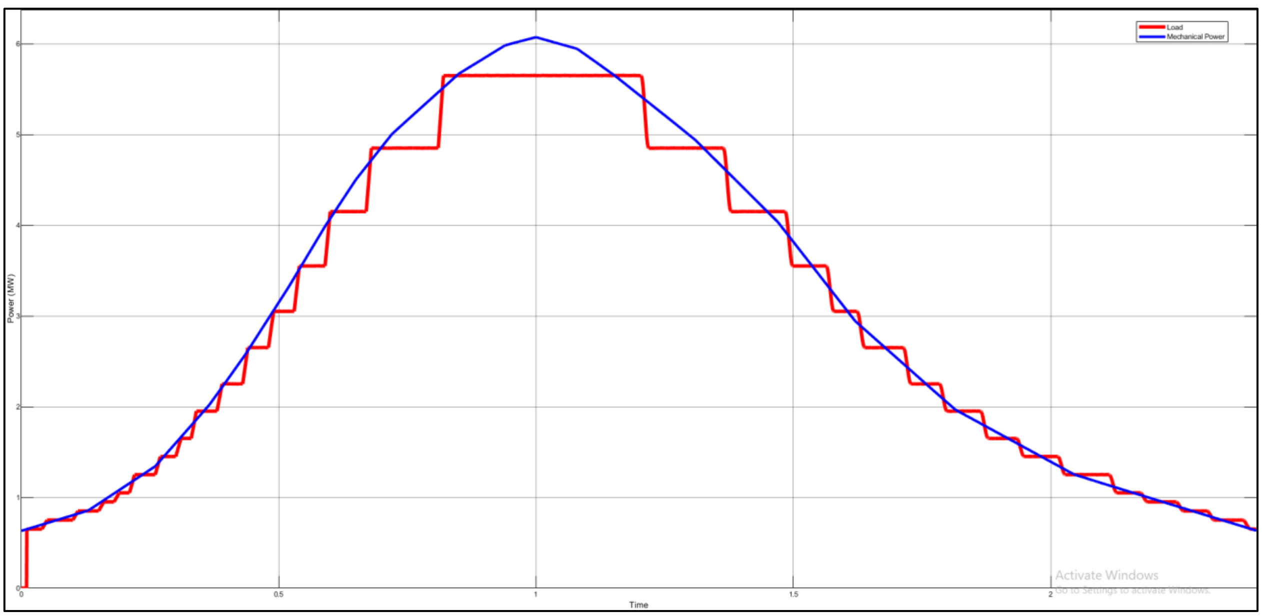

Figure (5.20) mechanical power of the Rankine cycle with the load (electrical power)

5.4.2 Closed loop case study

The change in the frequency must be within an acceptable range (±0.1%), and since naturally the load isn't constant, the produced power isn't matched with the load, thus a change in the frequency will occur.

To minimize this change within the acceptable range, a speed drop control method is introduced, the governor is used to match the produced power with the load to stabilize the frequency.

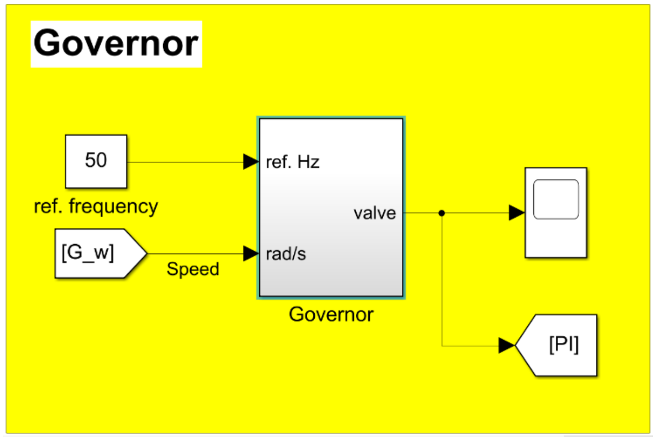

Figure (5.21) Governor

The governor will compare the frequency of the system with a reference value, and then using a controller, the valve will be opened to match a specific pressure that is responsible of changing the mechanical power of the cycle and thus matching it with the load within the valve limits.

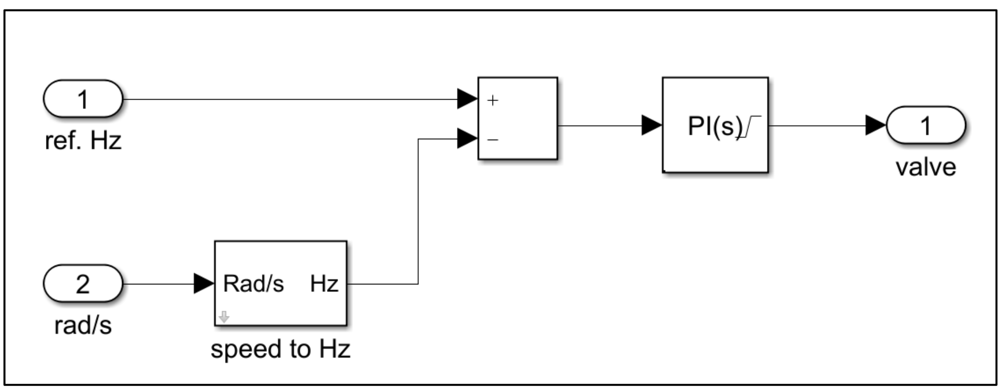

Figure (5.22) Governor under mask

The control is limited with valve max and minimum opening, figure (5.23) shows the max and minimum limits of valve opening and its effect on the power produced.

So for a precise control and to make the frequency constant within the safe range, the load must be in-between the limits of the control as shown in figure (5.24).

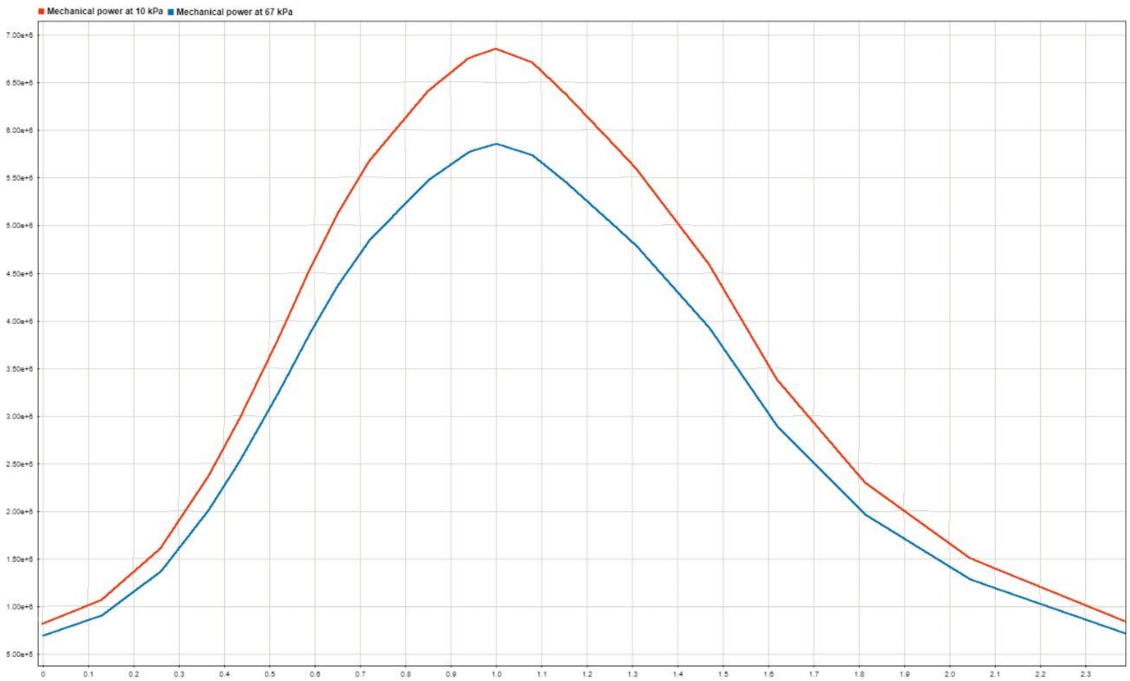

Figure (5.23) Valve maximum and minimum opening (limits of the control)

As shown the max limit of the valve is giving a pressure of 67 kPa, and the minimum limit is giving a pressure of 10kPa.

The experimental load profile is shown in figure (5.24), and the governor is connected.

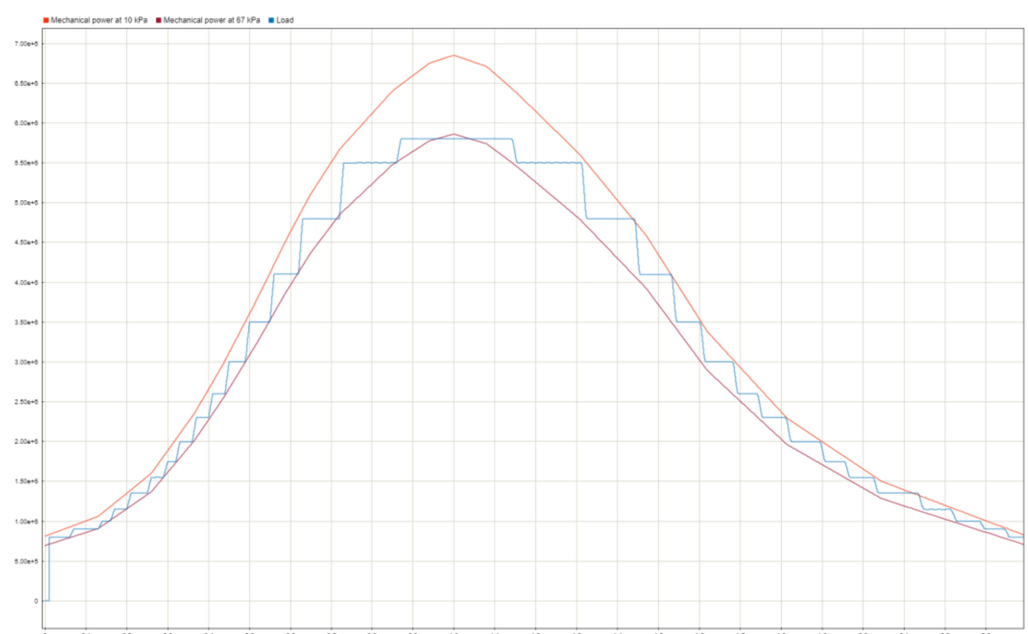

Figure (5.24) Load profile within the limits of the control.

It's noticed that the mechanical power is now changed depending on the load of the generator as shown in figure (5.25), and thus the mechanical power is matching the load, this change will maintain a constant frequency as shown in figure (5.26).

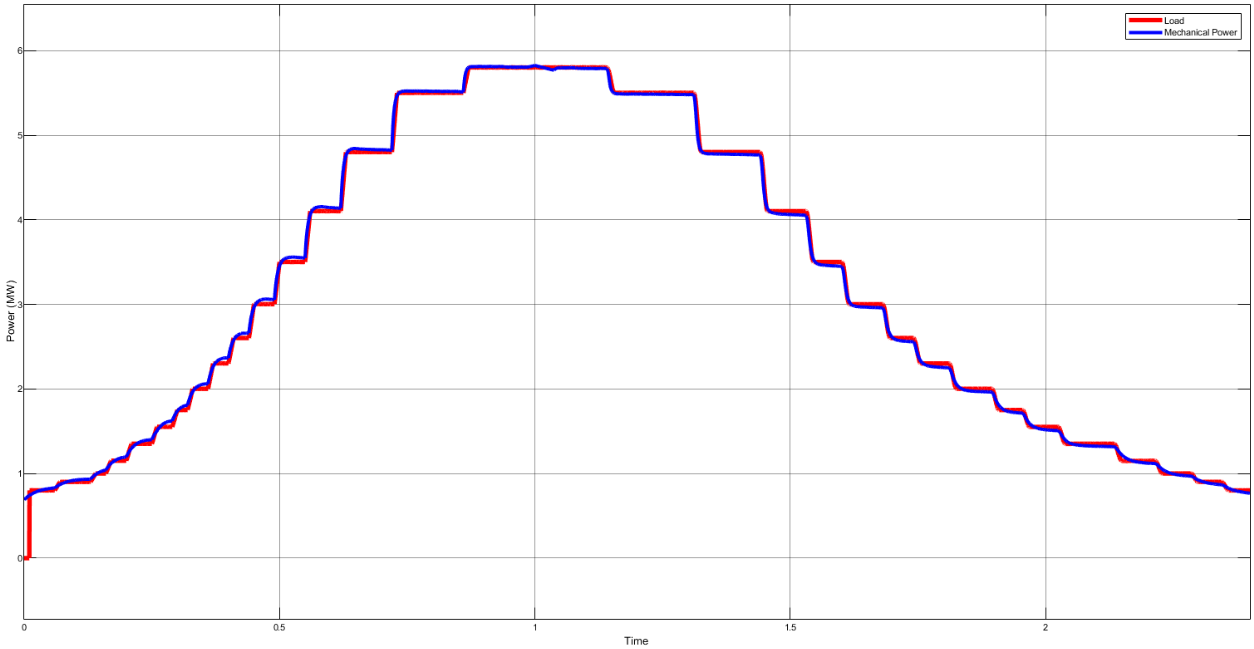

Figure (5.25) Closed loop mechanical power of the turbines with the load (electrical power)

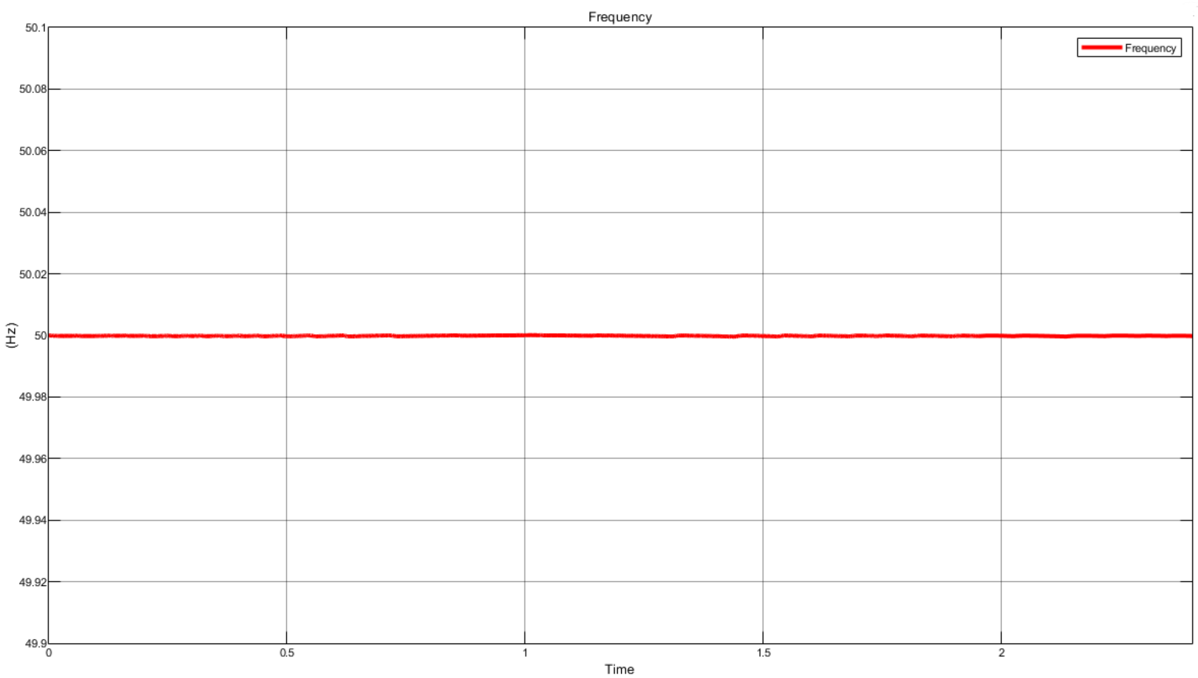

Figure (5.26) System frequency in closed loop case

The efficiency of this case is shown in figure (5.27), the efficiency is changing depending on the valve opening, so to maintain a stable frequency the produced power is sometimes less than the max power produced at the same given condition, which result in lowering the efficiency, buts it’s needed to stabilize the frequency, because of that the efficiency is changing between (42% - 49%).

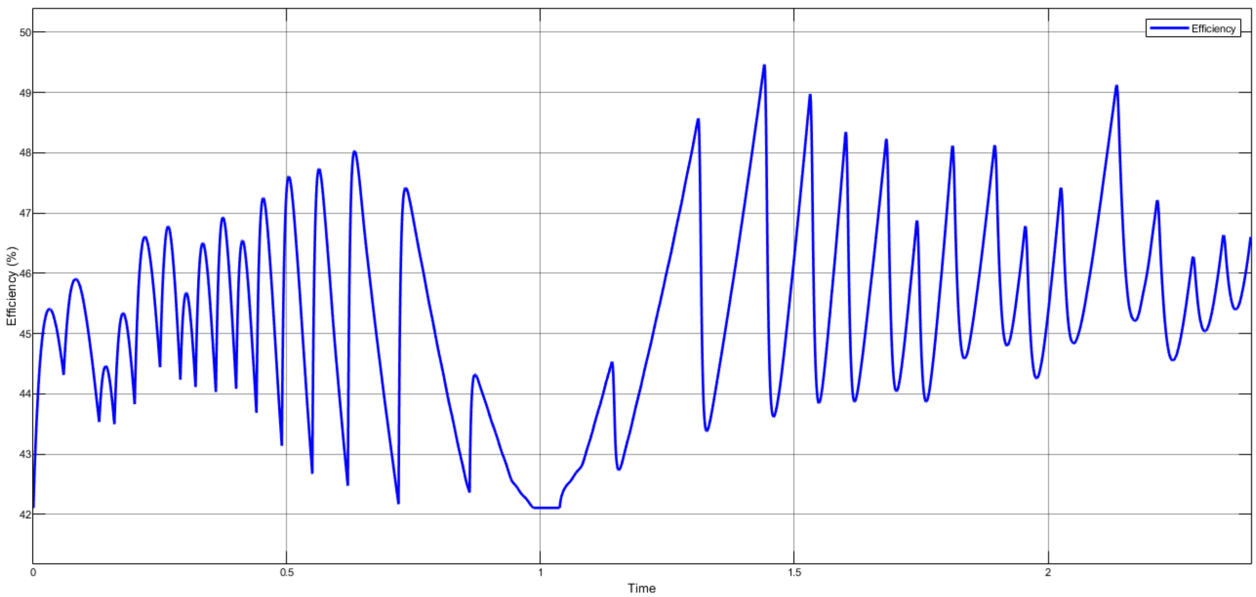

Figure (5.27) Efficiency of the closed loop case

6

Chapter 6

Conclusion

6.1 Conclusion

The peak energy production of the plant is between **7:30 AM** to **5:00 PM**, which sets in the range of the high demand period, which in turn help reducing the stress on the other constant operating power plants at the high demand period.

The proposed power plant has an annual net energy production of **10.4 GWh/year**, which is **2.82%** of Hebron power consumption.

Renewable power plants rely on a non-controlled source of power which is in case of parabolic trough it's the sun, thus the produced power isn't constant, and to maintain a stable frequency the load must be within the limits of the power generation, which means, a precise study of the power production over the year is needed to be able to manage the suitable load for the plant and to maintain a stable frequency.

The proposed speed drop control design worked within the limits of the control.

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Appendices

Appendix A (Tables used in the power conversion calculation)

Superheated Vapor Properties for Steam - (9 MPa - 40 MPa)

	P=9.0 MPa (303.3°C)				P=10.0 MPa (311.0°C)				P=12.5 MPa (327.8°C)			
Temp	volume	energy	enthalpy	entropy	volume	energy	enthalpy	entropy	volume	energy	enthalpy	entropy
°C	v(m^3/kg)	u(kJ/kg)	h(kJ/kg)	s(kJ/kg.K)	v(m^3/kg)	u(kJ/kg)	h(kJ/kg)	s(kJ/kg.K)	v(m^3/kg)	u(kJ/kg)	h(kJ/kg)	s(kJ/kg.K)
Sat.	0.0205	2558.5	2742.9	5.679	0.0180	2545.2	2725.5	5.616	0.0135	2505.6	2674.3	5.464
350	0.0258	2724.9	2957.3	6.038	0.0224	2699.6	2924.0	5.946	0.0161	2624.8	2826.6	5.713
400	0.0300	2849.2	3118.8	6.288	0.0264	2833.1	3097.4	6.214	0.0200	2789.6	3040.0	6.043
450	0.0335	2956.3	3258.0	6.487	0.0298	2944.5	3242.3	6.422	0.0230	2913.7	3201.4	6.275
500	0.0368	3056.3	3387.4	6.660	0.0328	3047.0	3375.1	6.600	0.0256	3023.2	3343.6	6.465
600	0.0429	3248.4	3634.1	6.961	0.0384	3242.0	3625.8	6.905	0.0303	3225.8	3604.6	6.783
700	0.0486	3438.8	3876.1	7.223	0.0436	3434.0	3870.0	7.169	0.0346	3422.0	3854.6	7.054
800	0.0541	3632.0	4119.1	7.461	0.0486	3628.2	4114.5	7.409	0.0387	3618.7	4102.8	7.297
900	0.0596	3829.6	4365.7	7.680	0.0536	3826.5	4362.0	7.629	0.0427	3818.9	4352.9	7.519
1000	0.0649	4032.4	4616.7	7.886	0.0584	4029.9	4613.8	7.835	0.0466	4023.5	4606.5	7.727

P=1.00 MPa (179.9°C)				
Temp	volume	energy	enthalpy	entropy
°C	v(m^3/kg)	u(kJ/kg)	h(kJ/kg)	s(kJ/kg.K)
Sat.	0.1944	2582.7	2777.1	6.585
200	0.2060	2622.2	2828.3	6.696
250	0.2328	2710.4	2943.1	6.927
300	0.2580	2793.6	3051.6	7.125
350	0.2825	2875.7	3158.2	7.303
400	0.3066	2957.9	3264.5	7.467
450	0.3305	3040.9	3371.3	7.620
500	0.3541	3125.0	3479.1	7.764
600	0.4011	3297.5	3698.6	8.031
700	0.4478	3476.2	3924.1	8.276
800	0.4944	3661.7	4156.1	8.502
900	0.5408	3853.9	4394.8	8.715
1000	0.5872	4052.7	4639.9	8.916

Superheated Vapor Properties for Steam (0.5 MPa - 1.4 MPa)

Saturation Properties for Steam - Pressure Table (1 kPa - 1 MPa)

Pressure	Temp	volume (m^3/kg)		energy (kJ/kg)		enthalpy (kJ/kg)			entropy (kJ/kg.K)		
MPa	°C	vf	vg	uf	ug	hf	hfg	hg	sf	sfg	sg
0.001	6.97	0.00100	129.18	29.3	2384.5	29.3	2484.4	2513.7	0.1059	8.8690	8.9749
0.0012	9.65	0.00100	108.67	40.6	2388.2	40.6	2478.0	2518.6	0.1460	8.7622	8.9082
0.0014	11.97	0.00100	93.90	50.3	2391.3	50.3	2472.5	2522.8	0.1802	8.6720	8.8522
0.0016	14.01	0.00100	82.74	58.8	2394.1	58.8	2467.7	2526.5	0.2100	8.5935	8.8035
0.0018	15.84	0.00100	74.01	66.5	2396.6	66.5	2463.4	2529.9	0.2366	8.5242	8.7608
0.002	17.50	0.00100	66.99	73.4	2398.9	73.4	2459.5	2532.9	0.2606	8.4620	8.7226
0.003	24.08	0.00100	45.65	101.0	2407.9	101.0	2443.8	2544.8	0.3543	8.2221	8.5764
0.004	28.96	0.00100	34.79	121.4	2414.5	121.4	2432.3	2553.7	0.4224	8.0510	8.4734
0.006	36.16	0.00101	23.73	151.5	2424.2	151.5	2415.1	2566.6	0.5208	7.8082	8.3290
0.008	41.51	0.00101	18.10	173.8	2431.4	173.8	2402.4	2576.2	0.5925	7.6348	8.2273
0.01	45.81	0.00101	14.67	191.8	2437.2	191.8	2392.1	2583.9	0.6492	7.4996	8.1488
0.012	49.42	0.00101	12.36	206.9	2442.0	206.9	2383.4	2590.3	0.6963	7.3886	8.0849
0.014	52.55	0.00101	10.69	220.0	2446.1	220.0	2375.8	2595.8	0.7366	7.2945	8.0311
0.016	55.31	0.00102	9.431	231.6	2449.8	231.6	2369.0	2600.6	0.7720	7.2126	7.9846
0.018	57.80	0.00102	8.443	242.0	2453.0	242.0	2363.0	2605.0	0.8036	7.1401	7.9437
0.02	60.06	0.00102	7.648	251.4	2456.0	251.4	2357.5	2608.9	0.8320	7.0752	7.9072
0.03	69.10	0.00102	5.228	289.2	2467.7	289.3	2335.2	2624.5	0.9441	6.8234	7.7675
0.04	75.86	0.00103	3.993	317.6	2476.3	317.6	2318.5	2636.1	1.0261	6.6429	7.6690
0.06	85.93	0.00103	2.732	360.0	2489.0	359.9	2293.0	2652.9	1.1454	6.3857	7.5311
0.08	93.49	0.00104	2.087	391.6	2498.2	391.7	2273.5	2665.2	1.2330	6.2009	7.4339
0.1	99.61	0.00104	1.694	417.4	2505.6	417.5	2257.4	2674.9	1.3028	6.0560	7.3588
0.12	104.78	0.00105	1.428	439.2	2511.7	439.4	2243.7	2683.1	1.3609	5.9368	7.2977
0.14	109.29	0.00105	1.2366	458.3	2516.9	458.4	2231.6	2690.0	1.4110	5.8351	7.2461
0.16	113.30	0.00105	1.0914	475.2	2521.4	475.4	2220.6	2696.0	1.4551	5.7463	7.2014
0.18	116.91	0.00106	0.9775	490.5	2525.5	490.7	2210.7	2701.4	1.4945	5.6676	7.1621
0.2	120.21	0.00106	0.8857	504.5	2529.1	504.7	2201.5	2706.2	1.5302	5.5967	7.1269
0.3	133.52	0.00107	0.6058	561.1	2543.2	561.4	2163.5	2724.9	1.6717	5.3199	6.9916
0.4	143.61	0.00108	0.4624	604.2	2553.1	604.7	2133.4	2738.1	1.7765	5.1190	6.8955
0.6	158.83	0.00110	0.3156	669.7	2566.8	670.4	2085.7	2756.1	1.9308	4.8284	6.7592
0.8	170.41	0.00112	0.2403	720.0	2576.0	720.9	2047.4	2768.3	2.0457	4.6159	6.6616
1	179.88	0.00113	0.1944	761.4	2582.7	762.5	2014.6	2777.1	2.1381	4.4469	6.5850

Saturation Properties for Steam - Temperature Table (0.01°C - 150°C)

Temp	Pressure	volume (m^3/kg)		energy (kJ/kg)		enthalpy (kJ/kg)			entropy (kJ/kg.K)		
°C	MPa	vf	vg	uf	ug	hf	hfg	hg	sf	sfg	sg
0.01	0.00061	0.00100	205.99	0	2374.9	0.001	2500.9	2500.9	0	9.1555	9.1555
5	0.00087	0.00100	147.01	21.02	2381.8	21.0	2489.1	2510.1	0.0763	8.9485	9.0248
10	0.00123	0.00100	106.30	42.02	2388.6	42.0	2477.2	2519.2	0.1511	8.7487	8.8998
15	0.00171	0.00100	77.875	62.98	2395.5	63.0	2465.3	2528.3	0.2245	8.5558	8.7803
20	0.00234	0.00100	57.757	83.91	2402.3	83.9	2453.5	2537.4	0.2965	8.3695	8.6660
25	0.00317	0.00100	43.337	104.83	2409.1	104.8	2441.7	2546.5	0.3672	8.1894	8.5566
30	0.00425	0.00100	32.878	125.73	2415.9	125.7	2429.8	2555.5	0.4368	8.0152	8.4520
35	0.00563	0.00101	25.205	146.63	2422.7	146.6	2417.9	2564.5	0.5051	7.8466	8.3517
40	0.00739	0.00101	19.515	167.53	2429.4	167.5	2406.0	2573.5	0.5724	7.6831	8.2555
45	0.00960	0.00101	15.252	188.43	2436.1	188.4	2394.0	2582.4	0.6386	7.5247	8.1633
50	0.01235	0.00101	12.027	209.33	2442.7	209.3	2382.0	2591.3	0.7038	7.3710	8.0748
55	0.01576	0.00102	9.5643	230.24	2449.3	230.3	2369.8	2600.1	0.7680	7.2218	7.9898
60	0.01995	0.00102	7.6672	251.16	2455.9	251.2	2357.6	2608.8	0.8313	7.0768	7.9081
65	0.02504	0.00102	6.1935	272.09	2462.4	272.1	2345.4	2617.5	0.8937	6.9359	7.8296
70	0.03120	0.00102	5.0395	293.03	2468.9	293.2	2333.0	2626.1	0.9551	6.7989	7.7540
75	0.03860	0.00103	4.1289	313.99	2475.2	314.0	2320.6	2634.6	1.0158	6.6654	7.6812
80	0.04741	0.00103	3.4052	334.96	2481.6	335.0	2308.0	2643.0	1.0756	6.5355	7.6111
85	0.05787	0.00103	2.8258	355.95	2487.8	356.0	2295.3	2651.3	1.1346	6.4088	7.5434
90	0.07018	0.00104	2.3591	376.97	2494.0	377.0	2282.5	2659.5	1.1929	6.2852	7.4781
95	0.08461	0.00104	1.9806	398.00	2500.0	398.1	2269.5	2667.6	1.2504	6.1647	7.4151
100	0.10142	0.00104	1.6718	419.06	2506.0	419.2	2256.4	2675.6	1.3072	6.0469	7.3541
110	0.14338	0.00105	1.2093	461.26	2517.7	461.4	2229.7	2691.1	1.4188	5.8193	7.2381
120	0.19867	0.00106	0.8912	503.60	2528.9	503.8	2202.1	2705.9	1.5279	5.6012	7.1291
130	0.27028	0.00107	0.66800	546.09	2539.5	546.4	2173.7	2720.1	1.6346	5.3918	7.0264
140	0.36154	0.00108	0.50845	588.77	2549.6	589.2	2144.2	2733.4	1.7392	5.1901	6.9293
150	0.47616	0.00109	0.39245	631.66	2559.1	632.2	2113.7	2745.9	1.8418	4.9953	6.8371

Appendix B (UL Calculation)

$$U_L = \left[\frac{A_r}{(h_w + h_{r,c-a}) * A_g} + \frac{1}{h_{r,r-c}}\right]^{-1}$$

Ag = glass cover area = $\pi \times D_g \times L$ = π *0.125*99.5 = 39.07 m2
$h_w = (Nu)\, k/D_g$
$Nu = 0.3(Re)^{0.6}$

$$Re = \rho V D_g/\mu$$

ρ = Density of the fluid = 1046 Kg/m3
V = wind velocity = 8.4 km/s in Palestine (annual mean)[8]
Dg = glass outer diameter of the receiver tube = 0.125 m
μ = Viscosity 'μ' = 3.2 x 10-3 Pa.sec.

$Re = (1046 \times 8.4 \times 10^3 \times 0.125)/3.2x10^{-3}$
Re = 343,218,750

Nu = 0.3 * (Re)0.6
Nu = 0.3 * (343218750)0.6 = 39,670

Now we can calculate hw .

hw = (Nu)k/Dg
hw = (39,670)* 0.135/0.125
hw = 42,843.7

Next is $h_{r,c-a}$ which is the heat transfer coefficient for the glass cover to the ambient temp.

$$h_{r,c-a} = \varepsilon_g \sigma (T_g + T_a)(T_g^2 + T_a^2)$$

ε_g = 0.97
σ = Stefan–Boltzmann constant = 5.67 * 10-8 W/m2 K4
Tg = Glass cover temperature, assumed to be 27 Co = 300 K
Ta = ambient temperature = 25 Co = 298 K

hr,c-a = 0.97* 5.67*10-8 (300 + 298)(3002 + 2982)
hr,c-a = 5.88 W/m2 K

Now we need to calculate $h_{r,r-c}$ which is the radiation heat transfer coefficient between the receiver tube and the glass cover.

$$h_{r,r-c} = \frac{\sigma\left(T_r^2 + T_g^2\right)\left(T_r + T_g\right)}{\frac{1}{\varepsilon_r} + \frac{A_r}{A_g}\left(\frac{1}{\varepsilon_g} - 1\right)}$$

ε_r = 0.96
ε_g = 0.97
Tr = receiver temperature = 277 Co = 550 K
Tg = Glass cover temperature (assumed to be 300K, will be proved later)

$$\mathbf{h_{r,r-c}} = \frac{5.6 \times 10^{-8}(550^2 + 300^2)(550 + 300)}{\frac{1}{0.96} + \frac{21.88}{39.07}\left(\frac{1}{0.97} - 1\right)}$$

$$\mathbf{h_{r,r-c}} = \frac{18.688}{1.05898}$$

$$\mathbf{h_{r,r-c}} = 17.64 \text{ W/m2 K}$$

Now we can calculate UL :

$$\mathbf{U_L} = \left[\frac{21.88}{(42843.7 + 5.88) * 39.07} + \frac{1}{17.64}\right]^{-1}$$

$$\mathbf{U_L} = [0.05670241]^{-1}$$

$$\mathbf{U_L} = 17.64 \text{ W/m2 K}$$

Finally, since we assumed Tg(glass cover temperature) as 27Co, we need to check if our assumption was correct using the following formula[16] :

$$T_g = \frac{A_r h_{r,r-c} T_r + A_g\left(h_{r,c-a} + h_w\right)T_a}{A_r h_{r,r-c} + A_g\left(h_{r,c-a} + h_w\right)}$$

$$\mathbf{T_g} = \frac{21.88 \times 17.64 \times 277 + 39.07(5.88 + 42843.7)25}{21.88 \times 17.64 + 39.07(5.88 + 42843.7)}$$

$$\mathbf{T_g} = \frac{385.96 \times 277 + 1674133 \times 25}{385.96 + 1674133}$$

$\mathbf{T_g} = 25.05$ ℃, and it’s close to our assumption therefore it’s correct.

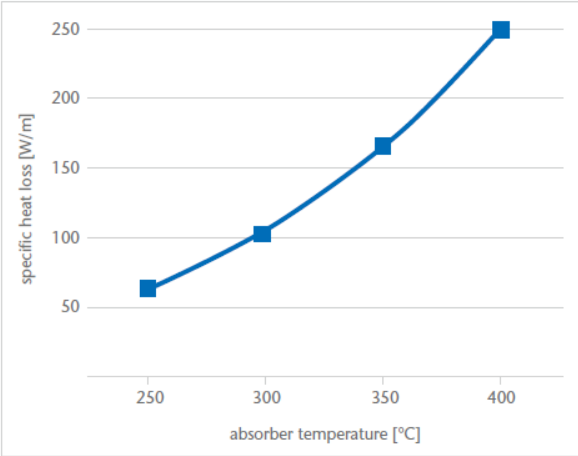
Appendix C (PTR 70 Specification)

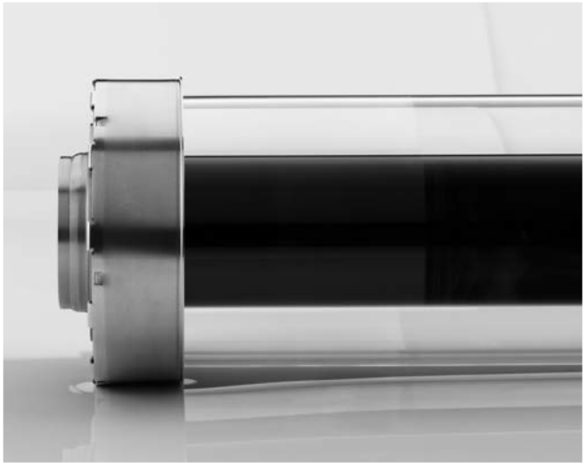
Heat loss measurements carried out in a round robin test performed by SCHOTT Solar CSP in cooperation with NREL (US National Renewable Energy Laboratory) and DLR confirmed a heat loss of less than 250 W/m at working temperatures (400 °C).

Technical specification

Components	Specification
Dimension	• length: 4060 mm at 20 °C ambient temperature (159.8 inches at 68 °F) • aperture length: > 96.7 % of the bulk length at 350 °C / 662 °F working temperature
Absorber	• outer diameter: 70 mm / 2.75 inches • steel-type: DIN 1.4541 or similar • solar absorptance: α_{ISO} ≥ 95.5 % α_{ASTM} ≥ 96 % • thermal emittance: $\varepsilon \leq 9.5\%$
Glass envelope	• Borosilicate glass • outer diameter: 125 mm / 4.9 inches • antireflective coating • solar transmittance: $\tau \geq 97\%$
Thermal losses	• in conjunction with SCHOTT Solar CSP patented shields < 250 W/m (@ 400 °C) < 165 W/m (@ 350 °C) < 110 W/m (@ 300 °C) < 70 W/m (@ 250 °C)
Vacuum	• residual gas pressure: ≤ 10^{-3} mbar
Heat transfer fluid	• non-corrosive thermal oil with an effective partial pressure of dissolved Hydrogen of p_{H2} < 30 Pa
Operating pressure	• ≤ 41 bar (absolute)

Thermal losses





Appendix D (AALBORG Steam Generation Unit)

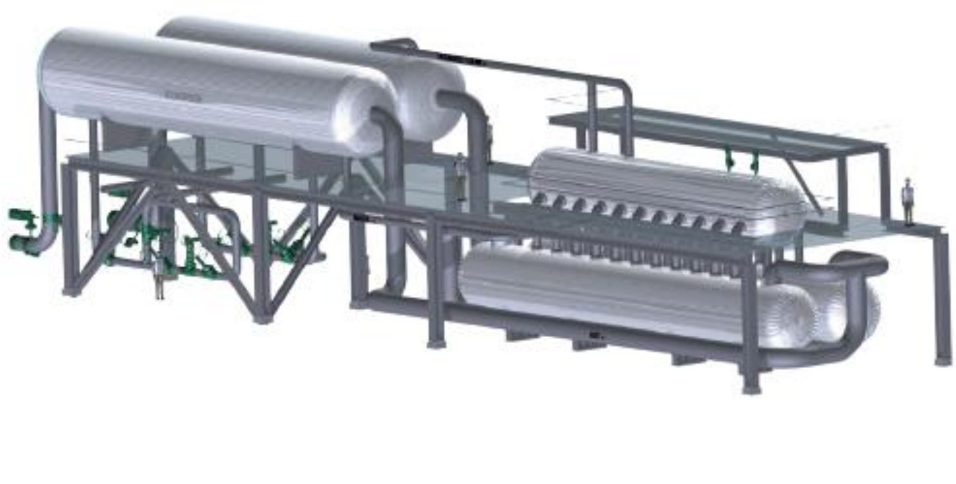
AALBORG CSP

- your green thermal energy partner

Aalborg CSP steam generators

Technical information

- Millions of dollars to be saved by correct selection of steam generator!



Aalborg CSP steam plant configuration

The parabolic trough solar power plant operates with a heat transfer fluid (HTF) that is heated by the sun in linear concentrators. The HTF is heated to maximum 393°C by the sun and cooled to a temperature just below 300°C in the steam generator. From the steam generator, the HTF is heated again to 393°C to form a closed cycle.

The HTF is cooled in heat exchangers for generation of high pressure steam and is used in a high pressure steam turbine generator for generation of electric power. The steam from the outlet of the steam turbine is normally reheated and used in a low pressure steam turbine generator for increasing the efficiency.

The data in the fig. 2 are typical for a power plant with 25MW electric power output. Some variation in data may be seen depending on the steam turbine chosen.

The high pressure (HP) steam generator consists of one superheater, one evaporator unit and one economizer. The reheater is a separate heat exchanger operated in parallel.

The steam flow is around 28.5kg/s per 25MW electric output. The HP steam is generated at around 105bar at 380°C for the HP turbine. The reheater heats the outlet steam from the HP steam turbine to 380°C again before it enters the low pressure (LP) steam turbine. The inlet steam to the reheater is typically 15 to 20bar with a water content of around 1%.

The plant can be configured with several parallel steam generator lines. A 100MWe power plant can, for example, has four steam generator lines generating 28.5kg/s each. Line sizes can vary, and Aalborg CSP offers lines with capacity of 28, 56 and 75kg/s steam flow as standard. Other capacities can be designed and supplied upon request.

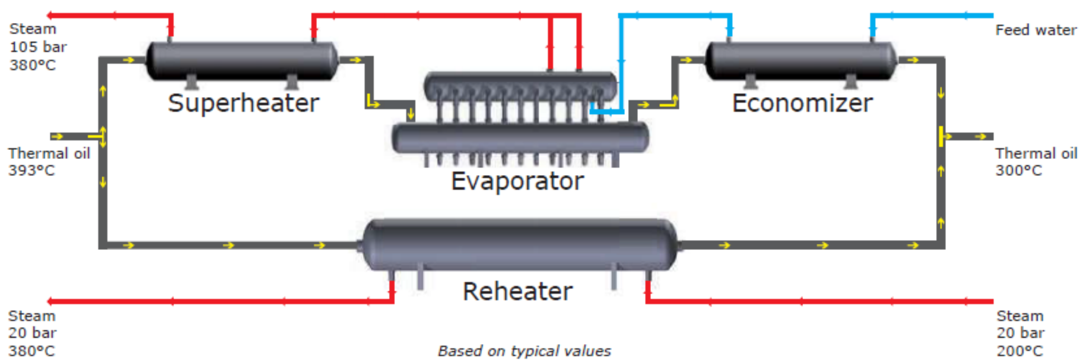
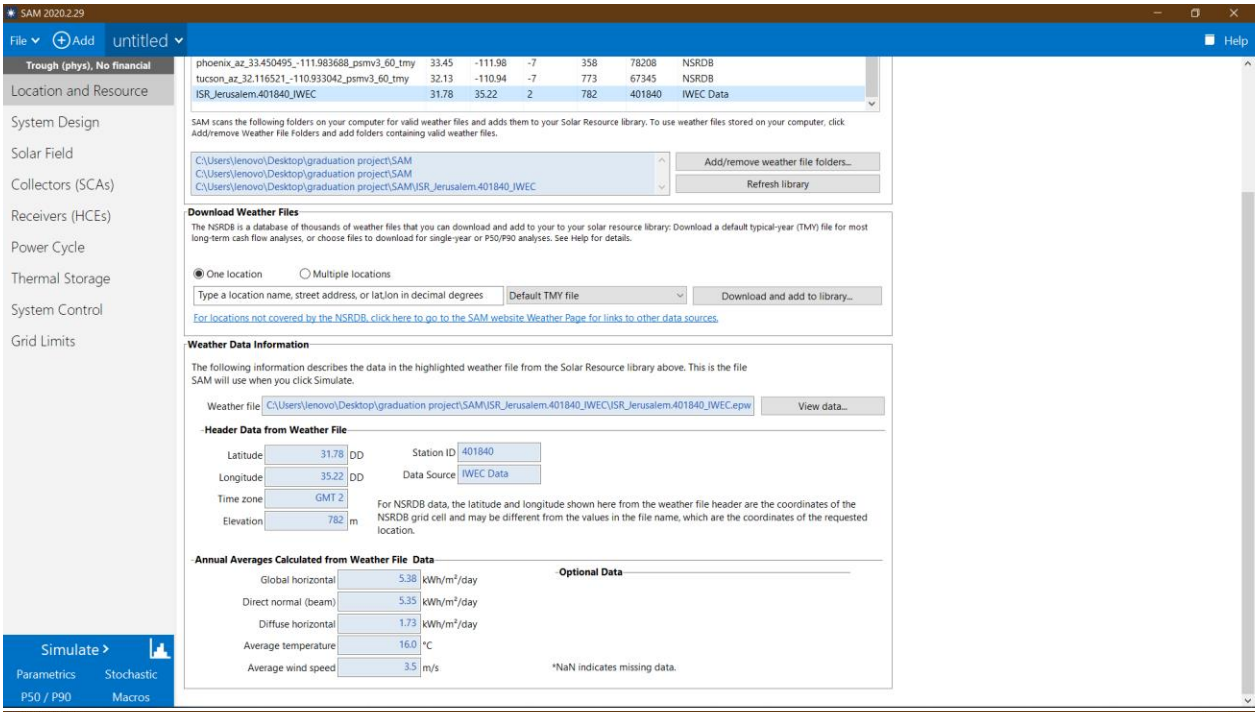
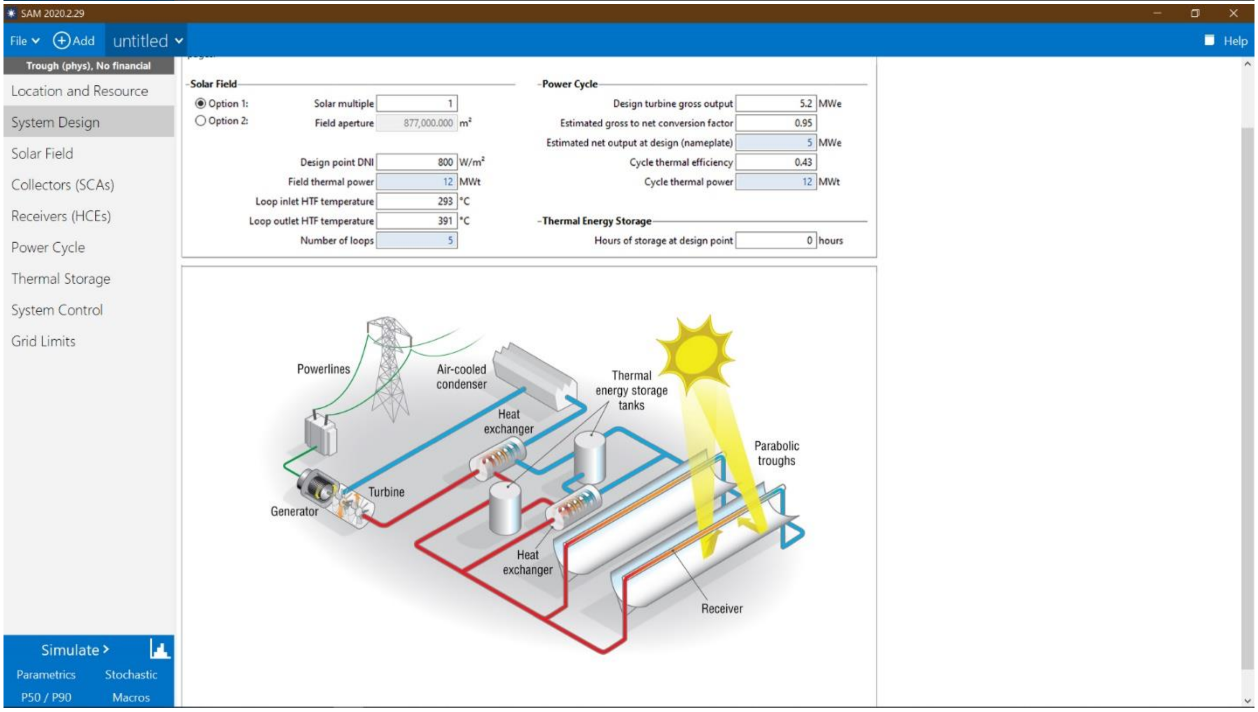
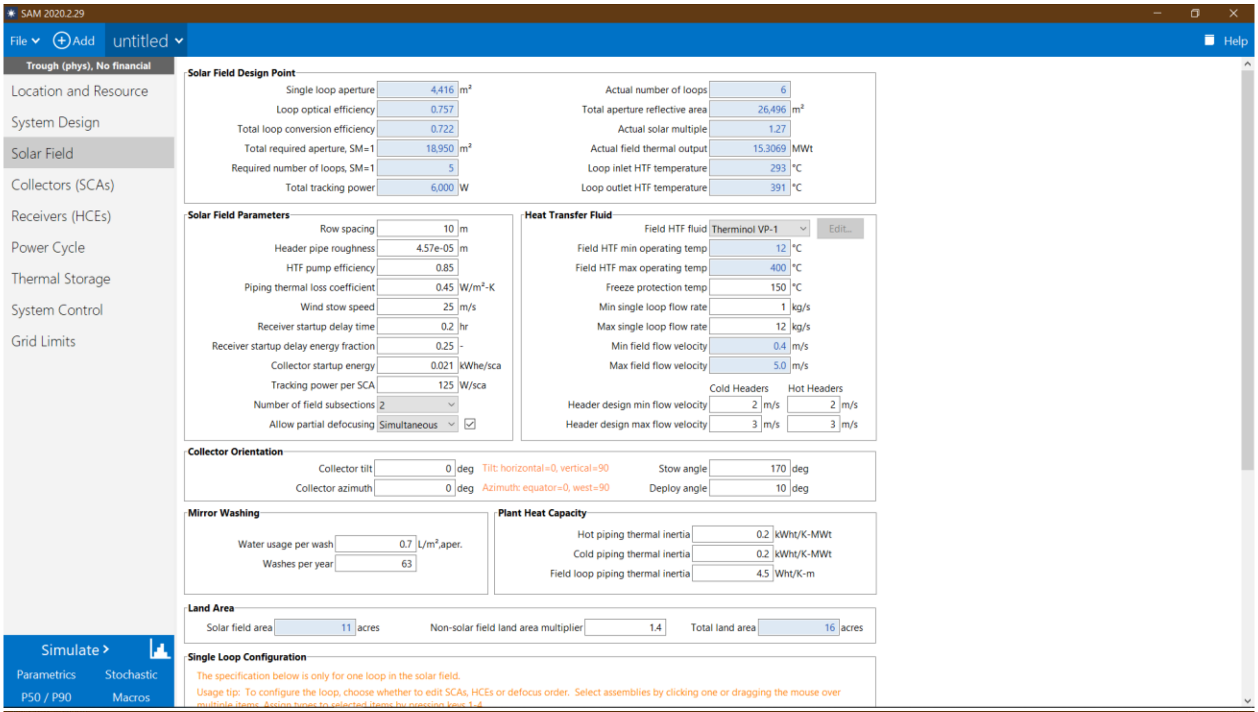


Fig. 2: Heat balance for typical 25MWe line

Appendix E (SAM software setup)






SAM 2020.2.29
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Help
Trough (phys), No financial
Location and Resource
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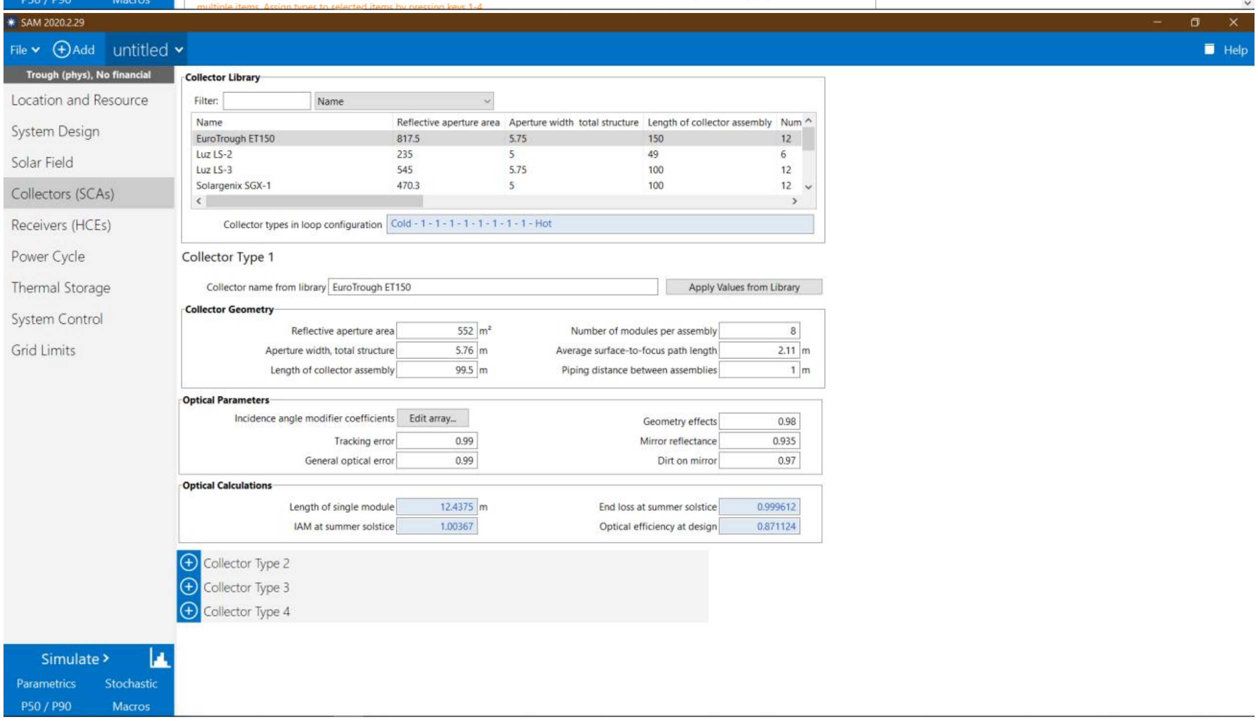
Solar Field
Collectors (SCAs)
Receivers (HCEs)
Power Cycle
Thermal Storage
System Control
Grid Limits
Simulate >
Parametrics
Stochastic
P50 / P90
Macros
Solar Field Design Point
Single loop aperture 4,416 m²
Loop optical efficiency 0.757
Total loop conversion efficiency 0.722
Total required aperture, SM=1 18,950 m²
Required number of loops, SM=1 5
Total tracking power 6,000 W
Actual number of loops 6
Total aperture reflective area 26,496 m²
Actual solar multiple 1.27
Actual field thermal output 15.3069 MWt
Loop inlet HTF temperature 293 °C
Loop outlet HTF temperature 391 °C
Solar Field Parameters
Row spacing 10 m
Header pipe roughness 4.57e-05 m
HTF pump efficiency 0.85
Piping thermal loss coefficient 0.45 W/m²-K
Wind stow speed 25 m/s
Receiver startup delay time 0.2 hr
Receiver startup delay energy fraction 0.25 -
Collector startup energy 0.021 kWhe/sca
Tracking power per SCA 125 W/sca
Number of field subsections 2
Allow partial defocusing Simultaneous
Heat Transfer Fluid
Field HTF fluid Therminol VP-1
Edit...
Field HTF min operating temp 12 °C
Field HTF max operating temp 400 °C
Freeze protection temp 150 °C
Min single loop flow rate 1 kg/s
Max single loop flow rate 12 kg/s
Min field flow velocity 0.4 m/s
Max field flow velocity 5.0 m/s
Cold Headers
Hot Headers
Header design min flow velocity 2 m/s 2 m/s
Header design max flow velocity 3 m/s 3 m/s
Collector Orientation
Collector tilt 0 deg
Tilt: horizontal=0, vertical=90
Collector azimuth 0 deg
Azimuth: equator=0, west=90
Stow angle 170 deg
Deploy angle 10 deg
Mirror Washing
Water usage per wash 0.7 L/m²,aper.
Washes per year 63
Plant Heat Capacity
Hot piping thermal inertia 0.2 kWht/K-MWt
Cold piping thermal inertia 0.2 kWht/K-MWt
Field loop piping thermal inertia 4.5 Wht/K-m
Land Area
Solar field area 11 acres
Non-solar field land area multiplier 1.4
Total land area 16 acres
Single Loop Configuration
The specification below is only for one loop in the solar field.
Usage tip: To configure the loop, choose whether to edit SCAs, HCEs or defocus order. Select assemblies by clicking one or dragging the mouse over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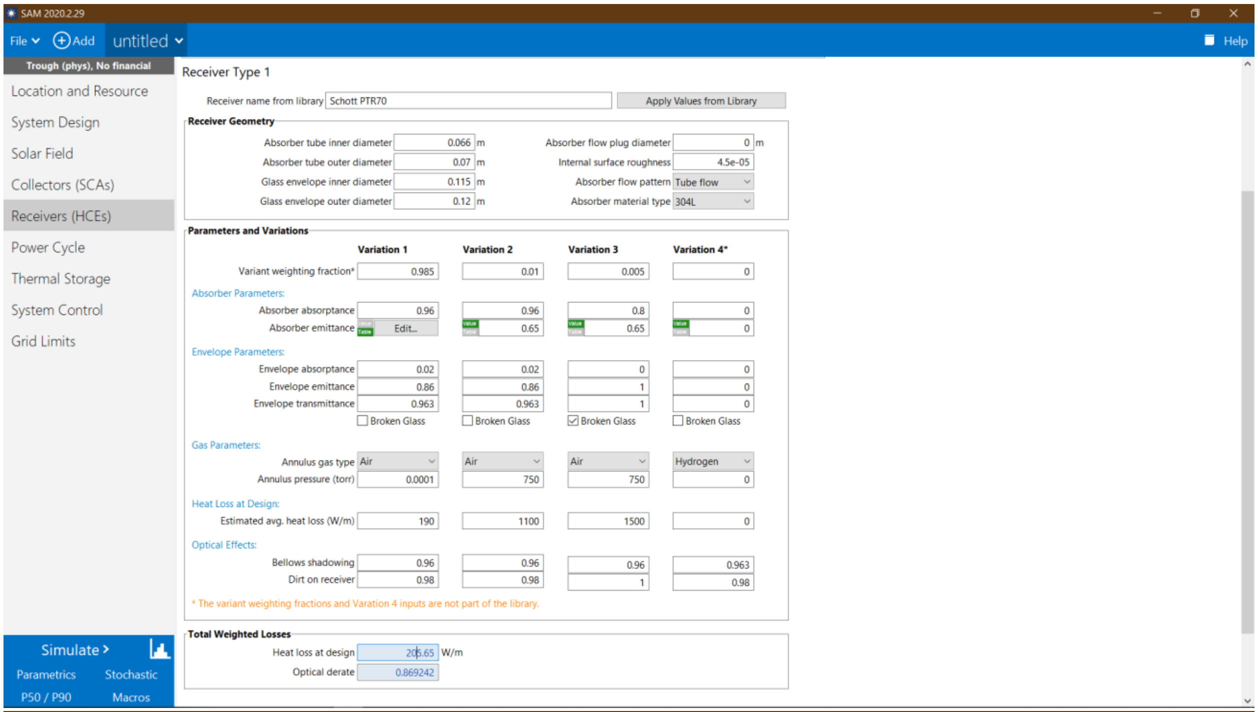
Collector Library
Filter:
Name
Name
Reflective aperture area
Aperture width, total structure
Length of collector assembly
Num
EuroTrough ET150 817.5 5.75 150 12
Luz LS-2 235 5 49 6
Luz LS-3 545 5.75 100 12
Solargenix SGX-1 470.3 5 100 12
Collector types in loop configuration
Cold - 1 - 1 - 1 - 1 - 1 - 1 - 1 - 1 - Hot
Collector Type 1
Collector name from library EuroTrough ET150
Apply Values from Library
Collector Geometry
Reflective aperture area 552 m²
Aperture width, total structure 5.76 m
Length of collector assembly 99.5 m
Number of modules per assembly 8
Average surface-to-focus path length 2.11 m
Piping distance between assemblies 1 m
Optical Parameters
Incidence angle modifier coefficients
Edit array...
Tracking error 0.99
General optical error 0.99
Geometry effects 0.98
Mirror reflectance 0.935
Dirt on mirror 0.97
Optical Calculations
Length of single module 12.4375 m
IAM at summer solstice 1.00367
End loss at summer solstice 0.999612
Optical efficiency at design 0.871124
Collector Type 2
Collector Type 3
Collector Type 4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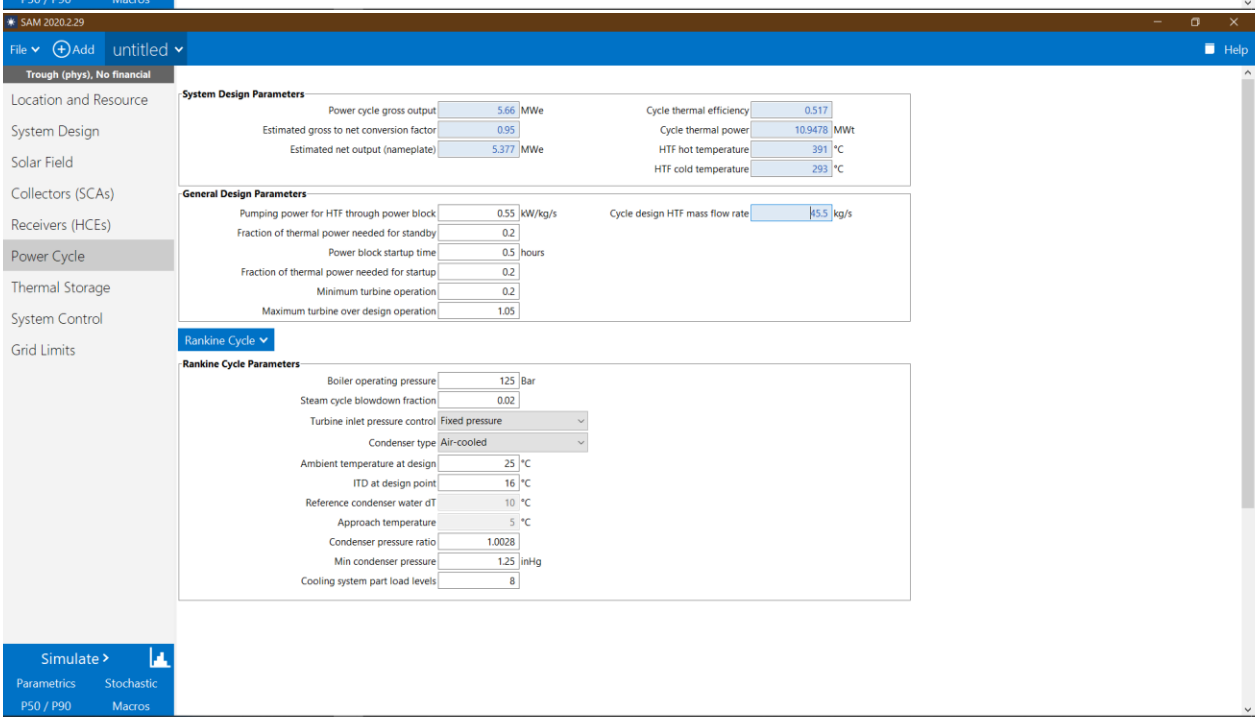
Receiver Type 1
Receiver name from library Schott PTR70
Apply Values from Library
Receiver Geometry
Absorber tube inner diameter 0.066 m
Absorber tube outer diameter 0.07 m
Glass envelope inner diameter 0.115 m
Glass envelope outer diameter 0.12 m
Absorber flow plug diameter 0 m
Internal surface roughness 4.5e-05
Absorber flow pattern Tube flow
Absorber material type 304L
Parameters and Variations
Variation 1
Variation 2
Variation 3
Variation 4*
Variant weighting fraction* 0.985 0.01 0.005 0
Absorber Parameters:
Absorber absorptance 0.96 0.96 0.8 0
Absorber emittance Edit... 0.65 0.65 0
Envelope Parameters:
Envelope absorptance 0.02 0.02 0 0
Envelope emittance 0.86 0.86 1 0
Envelope transmittance 0.963 0.963 1 0
Broken Glass
Broken Glass
Broken Glass
Broken Glass
Gas Parameters:
Annulus gas type Air Air Air Hydrogen
Annulus pressure (torr) 0.0001 750 750 0
Heat Loss at Design:
Estimated avg. heat loss (W/m) 190 1100 1500 0
Optical Effects:
Bellows shadowing 0.96 0.96 0.96 0.963
Dirt on receiver 0.98 0.98 1 0.98
* The variant weighting fractions and Variation 4 inputs are not part of the library.
Total Weighted Losses
Heat loss at design 205.65 W/m
Optical derate 0.869242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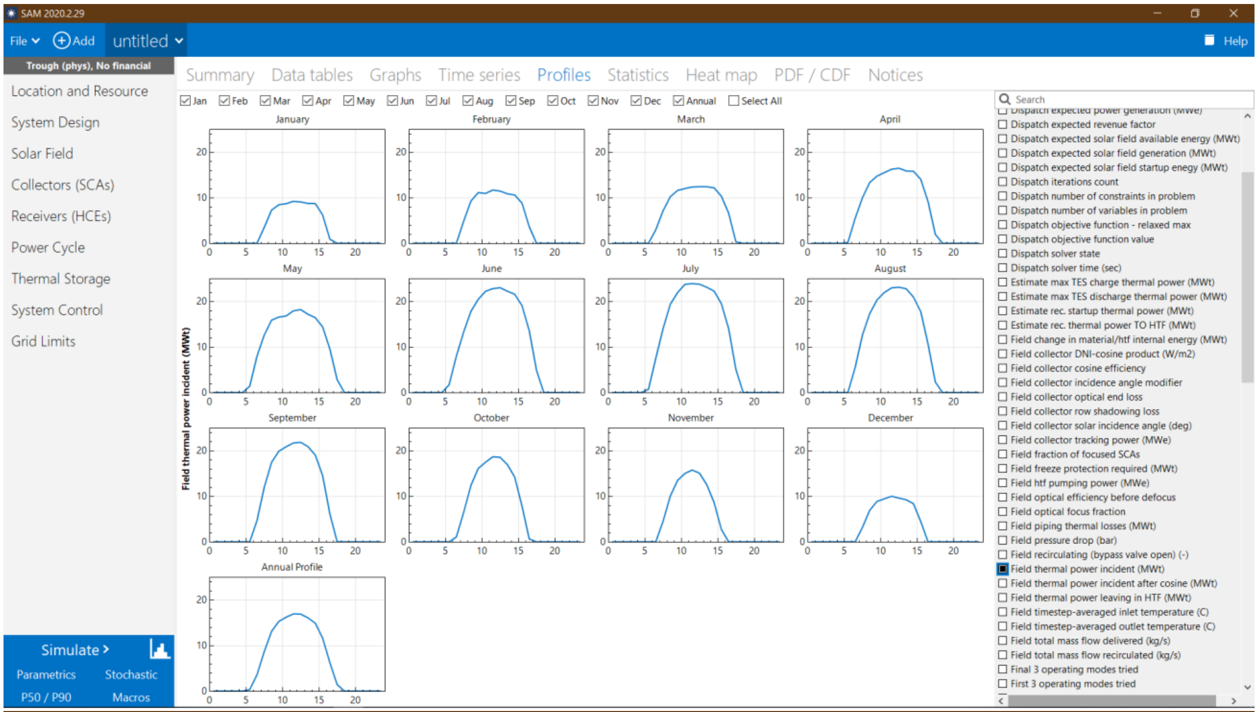
System Design Parameters
Power cycle gross output 5.66 MWe
Estimated gross to net conversion factor 0.95
Estimated net output (nameplate) 5.377 MWe
Cycle thermal efficiency 0.517
Cycle thermal power 10.9478 MWt
HTF hot temperature 391 °C
HTF cold temperature 293 °C
General Design Parameters
Pumping power for HTF through power block 0.55 kW/kg/s
Fraction of thermal power needed for standby 0.2
Power block startup time 0.5 hours
Fraction of thermal power needed for startup 0.2
Minimum turbine operation 0.2
Maximum turbine over design operation 1.05
Cycle design HTF mass flow rate 45.5 kg/s
Rankine Cycle
Rankine Cycle Parameters
Boiler operating pressure 125 Bar
Steam cycle blowdown fraction 0.02
Turbine inlet pressure control Fixed pressure
Condenser type Air-cooled
Ambient temperature at design 25 °C
ITD at design point 16 °C
Reference condenser water dT 10 °C
Approach temperature 5 °C
Condenser pressure ratio 1.0028
Min condenser pressure 1.25 inHg
Cooling system part load levels 8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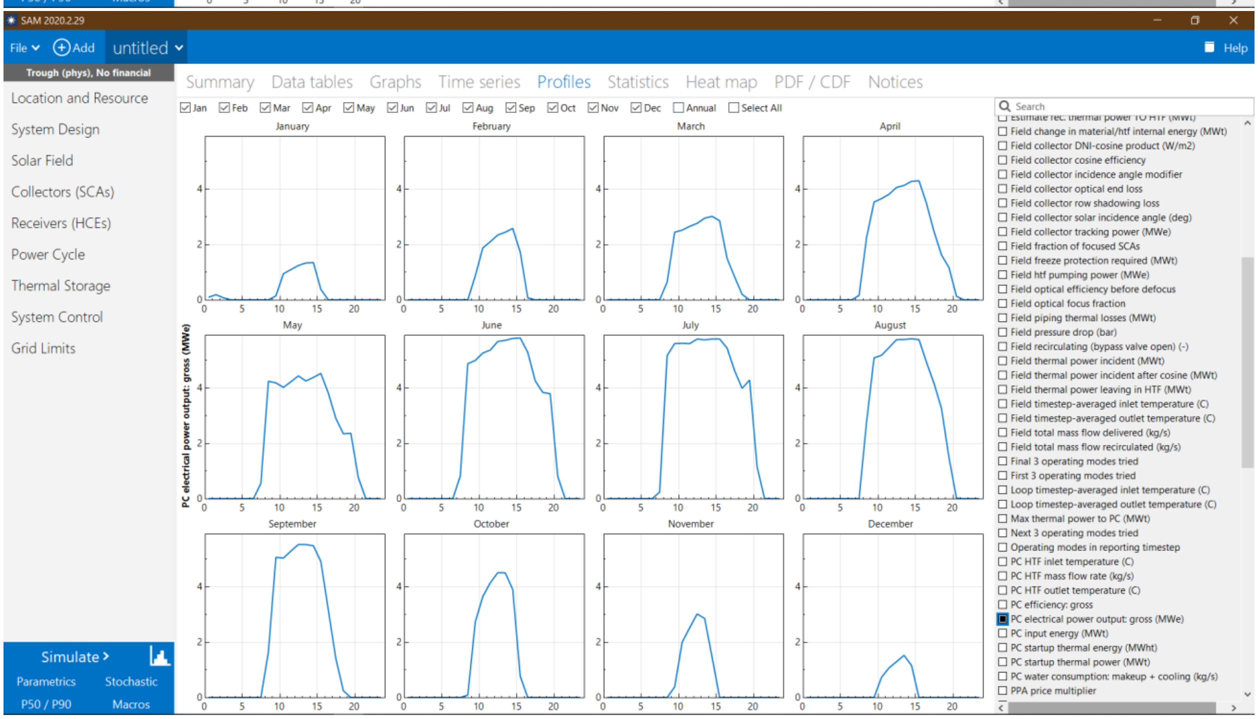
Field thermal power incident (MWt)
Search
Dispatch expected revenue factor
Dispatch expected solar field available energy (MWt)
Dispatch expected solar field generation (MWt)
Dispatch expected solar field startup enegy (MWt)
Dispatch iterations count
Dispatch number of constraints in problem
Dispatch number of variables in problem
Dispatch objective function - relaxed max
Dispatch objective function value
Dispatch solver state
Dispatch solver time (sec)
Estimate max TES charge thermal power (MWt)
Estimate max TES discharge thermal power (MWt)
Estimate rec. startup thermal power (MWt)
Estimate rec. thermal power TO HTF (MWt)
Field change in material/htf internal energy (MWt)
Field collector DNI-cosine product (W/m2)
Field collector cosine efficiency
Field collector incidence angle modifier
Field collector optical end loss
Field collector row shadowing loss
Field collector solar incidence angle (deg)
Field collector tracking power (MWe)
Field fraction of focused SCAs
Field freeze protection required (MWt)
Field htf pumping power (MWe)
Field optical efficiency before defocus
Field optical focus fraction
Field piping thermal losses (MWt)
Field pressure drop (bar)
Field recirculating (bypass valve open) (-)
Field thermal power incident (MWt)
Field thermal power incident after cosine (MWt)
Field thermal power leaving in HTF (MWt)
Field timestep-averaged inlet temperature (C)
Field timestep-averaged outlet temperature (C)
Field total mass flow delivered (kg/s)
Field total mass flow recirculated (kg/s)
Final 3 operating modes tried
First 3 operating modes tried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PC electrical power output: gross (MWe)
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Field change in material/htf internal energy (MWt)
Field collector DNI-cosine product (W/m2)
Field collector cosine efficiency
Field collector incidence angle modifier
Field collector optical end loss
Field collector row shadowing loss
Field collector solar incidence angle (deg)
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Field pressure drop (bar)
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Field thermal power incident after cosine (MWt)
Field thermal power leaving in HTF (MWt)
Field timestep-averaged inlet temperature (C)
Field timestep-averaged outlet temperature (C)
Field total mass flow delivered (kg/s)
Field total mass flow recirculated (kg/s)
Final 3 operating modes tried
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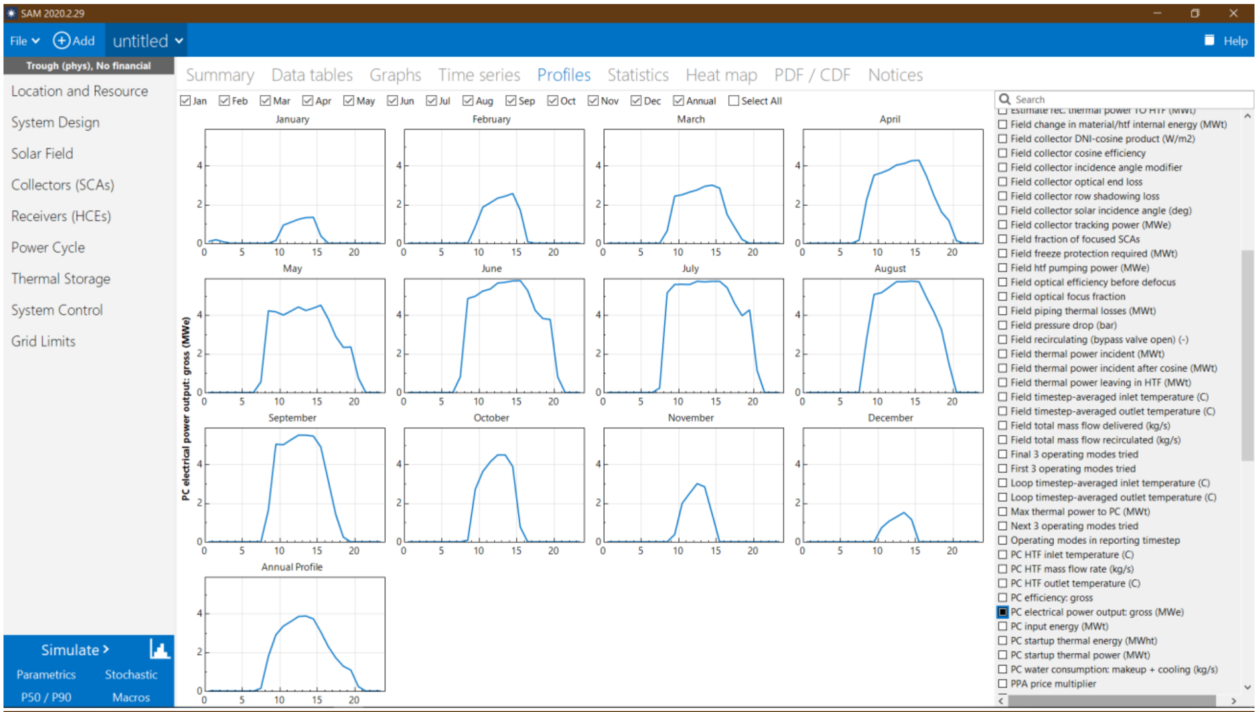
Loop timestep-averaged inlet temperature (C)
Loop timestep-averaged outlet temperature (C)
Max thermal power to PC (MWt)
Next 3 operating modes tried
Operating modes in reporting timestep
PC HTF inlet temperature (C)
PC HTF mass flow rate (kg/s)
PC HTF outlet temperature (C)
PC efficiency: gross
PC electrical power output: gross (MWe)
PC input energy (MWt)
PC startup thermal energy (MWht)
PC startup thermal power (MWt)
PC water consumption: makeup + cooling (kg/s)
PPA price multiplier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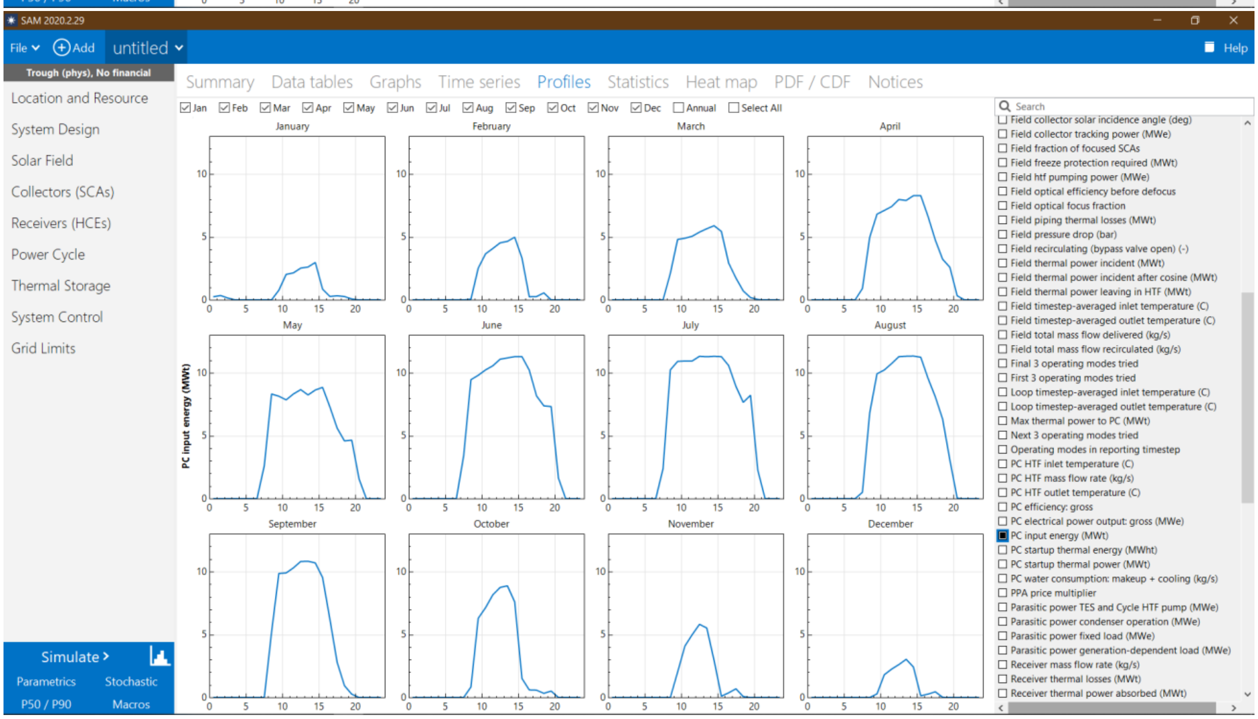
PC electrical power output: gross (MWe)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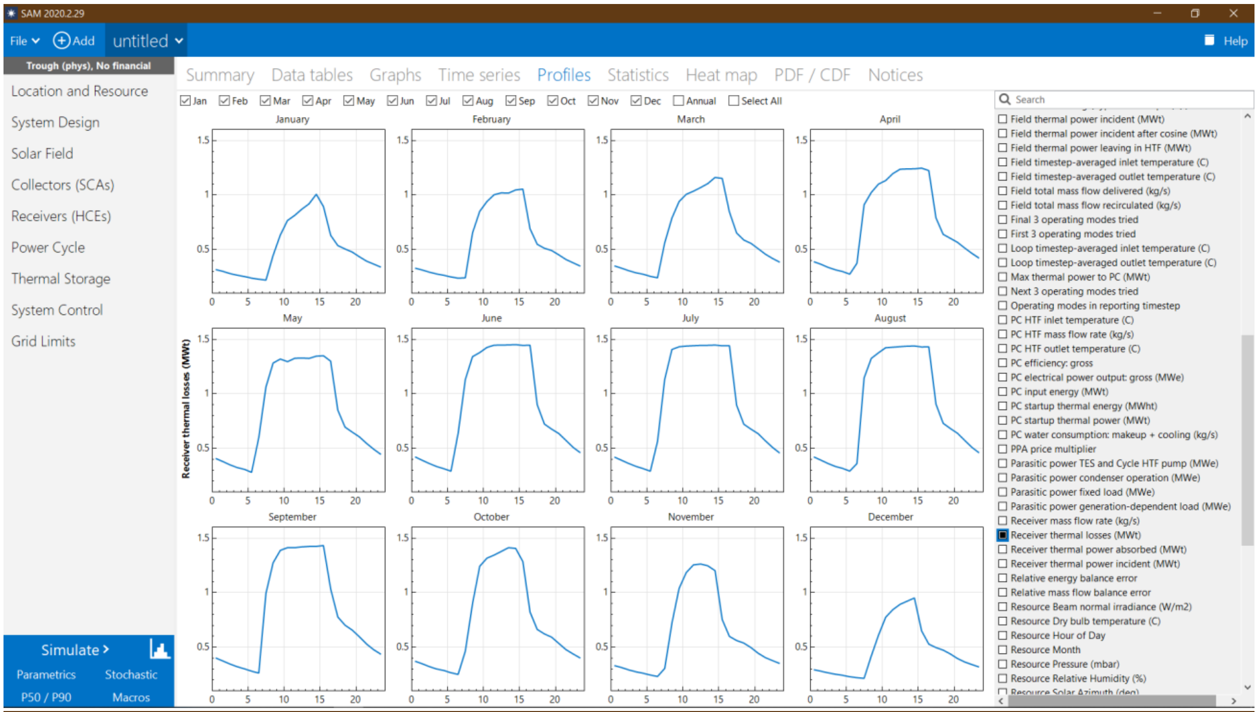
PC input energy (MWt)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Receiver thermal losses (MWt)
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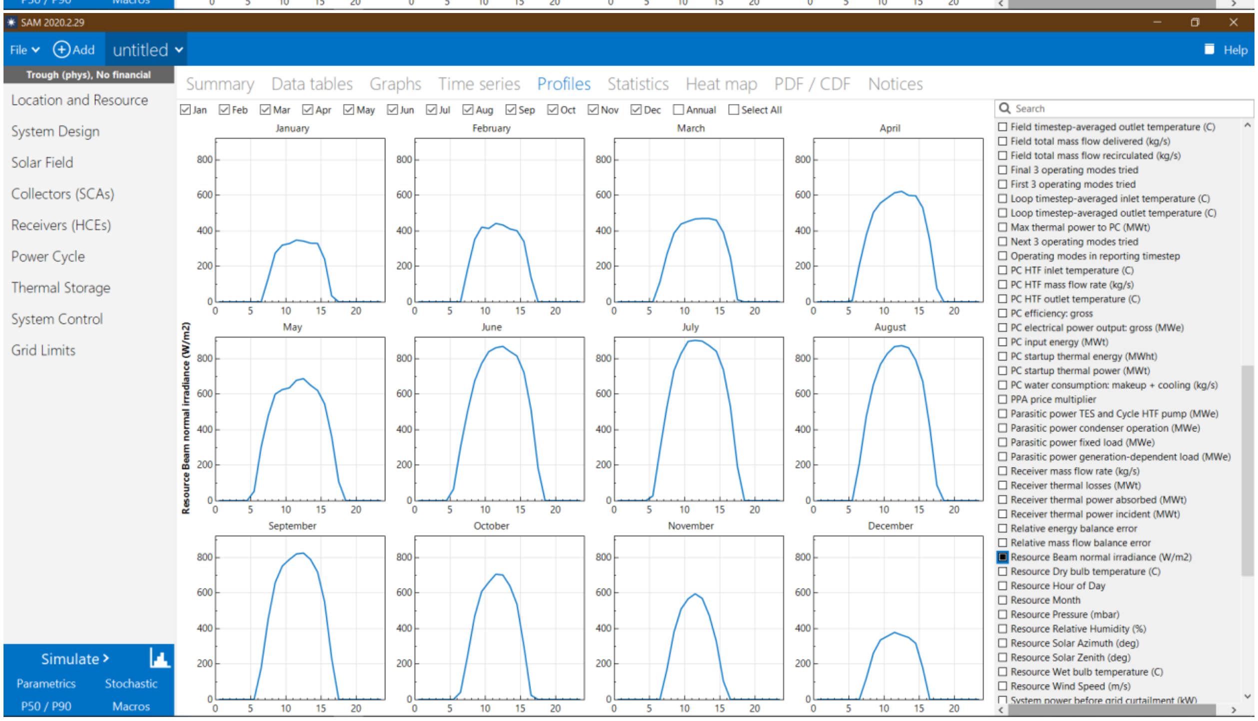
Field thermal power incident (MWt)
Field thermal power incident after cosine (MWt)
Field thermal power leaving in HTF (MWt)
Field timestep-averaged inlet temperature (C)
Field timestep-averaged outlet temperature (C)
Field total mass flow delivered (kg/s)
Field total mass flow recirculated (kg/s)
Final 3 operating modes tried
First 3 operating modes tried
Loop timestep-averaged inlet temperature (C)
Loop timestep-averaged outlet temperature (C)
Max thermal power to PC (MWt)
Next 3 operating modes tried
Operating modes in reporting timestep
PC HTF inlet temperature (C)
PC HTF mass flow rate (kg/s)
PC HTF outlet temperature (C)
PC efficiency: gross
PC electrical power output: gross (MWe)
PC input energy (MWt)
PC startup thermal energy (MWht)
PC startup thermal power (MWt)
PC water consumption: makeup + cooling (kg/s)
PPA price multiplier
Parasitic power TES and Cycle HTF pump (MWe)
Parasitic power condenser operation (MWe)
Parasitic power fixed load (MWe)
Parasitic power generation-dependent load (MWe)
Receiver mass flow rate (kg/s)
Receiver thermal losses (MWt)
Receiver thermal power absorbed (MWt)
Receiver thermal power incident (MWt)
Relative energy balance error
Relative mass flow balance error
Resource Beam normal irradiance (W/m2)
Resource Dry bulb temperature (C)
Resource Hour of Day
Resource Month
Resource Pressure (mbar)
Resource Relative Humidity (%)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Resource Beam normal irradiance (W/m2)
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Field total mass flow delivered (kg/s)
Field total mass flow recirculated (kg/s)
Final 3 operating modes tried
First 3 operating modes tried
Loop timestep-averaged inlet temperature (C)
Loop timestep-averaged outlet temperature (C)
Max thermal power to PC (MWt)
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PC HTF mass flow rate (kg/s)
PC HTF outlet temperature (C)
PC efficiency: gross
PC electrical power output: gross (MWe)
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PC startup thermal energy (MWht)
PC startup thermal power (MWt)
PC water consumption: makeup + cooling (kg/s)
PPA price multiplier
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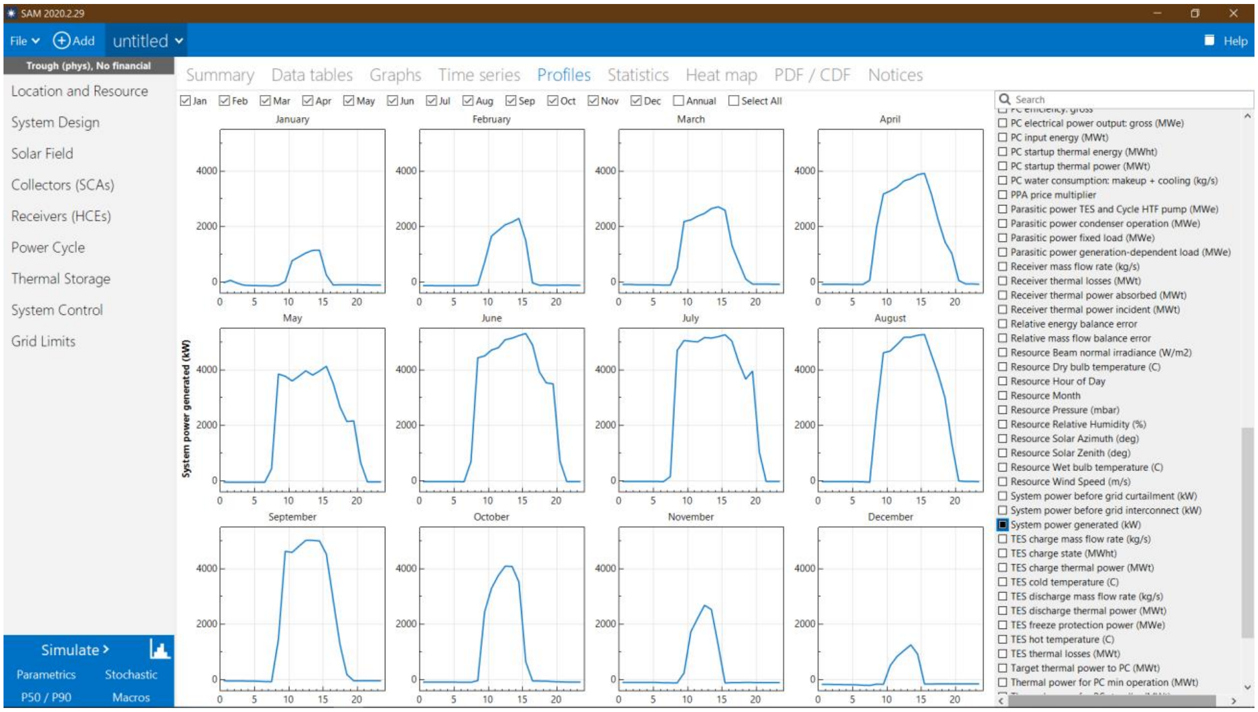
Parasitic power fixed load (MWe)
Parasitic power generation-dependent load (MWe)
Receiver mass flow rate (kg/s)
Receiver thermal losses (MWt)
Receiver thermal power absorbed (MWt)
Receiver thermal power incident (MWt)
Relative energy balance error
Relative mass flow balance error
Resource Beam normal irradiance (W/m2)
Resource Dry bulb temperature (C)
Resource Hour of Day
Resource Month
Resource Pressure (mbar)
Resource Relative Humidity (%)
Resource Solar Azimuth (deg)
Resource Solar Zenith (deg)
Resource Wet bulb temperature (C)
Resource Wind Speed (m/s)



Metric	Value
Annual Net Electrical Energy Production	10,383,083 kWh-e
Annual Freeze Protection	459,196 kWh-e
Annual TES Freeze Protection	375,021 kWh-e
Annual Field Freeze Protection	84,175 kWh-e
Capacity factor	22.0%
Power cycle gross electrical output	12,102,089 kWh-e
First year kWh/kW	1,931 -
Gross-to-net conversion	85.8 %
Annual Water Usage	2,061 m^3

Appendix F (Estimated lifespan of power plant)

Combined-Cycle Plant Life Assessments

ASSESSMENT EXPERTISE

- Plant Condition Assessments
- Corrosion Recommendations
- Facility Improvements
- Performance Testing
- Equipment Enhancements
- Life Extension Programs
- Electrical Degradation Reviews
- Aging DCS and I&C Issues
- Redundancy Evaluations
- Heat/Water Balance Changes
- Environmental Concerns
- O&M Best Practice Reviews
- NERC/GADS© Benchmarking
- Cyber Security Evaluations
- Alternate/Dual Fuel Design Feasibility Studies
- Remaining Useful Life (RUL) Studies
- Inventory Analysis
- Root-Cause Analyses (RCAs)
- Water Chemistry Analysis

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Most combined-cycle power plants—regardless of scheduled gas turbine, steam turbine, and other major equipment O&M practices—display signs of age and fatigue anywhere from 10 to 20 years after their initial commercial operation date, often more quickly in harsh ambient conditions. Depending on the original power plant's design and construction methods, and the suitability of the installed equipment for the plant's actual operating regimes, your combined-cycle power plant may be approaching the end of its original design life much sooner than expected.

25 to 30 years is a typical expected operating life for a combined-cycle power plant. Extensive maintenance work, component replacements, or failures in the plant's first decade of operation can often be tied to issues with its original engineering, procurement, or construction work. Failures after the plant's midlife may be the result of maintenance practices, harsh environmental conditions, or new power generation regimes. Changes to interconnecting conditions can also pose problems to successful operations.

Sargent & Lundy can dispatch a team of independent specialists to identify and analyze your plant's stress points, uncovering potential risks to continued successful operations.

If the end of your plant's design life is approaching, extension programs or other alternatives may offer a potential means to establish an end-of-life timeline better suited to your current needs. Or you can even use our many areas of expertise to tackle specific operating issues.

Call or email us today to find out how we can help.

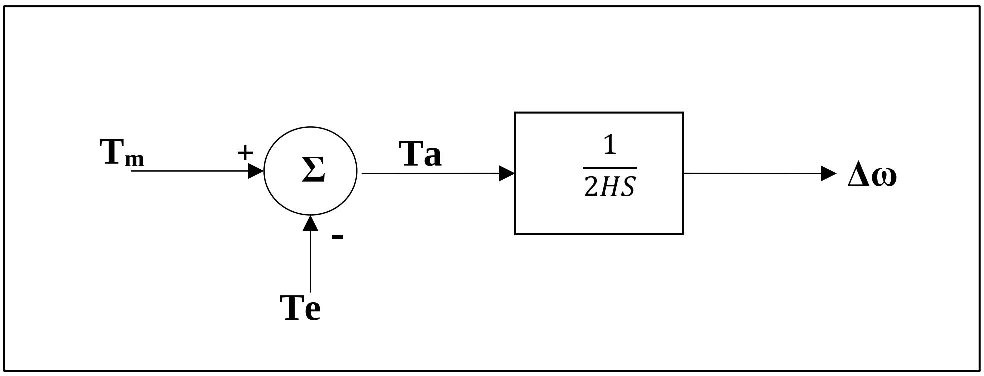
Over 125 years of powerful ideas   Sargent & Lundy LLC   sargentlundy.com

Appendix G (Deriving speed drop control)

when there is a load change , it's reflected instantaneously as a change in the electrical torque output T_e of the generator ,this causes mismatch between the mechanical torque T_m and the electrical torque, This causes a drop in the speed of the rotor , the following transfer function shows the relationship between a rotor speed and electrical torque and mechanical torque :

$$\Delta\omega_r \frac{T_m - T_e}{2HS} = \frac{T_a}{2HS}$$

(2.6)



where:

$\Delta\omega r$: Rotor speed deviation (pu)

Tm :Mechanical torque (pu)

Te : Electrical torque(pu)

H : Inertia constant (MW-Sec/MVA)

S :Laplace operator

Ta : Accelerating torque

The relationship between power and torque is given by :

$P = \omega r . Ta$

And

$P = P0 + \Delta P$

$T = T0 + \Delta T$

$\omega r = \omega 0 + \Delta\omega r$

from equation(2)

$P0 + \Delta P = (T0 + \Delta T) + (\omega 0 + \Delta\omega r)$

$P0 + \Delta P = T0\omega 0 + T0\ \Delta\omega r + \Delta T\ \omega 0 + \Delta T\ \Delta\omega r$

$P0 + \Delta P = P0 + T0\ \Delta\omega r + \Delta T\ \omega 0 + \Delta T\ \Delta\omega r$

$\Delta P = T0\ \Delta\omega r + \Delta T\ \omega 0 + \Delta T\ \Delta\omega r$

With higher- order neglected:

$\Delta P = T0\ \Delta\omega r + \Delta T\ \omega 0$

$\Delta Pm - \Delta Pe = (Tm0 - Te0)\Delta\omega r + (\Delta Tm - \Delta Te)\omega 0$

in steady state $Tm0 = Te0$, $\omega 0$ in pu equal 1

Hence

$\Delta Pm - \Delta Pe = \Delta Tm - \Delta Te$

From equation (1)

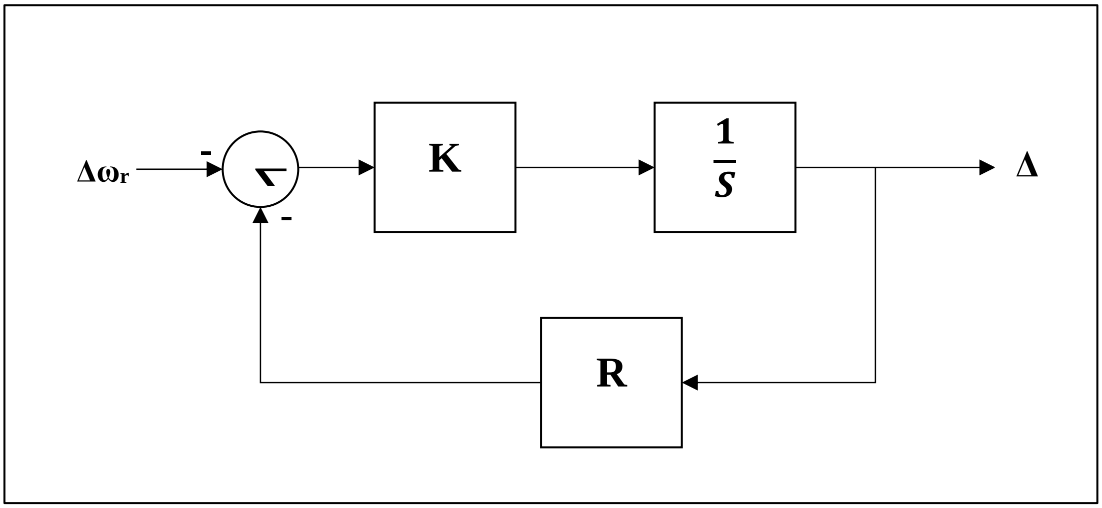
$\Delta\omega r = (\Delta Pm - \Delta Pe)/MS$

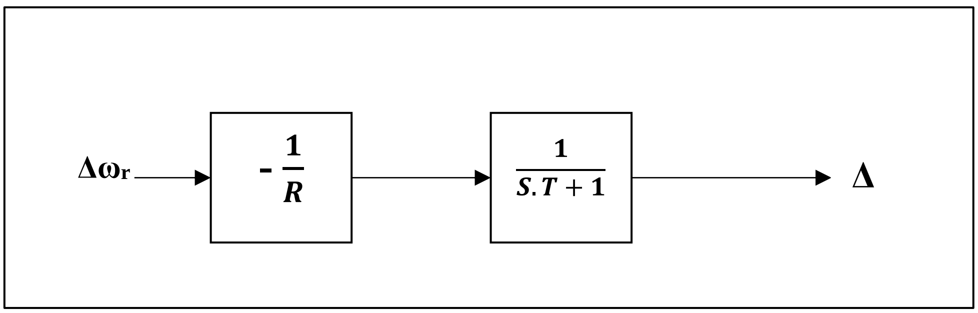
$M = 2H$

$\Delta Pe = \Delta PL + D.\Delta\omega r$

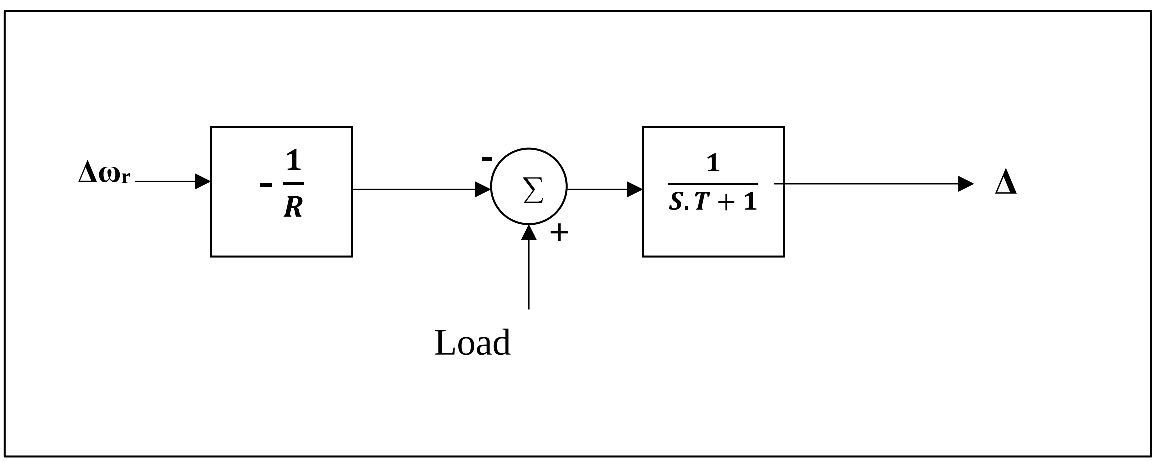
Where

D : load damping constant

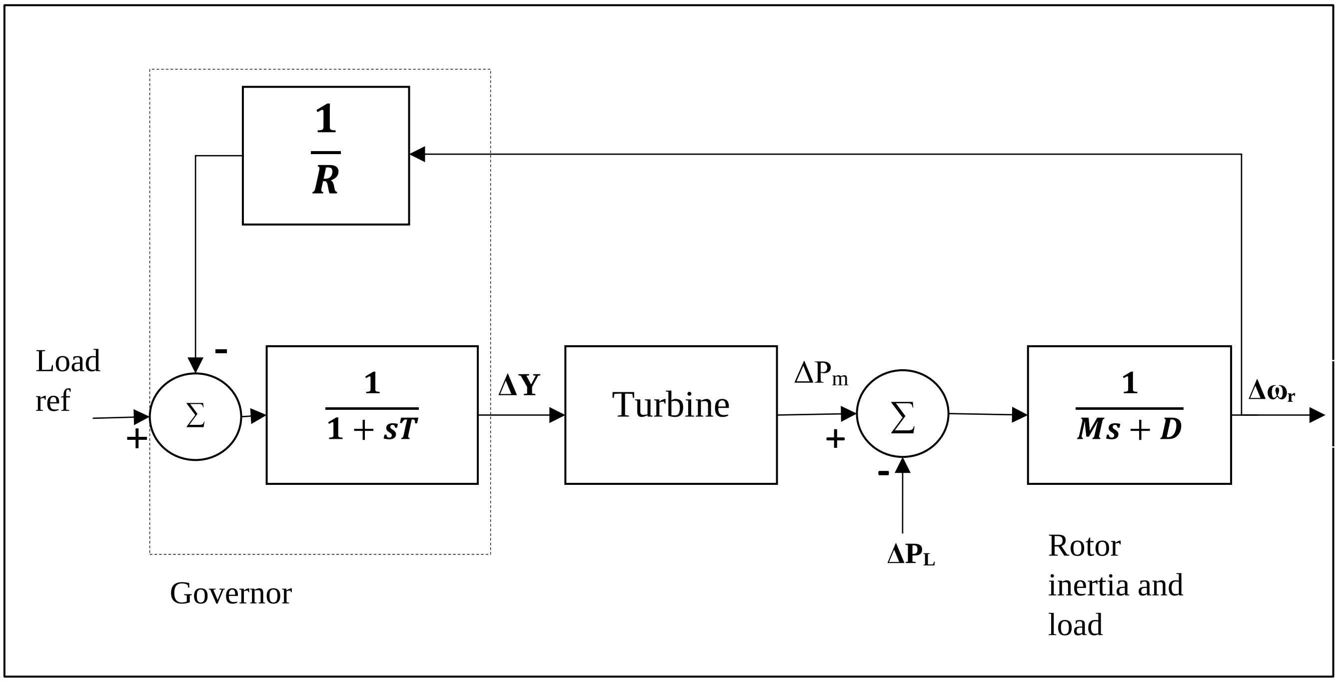




T = 1/KR



In general



1/R
Load ref
1/(1 + sT)
ΔY
Turbine
ΔPm
1/(Ms + D)
Δωr
ΔPL
Governor
Rotor inertia and load