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Stirling Engines for Low-Temperature Solar-Thermal-Electric Power Generation

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Μεταπτυχιακό Πρόγραμμα Σπουδών *Sustainable Energy Systems*

Μεταπτυχιακή Διατριβή

Stirling Engines for Low-Temperature Solar-Thermal-Electric Power Generation

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Η παρούσα μεταπτυχιακή διατριβή υποβλήθηκε προς μερική εκπλήρωση των
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Περίληψη

Η εποχή των ορυκτών καυσίμων έδωσε την ευκαιρία για μεγάλες τεχνολογικές εξελίξεις που «οδήγησαν» στη λεγόμενη εποχή της βιομηχανικής επανάστασης αλλάζοντας τον τρόπο ζωής των ανθρώπων ριζικά. Ένα από τα μειονεκτήματα που οφείλονται σε αυτήν την ταχεία αλλαγή είναι η ρύπανση του περιβάλλοντος σε σημείο απειλής για την ανθρώπινη ύπαρξη. Για να συνεχιστεί η τεχνολογική και κοινωνική ανάπτυξη των ανθρώπων χωρίς την απειλή για την ζωή στον πλανήτη, πρέπει να επιτευχθεί πιο βιώσιμη περιβαλλοντική ανάπτυξη. Η αρχή γίνεται από το πρόβλημα της παραγωγής ενέργειας. Το οποίο θα πρέπει να λυθεί μέσω της ανάπτυξης συστημάτων ανανεώσιμων πηγών ενέργειας. Αντιμετωπίζοντας αυτό το πρόβλημα πρέπει να αντιμετωπίσουμε αυτό το ζήτημα σε παγκόσμια και τοπική κλίμακα. Για να γίνει αυτό, τα συστήματα παραγωγής ανανεώσιμων πηγών ενέργειας αποτελούν τον ακρογωνιαίο λίθο του στόχου της διατήρησης του περιβάλλοντος και του μετριασμού του φαινομένου της κλιματικής αλλαγής.

Στην παρούσα εργασία μελετάται ένα ηλιακό σύστημα παραγωγής ηλεκτρικής ενέργειας που χρησιμοποιεί κινητήρα Stirling για την παραγωγή ηλεκτρικής ενέργειας. Στόχος είναι ο σχεδιασμός του συστήματος και η ανάλυση της απόδοσής του για τη χρήση εμπορικής παραγωγής ηλεκτρικής ενέργειας και την βελτιστοποίηση του σχεδιασμού του για μελλοντική ανάπτυξη. Η μηχανή Stirling είναι το κύριο μέρος του συστήματος και χρησιμοποιείται για την παραγωγή ισχύος χρησιμοποιώντας τη θερμότητα που παρέχεται από το σύστημα ηλιακών συλλεκτών. Τα βασικά στοιχεία ολόκληρου του σχεδιασμού περιλαμβάνουν το ηλιακό θερμικό σύστημα με τον συλλέκτη να παράγει τη θερμότητα που χρησιμοποιείται από τον στερλίν κινητήρα για παραγωγή ενέργειας. Ο σχεδιασμός προσπαθεί να εκμεταλλευτεί τους χαμηλούς δείκτες συγκέντρωσης του συλλέκτη ηλιακής ακτινοβολίας και να παράγει ηλεκτρισμό σε ένα ανταγωνιστικό σύστημα χαμηλού κόστους. Αυτή η αποθήκευση ενέργειας μπορεί να γίνει μέσω δεξαμενής νερού που χρησιμοποιείται συνήθως στα νοικοκυριά σήμερα και είναι φθηνή και ασφαλής.

Το προτεινόμενο σύστημα μετατροπής ενέργειας έχει σχεδιαστεί για να μετατρέπει την ηλιακή ενέργεια σε ηλεκτρική σε τρία κυρίως στάδια: 1. πρώτα από ηλιακή σε θερμική, 2. θερμική σε μηχανική και τέλος 3. από μηχανική σε ηλεκτρική. Το σύστημα έχει σχεδιαστεί για να λειτουργεί με θερμοκρασίες συλλέκτη στην περιοχή από 120 ◦C έως 150 ◦C, κάτι που συμβαδίζει με τη χρήση σταθερών ηλιακών θερμικών συλλεκτών.

Summary

The fossil fuel era gave the opportunity for great technological advances leading to the so-called industrial revolution and changed the way of living forever. One of the disadvantages due to this rapid change is the pollution of the environment to a threading point for human existence. To continue the technological and sociological growth of the world a more sustainable environmental development must be achieved. Power generation problem must be solved through the development over renewable energy systems. Tackling this problem, we need to address this issue in a global and local scale. To do this renewable energy generation systems are the cornerstone of the aim to preserve the environment and mitigate the climate change phenomenon.

In this project a solar thermal electric power generation system utilising a moderate temperature Stirling engine to generate electricity is introduced. The aim is to design the system and analyse its performance for the use of commercial electricity generation and the validation of the design for future development. The Stirling Engine is the main component of the system and is used to generate power utilising the heat that is provided by the solar collector system. The key components of the whole design include the solar thermal System with the collector generating the heat that is used by the sterling engine for power generation. The design is trying to take advantage the low concentration ratios of solar radiation collector and generate electricity at a competitive low-cost system. This storage of energy can be made via water tank commonly used in households today. This method of storage is inexpensive and safe.

The proposed energy conversion system is conceived to convert solar power into electricity in three stages: solar to thermal, thermal to mechanical, and mechanical to electric. The system is conceived to operate with collector temperatures in the range of 120 °C to 150 °C, which is consistent with the use of stationary solar thermal collectors.

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Chapter 1
Introduction

1.1 Introduction

Addressing the climate change problem, large scale developments of renewable energy generation systems are needed. On the other side recent experience showed that in order to balance the energy management problem and maintain a reliable electric grid when intermittent energy systems are used all forms and scales of renewable energy systems should be developed. Microgeneration systems generate power by individuals, small communities or businesses. These systems can use photovoltaics, micro-wind turbines or Combine heat and power using Stirling engines. This kind of systems can help to mitigate the environmental pollution limiting the greenhouse gas emissions and at the same time ensure the security of supply by decreasing energy imports.

Solar Thermal Power Systems combine with RES are still lack development and integration compared to other micro-power generation technologies despite their advantages regarding energy storage and combination of heat and power generation at low cost. Like the proposed one presented in this thesis that utilizes a moderate Stirling engine combined with a solar thermal source for heat conversion into power.

Within renewable energy sources, microgeneration systems combine with cogeneration have a great potential to be a part of the solution regarding all the challenges. Their benefits are various; first of all, they generate electricity as a by-product of heat implying that using the same resources they produce two products, being therefore much more energy efficient and have a potential to bring bill reductions and certain revenues, at the same time leading to a greater security of supply; secondly, using RES, these low-carbon technologies are more eco-friendly and help reduce Greenhouse Gasses (GHG) emissions and contribute towards a sustainable future; lastly, the widespread deployment of microgeneration systems would imply a vast amount of new market participants increasing the competition in the internal energy market. For this reasons, microgeneration systems are highly promoted through the European energy policies and recent binding legislation, having their place accordingly (figure 1.1).

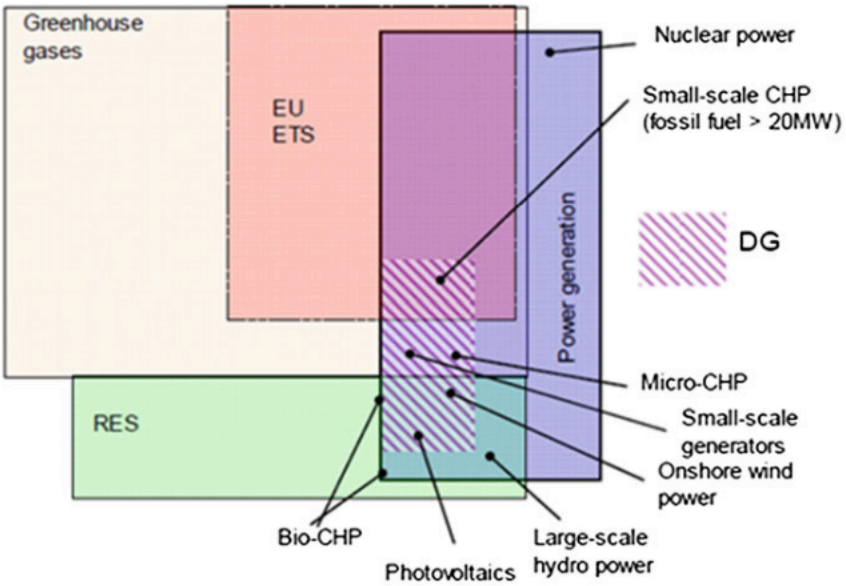


Figure 1.1: Microgeneration in European Union

1.2 European Union Energy Policy

In the last 30 years European Union has undergone major political changes along with major technological advancements. European Union aims to a more reliable and sustainable growth. Considering the energy, EU aims to the modernization of the energy sector through the development of renewable energy systems. This policy targets for better environmental growth and the independence from the increasing demand for energy imports. European Parliament wants more of the energy used across the EU to come from renewable sources, 32% by 2030.

This policy forced the European members to adapt a more decentralized energy production using small scale generation from renewable energy systems and using low carbon technologies. The traditional centralized energy production model is changing rapidly turning the consumers to become also producers at the same time. The EU aims to make it easier for consumers to generate, store and use their own energy without extra taxes or charges. This is a major change transforming the consumers from their current role as only user of useful energy to modern active ones that become themselves also producers. A lot of housing needs to be more energy efficient. All of the countries need to implement it themselves, but more energy efficient houses are going to be the biggest change for consumers under new rules countries will have to prioritize energy saving and production solutions.

All these changes rise the need for the development of various small renewable energy systems. This action force to a major change that is necessary to be done, in terms of energy supply. This is what EU refers as an intelligent energy supply system or Smart Grids. Electricity networks that intelligently monitoring the actions of all users and control and regulate the power demand from an increasing number of micro-generation systems. This entails that Smart Grid will have to regulate bidirectional flows of energy and monitoring information in order satisfying the demand needs in an efficient way.

1.3 Electrical Distribution Power Systems

A traditional power system consists of three main systems: the Generation, the Transmission and the Distribution System. It is called “traditional”, because the generation of electricity is centralized, meaning that only a few large power plants are involved. The generation system comprises the power plants that supply power to the system, also called generation stations or generation units (Figure 1.2).

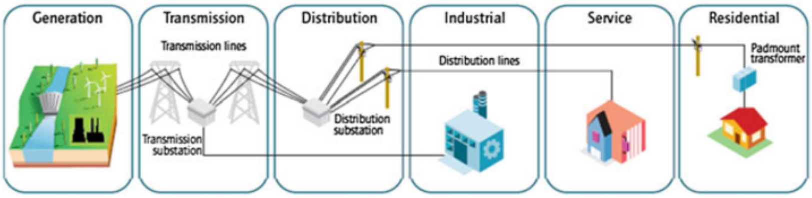


Figure 1.2: Traditional energy grid.

Some examples of traditional power plants are thermal, hydro and nuclear power plants. The transmission system is made up of transmission lines that transport the power from the generation system to the distribution system. Typical voltage levels for the transmission system range from 10 KV to 1100 KV. The distribution system is the network that feeds power to the load.

The load represents the power consumption of the system. It contains households, hospitals, commercial buildings and small to medium sized industries. Typical voltage levels for the distribution system go from 120 V up to 10 kV. The voltage levels of the transmission system are higher than those of the distribution system. This voltage level change from one system to the other is done mainly by means of transformers. A transformer uses electromagnetic induction to transfer electrical energy between two or more circuits. A typical transformer consists of two windings. Depending on the ratio between the primary and secondary winding, the voltage will be increased or decreased. Transformers are generally placed at substations. A substation contains many elements that are important for keeping the system operating between the admissible boundaries. Some of these elements are transformers, capacitor banks, switches, circuit breakers, monitoring equipment, among others. In short, an electric power system is a network used to supply, transport and distribute electric power to the loads.

There is a unidirectional power flow, which means that generation occurs only at the generation side of the power system, and consumption only at the distribution side. This is one important characteristic of traditional power systems, but there are some other characteristics that are worth mentioning, for example, Most power plants are controllable and large voltage is increased or decreased by means of transformers. Large power plants operate on alternating current.

Smart power systems often refer as “smart grid” are the evolution of the traditional ones under the continuous policy of the EU. At the end they will have generation units located at the distribution system. Smart power systems are not centralized as in the case of traditional power systems but distributed. Some examples are photovoltaic panels, small wind turbines and fuel cells. The power flow not only goes from the generation system towards the distribution system, but there are power flows going in the opposite direction as well. This occurs as a result of distributed generation, particularly in the case when more power is generated than consumed (figure 1.3)

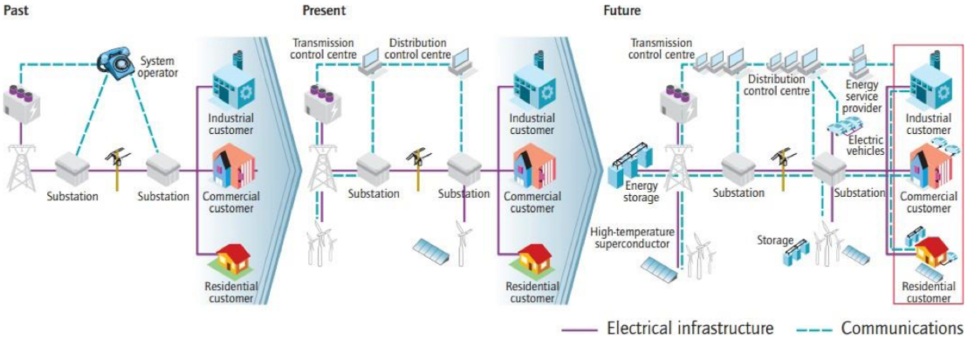


Figure 1.3: Traditional energy grid.

Another big alteration is the presence of large consumers, such as electric vehicles, and also the presence of intelligent nodes, or in other words, nodes in which smart grid concepts will be enabled. The European Technology Platform of Smart Grids terms “A smart grid is an electricity network that can intelligently integrate the actions of all users connected to it, in order to efficiently deliver sustainable, economic and secure electricity supplies”. The users can be generators, consumers and those that assume both roles.

The word intelligently means that the power system employs: Monitoring, Control, Communication and Self-healing technologies to enable a power balance between generation and consumption. A high percentage of power plants will be driven by uncontrollable sources, as opposed to the controlled centralized power plants, mostly driven on fossil fuels. Secondly, a considerable percentage of generation units will generate direct current, as opposed to the large power plants, which generate alternating current. Additionally, a considerable number of generation units will be based on renewable sources and will be of small-scale, located at the distribution system. There will a bidirectional power flow, for example when more power is generated at the distribution system than consumed. Storage will play a major role due to the uncontrollable sources. Finally, smart grid concepts will be introduced to balance generation and consumption.

1.4 Microgeneration Systems

Electricity needs are constantly increasing figure 1.4. Also centralize power loads are very expensive to reach energy supply. The solution to these problems comes from microgeneration systems, which are miniatures of the central production.

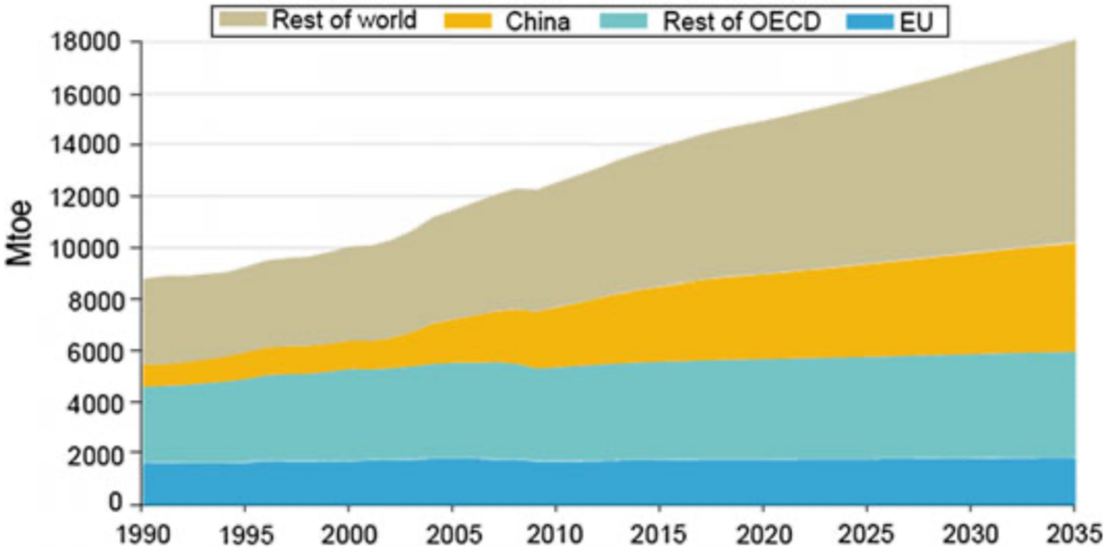


Figure 1.4: Evolution and Prediction of the world's energy demand.

This kind of systems contribute significantly to decentralized production, providing the possibility of uninterrupted supply of electricity mostly to isolated consumers. Microgeneration, like conventional electrical networks, consist of units that can be divided into the following categories:

. Controlled production units.
. Passive production units.
. Storage units.
. Consumption units.

The main role in a small network is played by the power inverses, since production units with continuous voltage output are used. In addition, if the system includes production units with a constantly changing voltage, an intermediate stage of conversion to a continuous voltage is required before the final reversal. In this case, the inverter again plays the main role, converting the continuous voltage to alternating current, resulting in charging the loads. If conventional production units, such as diesel generators, are used on the microphone, then inverters are not necessary because we have direct output of alternating voltage.

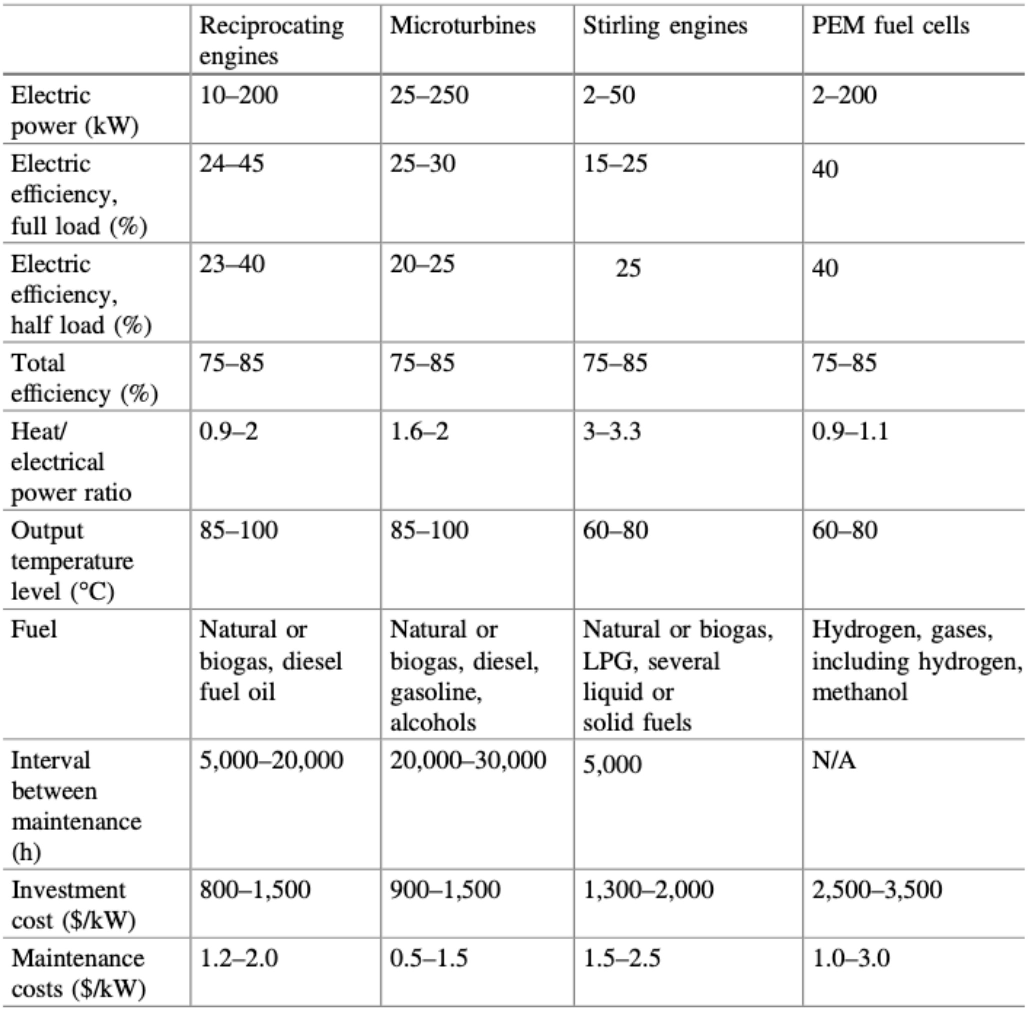
Achieving the implementation and formation of a Smart Grid microgeneration systems are essential. The implementation of such systems by residential consumers and small medium industrial companies with help to decentralized energy generation. In this way consumers could generate their own power satisfying their needs and at the same time providing power to the grid when they don't need it. This kind of small systems combined with renewable energy resources could slowly replace a large portion of the fossil fuels use. Microgeneration systems can be divided in three main categories.

- Generating electricity based on solar PV, microwind turbines and micro hydro.
- Heat generation via heat pumps, biomass and solar thermal systems.
- Combined heat and power or cogeneration systems based on internal combustion engines, Stirling engines, and fuel cells.

The diversification of generation technologies leads also to an easy and swift fuel substation as traditional energy resources are decreasing significantly and new energy sources need further development, indirectly helping energy security. In this context, microgeneration systems can play their part, if spread and used wide enough, as there are various microgeneration technologies using different energy sources that can help enhance the energy mix. Moreover, they are a sustainable alternative to fuel substitution.

1.5 Cogeneration Technologies in mCHP Systems.

Today’s energy supply systems are all based on central generation facilities operate and producing on high voltage units. Cogeneration is the combine production of two forms of energy-electric or mechanical power plus useful thermal energy in one technological process. In recent years the cogeneration technologies gain ground and studied by engineers for implementing them in residential buildings, small communities and small commercial applications. This kind of application could be implemented and provide electricity and heat to a residence and provide the local grid with extra electricity when is available. Table 1.1 shows best small-scale CHP systems for house units and their characteristics.



	Reciprocating engines	Microturbines	Stirling engines	PEM fuel cells
Electric power (kW)	10–200	25–250	2–50	2–200
Electric efficiency, full load (%)	24–45	25–30	15–25	40
Electric efficiency, half load (%)	23–40	20–25	25	40
Total efficiency (%)	75–85	75–85	75–85	75–85
Heat/ electrical power ratio	0.9–2	1.6–2	3–3.3	0.9–1.1
Output temperature level (°C)	85–100	85–100	60–80	60–80
Fuel	Natural or biogas, diesel fuel oil	Natural or biogas, diesel, gasoline, alcohols	Natural or biogas, LPG, several liquid or solid fuels	Hydrogen, gases, including hydrogen, methanol
Interval between maintenance (h)	5,000–20,000	20,000–30,000	5,000	N/A
Investment cost ($/kW)	800–1,500	900–1,500	1,300–2,000	2,500–3,500
Maintenance costs ($/kW)	1.2–2.0	0.5–1.5	1.5–2.5	1.0–3.0

Table 1.1: Technical features of small-scale CHP systems.

Reciprocating engines are the most efficient in comparison to Microturbines and Stirling engines. Fuel cells is a different promising technology but need further proof studies. One important property of those systems is that they usually have lower thermal efficiencies than condensing boilers and that is due to the use of heat to produce electricity. On the other hand, the net carbon benefit of the electricity generated by mCHP systems is higher than the condensing boilers.

CHP technologies refer to the energy conversion, recuperation, and management in view of obtaining heat and power from burning a fuel. The term CHP (Cooling, Heating, and Power) describes all electrical power generation systems that utilize recoverable waste heat for space heating, cooling, and domestic hot water purposes.

Micro-CHP encompasses all systems in the range of 15–35 kW of electrical production or less. These systems range from single family homes to small apartment complexes to small office buildings. In a typical micro-CHP system, electricity is generated on-site from the combustion of a fuel source in an electrical generation set (prime mover and generator). This combustion produces recoverable heat in the form of heated engine coolant and high temperature exhaust. The use of the recoverable thermal energy for space heating and cooling purposes is the driving factor behind the increased overall energy usage from conventional power generation systems.

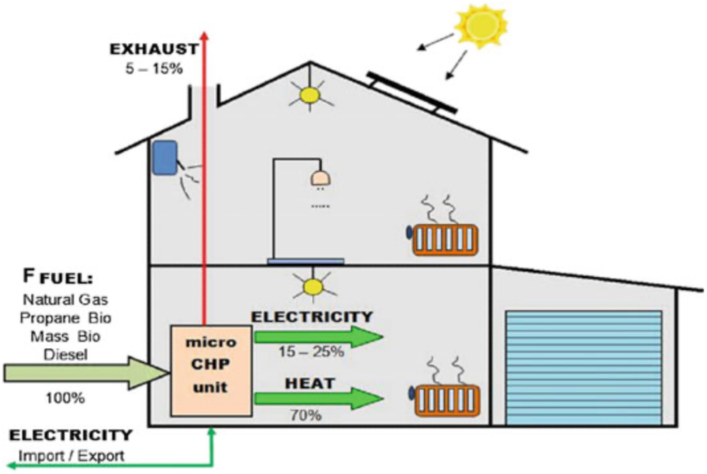


Figure 1.5: mCHP technologies.

The Stirling engine technology is already been used as cogeneration unit. Stirling engine is the most promising technology on the short medium term. It can be installed in urban environment every type of fuel can be utilized (methane, hydro- carbons, hydrogen, biomass, or heat from renewable sources). The Stirling technology is mainly mechanical, is well established, does not require special infrastructure. A Stirling engine is an internal combustion engine which uses a difference in temperature to create movement in the shaft. The functioning of a Stirling engine is based on the behavior of a fixed quantity of air or gas (like helium or hydrogen) inside the engine cylinders. Main characteristics of the CHP systems with Stirling engine is given in Table 4.1 chapter 4 where the system is analyzed. Stirling engines have an electric efficiency of 10–25 %. If, however, the heat lost is recuperated in CHP type systems, the overall efficiency of these systems may increase significantly. Typical normal temperatures for operating vary between 650 and 800 °C. The heat may be recuperated by using the heat exchanger in the cold source of the engine, as well as by using the heat exchanger through which the burnt gases are exhausted into the atmosphere.

The Stirling engine (SE) micro-CHP is the most appropriate type model that can be installed into building because are smaller and quieter than the internal combustion models. Stirling engines produce power not by explosive internal combustion, but by transferring heat from an external source, which produces heat. This source may be an external combustion (when the SE can be fueled with a wide variety of fuels, including all fossil fuels, e.g., natural gas), or as in this thesis solar energy. In the context of moving toward new low carbon solutions such microgeneration systems are essential.

1.6 Cyprus Energy Production and RES.

Cyprus as a member EU state must fulfil the environmental targets. The use of renewable energy sources is considered a top priority not only due to EU regulations but as it is an island and energy-isolated state with high, therefore, energy supply costs. This means that in the coming years investments will have to be made to put into operation more photovoltaic and wind farms, but most importantly microgeneration could help a lot and contribute to achieving higher penetration of RES in its energy balance.

This kind of investment is expected to boost the overall economy of Cyprus, especially with the creation of new jobs and the liberalization of the energy market. At the same time, the national strategy promotes complementary actions, such as energy upgrading of buildings and means of transport, as well as modernization of the network and infrastructure of electricity and gas, which are expected to help reduce energy consumption and improve quality of life. By turning to renewable energy sources, Cyprus will be able to take advantage of its natural advantage as a country with high rates of sunshine. In a small country with a population of about 700,000, the exploitation of renewable energy sources is a challenge, as it could ensure its full energy self-sufficiency in the future.

Chapter 2
Motivation

2.1 Motivation

Every year, the world uses billions of oil barrels. This massive scale of fossil fuel pollutes the Earth and it won't last forever. Scientists estimate that we've consumed about 45% of the world's oil. According to present estimates, at this rate, we'll run out of oil and gas in approximate 60 years, and in about a century coal also will be depleted . On the flip side, we have abundant sun, water, and wind. These are renewable energy sources, meaning that we won't use them up over time.

What if we could exchange our fossil fuel dependence for an existence based solely on renewables? We've pondered that question for decades, and yet, renewable energy still only provides about 12% of our needs. That's because reaching full percentage requires renewable energy that's inexpensive and accessible. This represents a huge challenge, even if we ignore politics involved and focus on the science and engineering. We can better understand the problem by understanding how we use energy. Global energy use is a diverse and complex system, and the different elements require their own solutions. One important portion of the global energy production is electricity. Electricity powers cities, machines like elevators, computers, and all manner of things in homes, businesses, and industry. The great news is that our technology is already advanced enough to capture all that energy from renewables, and there's an ample supply.

But there are hurdles in the way, like efficiency and energy transportation. To maximize efficiency, solar plants must be located in areas with lots of sunshine year round, like deserts. But those are far away from densely populated regions where energy demand is high. There are other forms of renewable energy we could draw from,such as hydroelectric, geothermal, and biomasses, but they also have limits based on availability and location. In principle, a connected electrical energy network referred as Smart Grid with power lines crisscrossing the globe would enable us to transport power from where it's generated to where it's needed. But building a system on this scale faces an astronomical price tag.

2.2 Solar Thermal Power Generation

As renewable energy sources getting a bigger portion of the energy needs their variability is becoming a bigger challenge. For the energy grid there is always the task to fulfill the demand at any given time. This can be done by the availability of energy sources and the storage of energy. With wind and photovoltaic industry at their mature level regarding prices and implementation, it is the right time to motivate and expand solar thermal technologies. This kind of system can potentially combine storage invariable distribution of energy. The fact that this technology is it combination of generation and built-in storage is ideal for integration with minimal effects on grid stability.

A Stirling engine thermal system offers many advantages. it's simple design for generation is reliable and consistent it does not require additional balancing for storage. The process is reversible allowing it to be used as pure energy storage by using it as a heat pump and based on the needs, utilize the stored energy for power generation system. Of course, such a system is difficult to be integrated in the existing energy industry but nevertheless is a valuable technology to research and optimize, preparing it along with the electricity market changes that inevitably will happen.

2.3 System Description.

The system that is been examined is suitable for residential scale demand. The main component is the Stirling engine, responsible for the power generation and excess heat utilization.

Other essential components are the flat solar collector subsystem and hot thermal storage tank (figure 2.1). As shown in the figure a second “waste” heat water tank can be installed, it can be used for the local heating needs of the unit, improving the total efficiency of the system.

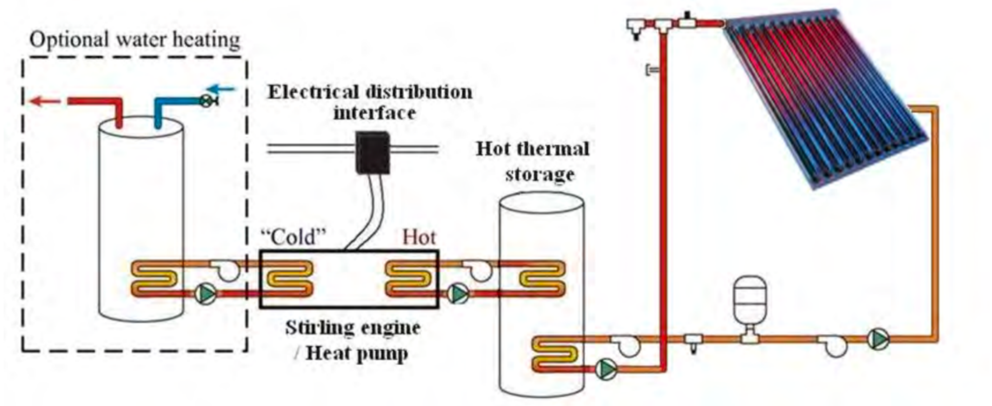


Figure 2.1: Solar thermal Stirling Engine System.

Evacuated tubes are calculated since they can provide highest temperature load and are the most efficient collectors with a price range logical for residential use. Connected to the collectors is the typical hot water tank providing the thermal load to the engine. The Stirling engine could also be connected to a combustion system to balance any needs when the solar system cannot provide. The whole design includes pipes, valves, heat exchangers and wiring. The most expensive part would be the Stirling engine, but it is estimate that the whole cost would be in a reasonable cost for an individual consumer to invest.

The proposed power conversion system is designed to convert solar energy into electricity in three stages: solar to thermal, thermal to mechanical and mechanical to electrical. The Stirling technology is the one with which we will have the conversion of solar into mechanical. A key advantage of this machines cycle is the possibility of using air as a working gas and thus avoids issues with possible long-term retention of a working gas such as He and related maintenance requirements.

The efficiency of a solar-thermal collector, η_{STC}, as measured experimentally, is given by,

$$\eta_{STC} = \eta_0 - \frac{U_1}{G}(T_m - T_{amb}) - \frac{U_2}{G}(T_m - T_{amb})^2$$

where η_0 is the maximum collector efficiency, U_1 and U_2 are the thermal loss coefficients, G is the power density of incident sunlight, T_m is the mean temperature of the collector in the Kelvin scale (K), and T_{amb} is the ambient temperature in K. Assuming there is no drop in temperature from the collector to engine, the efficiency of the heat engine, η_{eng}, is given by,

$$\eta_{eng} = \epsilon_{Carnot}\left(1 - \frac{T_{cold}}{T_m}\right)$$

where ε_{Carnot} is the fraction of the theoretical Carnot efficiency that the engine achieves and T_{cold} is the "cold side" working temperature of the Stirling engine in K. The system conversion efficiency, η_{sys}, is then given by,

$$\eta_{sys} = \eta_{STC} \cdot \eta_{eng}$$

For a representative system, the efficiencies of the collector, engine, and system are plotted as a function of temperature in Figure 2.2. To minimize cost per watt of output electricity, it is desirable to operate a system of given cost at the temperature corresponding to peak system efficiency. This temperature is a function of collector properties as well as ambient temperature and intensity of sunlight. The heat engine can be designed to regulate its loading to maintain optimum collector temperature and system efficiency. Figure 2.2 shows that the proposed system efficiency is rather flat over a range of temperatures near the extremum.

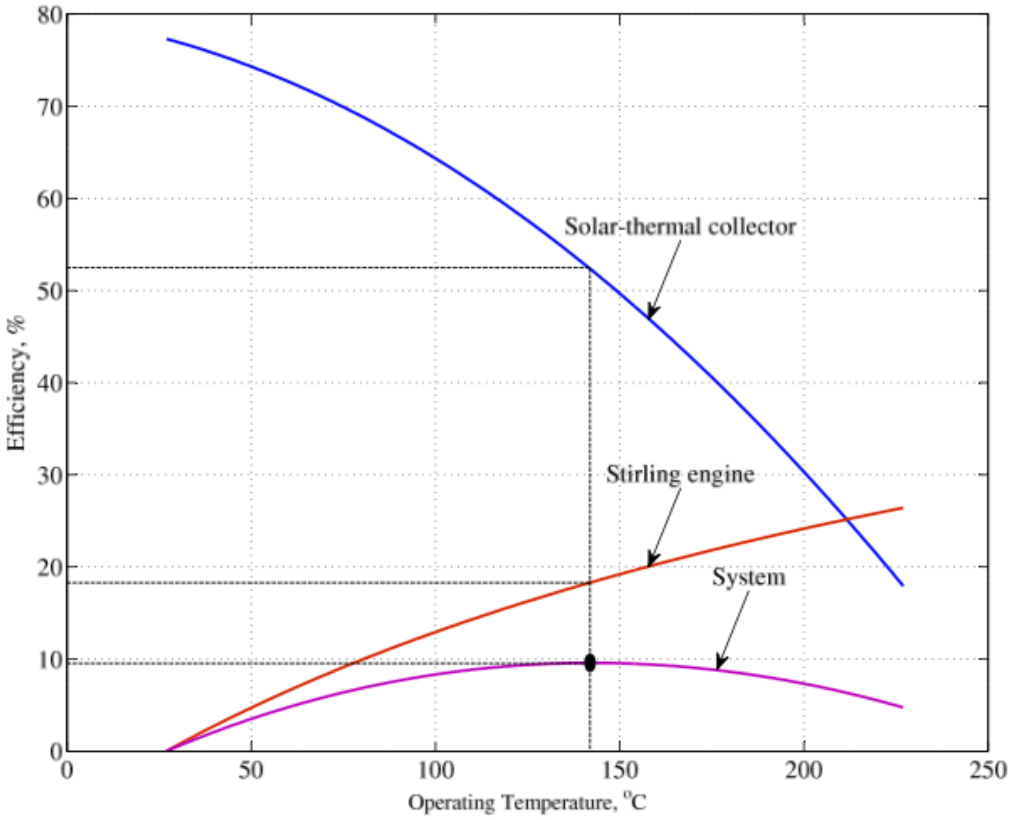


Figure 2.2: Efficiency as a function of temperature for a representative system.

An operating temperature of 140 °C permits a maximum thermodynamic (Carnot) efficiency of 32%, assuming the sink temperature is 25 °C. We might reasonably expect the Stirling engine and generator to achieve a thermal-electric efficiency of about 21%, roughly 65% of the Carnot efficiency, while the collector operates at a thermal efficiency of about 52%. Thus, the estimated overall efficiency of the system would be about 10%.

The idea of using a Stirling engine in a system that includes a solar water heater, that is, in our home, is very convenient for countries such as Cyprus and generally countries with intense solar radiation. This means that we already have the solar water heater installed in our home and we can use it for hot water, it saves us from a big expense in case we want extra use of our solar and more specifically for energy production in our case. Hot water that we will not be used during the day. For most consumers, installing such a system in the context of green growth and the use of alternative energy will be only beneficial and long-term service as installation costs will pay off in the first years of operation.

Chapter 3
Thermal Systems

3.1 Solar Thermal Energy.

The sun is a typical star, with a mass of $2x10^{30}$ kg, a radius of 700,000 km, an age of $5x10^{9}$ years. Estimated to have another 5 billion years of life. Its surface temperature is approximate ~ 5,800 K, while its internal temperature is about 15,000,000 K. The high temperature of the sun is due to the self-sustaining nuclear reactions that take place inside its core where the hydrogen fusion takes place. The sun radiates energy to the earth in the form of electromagnetic radiation. When this form of energy reach earth's atmosphere one third of it, is reflected back into space. The rest of this solar radiation is modified by absorption and scattering mechanisms, the incident energy is absorbed by matter and converted into heat. This is how energy from Sun reach earth. Solar thermal Systems are engineered systems that capture the sun's radiation store it and convert it into other form of energy or produce work.

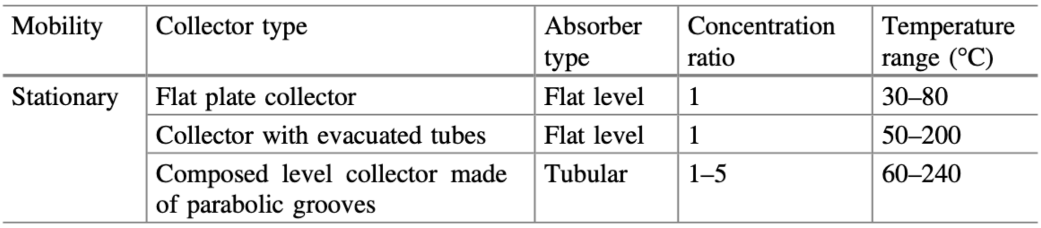
The idea of utilizing solar radiation by using solar panels to trap the energy of the sun is documented back in 212 BC when the Greek physicist Archimedes used them to burn Roman ships. During the 19th century, efforts to convert solar energy into other forms relied on the production of low-pressure steam for handling locomotives. However, when oil and gas became available to serve as fuel for handling engines, interest in high-temperature solar panels disappeared for obvious reasons. In the late 1960s and early 1970s, when it became clear that fossil fuel sources were limited and their non-distribution was leading to serious dependencies, systematic research began in a number of industrialized countries to developed alternative energy systems to produce power.

Thus, over the last 50 years many alternatives have been designed and manufactured using aggregate collectors as a means of heating the working medium (liquid) responsible for power generation. The two primary solar technologies used are the central collectors and the collectors who use multiple points to collect solar radiation. In the first category belongs the solar tower and in the second the parabolic plates and parabolic troughs.

Solar systems are a variety of different designs that utilise solar radiation energy by converting it to heat. The physical principles that are dominant to these systems are examined in order to be able to optimise each component of a solar system and improve the overall efficiency. The most important phenomenon is the conversion of short-wave lengths from the solar spectrum into heat. In the case of solar thermal systems short-wave lengths refer to visible light and ultraviolet wavelengths. To begin with, a solar energy system always uses some kind of collection device to collect concentrated and/or converted the radiation that reach its surface.

3.2 Collectors

The part of the solar system that converts solar radiation into heat. They absorb the incident radiation and transfer the heat to a medium, most often water, oil or air. The energy in the form of heat is transferred from the collector and it can be used in various ways like heating residential buildings, generate power, other industrial applications, etc. Often the heat is stored in an accumulation tank for later use. They can be classified by their design on how they are collecting solar radiation. There are two main types, the flat and the concentrated design. Another feature is the range of temperature operation. An important design property of collectors is the ratio of the incident surface to the absorbers surface area. This property is called concentration ratio. Table 3.1 shows the main types of solar collectors that are used on solar thermal systems.



Mobility	Collector type	Absorber type	Concentration ratio	Temperature range (°C)
Stationary	Flat plate collector	Flat level	1	30–80
	Collector with evacuated tubes	Flat level	1	50–200
	Composed level collector made of parabolic grooves	Tubular	1–5	60–240

Table 3.1: Solar collectors design types.

Concentrated collectors are basically a reflective (mirror) concave surface that directs the incident radiation on to the absorber surface. Usually they are installed with a censoring system to track and follow the sun for better efficiency of the system. Flat collectors encapsulate the absorber into a unibody system. They preferably used in warm and sunny climates due to their low efficiency if the weather conditions are not good. They need almost no maintenance but condensation inside the collector’s box and on the absorber’s surface can significant deteriorate the efficiency. Figure 3.1 shows a typical schematic of a flat collector consisting of the absorber which is the part that absorbs the incident radiation and converts it into heat, the heat carrier tube system from the collector, the insulation materials and last the cover along with the frame structure that encapsulating all former components.

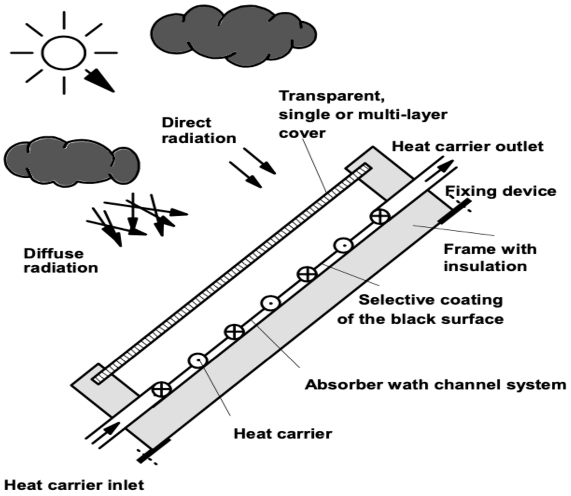


Figure 3.1: Main components of a solar radiation collector.

The cover usually is glass or Teflon not the transparent material needs to allow the short wave radiation and block the long-wave thermal reflection of the absorber. Also on the inside of the cover we need to block the convective heat losses due to air currents inside the box. Usually the cover it's made out of glass because it can resist environmental factors that deteriorate the optical properties of the cover comparing to other materials. Improved transmittance can be achieved by using antireflective coated clear glass. The whole structure usually is called the box is made by aluminium galvanise steel or wood. Aluminium is the best choice due to price comparing to other materials excellent corrosion resistance and reduced weight of the finished structure. There are many designs for the box dependent where the structure is positioned. On one side of the box there is the inlet pipe that carries fluid that passes through the absorber and the heat transfer takes place. The most common use of the collectors are for heating water. Most often the collectors are installed on the roof also they can be integrated at the structure of the roof. Because of their fixed design collectors are positioned in a slope for maximizing the solar radiation collection through daylight. Typically, the position angle is the same as the latitude when the latitude is small, and increases by 10° when the latitude is above 40 °.

One of the designs that eliminate condensation issues and have better efficiency are the collectors that use vacuum tubes system that has the absorber inside and the circulation medium in a coaxial tube system. The vacuum tubes minimise the conduction and convection losses and have no condensation problems. The vacuum tubes are often made from borosilicate transparent glass and the absorber is made of selective cover copper. This kind of collectors are construct out of an array of vacuum tubes connected to manifold for the working fluid to circulate. Often this heat transfer fluid is water or a mixture of water/glycol. They work at higher temperatures and have higher efficiencies compare to the flat plate absorber design. Figure 3.2 shows a vacuum tube collector.

Figure 3.2: Vacuum tubes solar collector.

In general principle, Inside the vacuum tubes there are copper tubes that contain small of amount of fluid in partial vacuum. Through the temperature elevation the fluid evaporates and rises where the main fluid pipe is. Through heat transfer the vapor condensed and goes back again liquid in the vacuum tube. This repeating phase change is basically the exchange of latent heat. Another design is with o coaxial U-shaped tube where the heat transfer fluid pass through inside the pipe and back to the storage tank (figure 3.4).

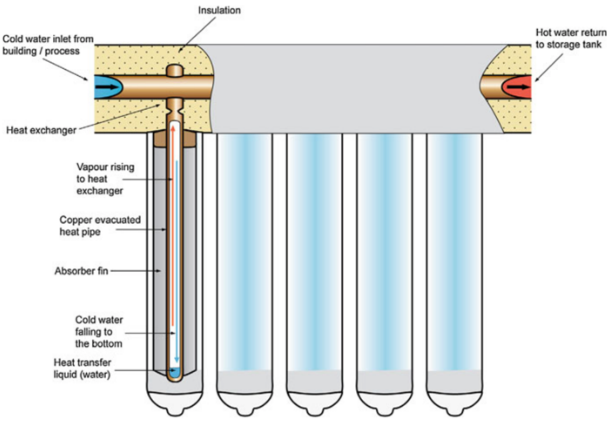


Figure 3.3: Vacuum tube heat transfer process.

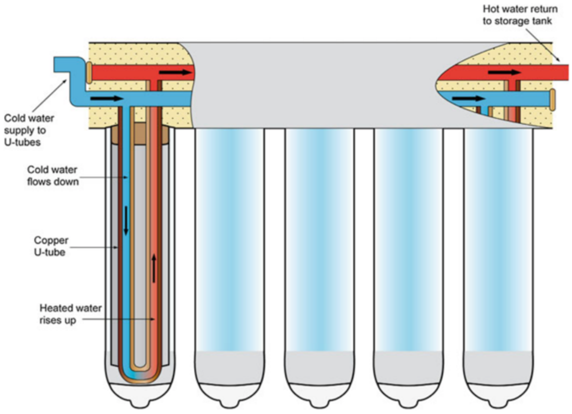


Figure 3.4: Vacuum tubes with the U shape design.

New design makes use of special reflector surfaces to increase concertation at the absorber during the daytime. This kind of design is utilized in a compound parabolic concentrator collector, the result is the incident radiation is reflected at the absorber elevating the temperature of the work fluid more (figure 3.5). This design has improved thermodynamic efficiency.

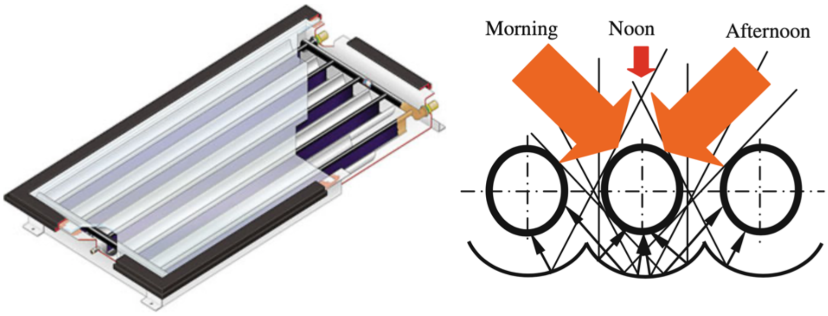


Figure 3.5: Compound parabolic concentrator.

In recent years there are hybrid thermophotovoltaic collectors that convert solar energy into electricity and heat (figure 3.6). The photovoltaic cells are placed on the top of the absorber. In this way the absorber is utilizing the extra heat from the cells and also cools the PV cells down for better efficiency. Usually this kind of collectors are best when the surface area for placing the solar thermal systems is limited.

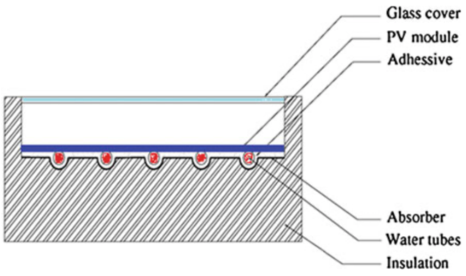


Figure 3.6: Compound parabolic concentrator.

3.1.2 Performance of Solar Collectors.

The solar radiation pass through the cover and hits the absorbers surface. The absorber converts the radiation into heat in the carrier fluid gains temperature through thermal conduction. Its typical design use heat exchangers to transfer the energy for its utilization. Through this process there are various losses of energy that play a critical role to the overall efficiency of the system. The most common domestic use of the small solar thermal system Is for heating water. Figure 3.7 shows the energy path through a flat plate collector to the storage tank and the final use of the energy. In each step they're always energy losses mostly related with insulation efficiency.

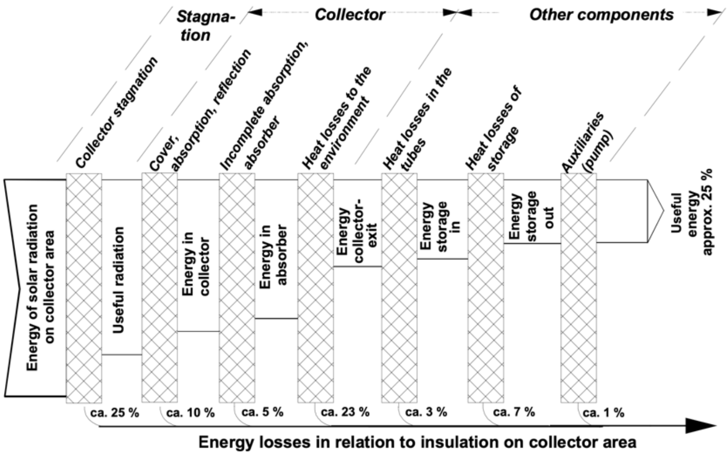


Figure 3.7: Energy losses for every step in a solar thermal system.

Given the typical design of a stationary collector figure 3.8 shows the energy balance within the boundaries of the system that includes the cover, the absorber, the frame and the insulation materials.

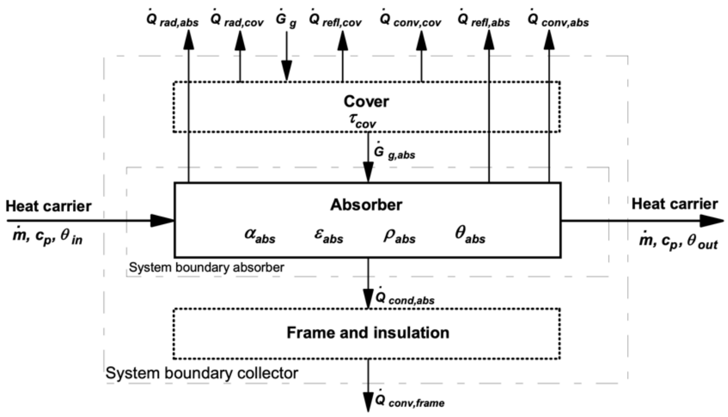


Figure 3.8: Energy balance within the collector boundaries.

The sun emits photons, reaching earth's atmosphere as short wave radiation. A solar system collects this energy by using some kind of absorbers. When the radiation incidences on the absorbers, a portion of the energy is absorbed. Absorption ***α,*** characterizes the material's ability to absorb an amount of radiation. Some of it is reflected back by the material and is measured as the reflection ***ρ***. Every material also emits back radiation given by the emission ***ε,*** of the material. Transmission ***τ,*** of the material describe the ability to transmit radiation through the material. Those properties are given as coefficients to the entire radiation incident and are important to the selection of the materials and the design of the absorbers component of a solar thermal system.

As mentioned, the absorbers transform radiation into heat. Given this, the absorber is designed to absorb as much radiation reaches its surface and reflects none. An ideal case would be an absorbent with zero reflection ($\rho = 0$) on the short-wavelength spectrum and total absorption ($\alpha = 1$). Since this is a theoretical case, in reality materials approaching the ideal scenario are chosen. Metals like Cu, Fe, Al are used. Some plastic materials also like Polypropylene and Polyethylene used. Furthermore, thin films have been deposited on absorbers surfaces called selective surfaces, to further improve the absorption near to the ideal limit. The absorber usually is manufactured through techniques like galvanization, anodization process and selective paint coating.

The energy balance at the absorber as shown can be expressed with equation 3.1 as an energy general balance of the energy conversion that takes place on the absorber's surface.

$$\dot{G}_{G,abs} = \dot{Q}_{conv,abs} + \dot{Q}_{rad,abs} + \dot{Q}_{refl,abs} + \dot{Q}_{cond,abs} + \dot{Q}_{useful} \qquad (3.1)$$

Where

$G_{G,abs}$ is the entire global radiation incident on the absorber surface. Q_{useful} is the utilisable thermal flow. In addition there are four different loss flows:

- convection losses of the absorber to the ambient air $Q_{conv,abs}$.
- long-wave radiation losses of the absorber $Q_{rad,abs}$.
- reflection losses of the absorber $Q_{refl,abs}$.
- thermal conductivity losses $Q_{cond,abs}$.

The energy that the system produces is the heat gain by the fluid carrier. The quantity Q_{useful} is a function of this specific heat capacity of the fluid the mass flow and the temperature difference between the inlet an outlet of the collector.

$$\dot{Q}_{useful} = c_p \dot{m}(\theta_{out} - \theta_{in}). \qquad (3.2)$$

The radiation that reach the absorber is estimate through the product of the incident global radiation on the cover with the corresponding transmission coefficient τ_{cov} .

$$\dot{G}_{G,abs} = \tau_{cov}\dot{G}_g \qquad (3.3)$$

Additionally, there are reflections due to emission ε, that are calculated by the Stefan-Boltzmann radiation law. This kind of losses are dependent on the material and the temperature difference between the absorber surface temperature and the environments ambient temperature. The convective heat transfer losses are also depended on the differential temperature between the absorber and the ambient temperature. Any conduction losses are often neglected due to their small value compared to other losses. The efficiency of this process is the ratio between Q_{useful} and the global radiation G_{global} on the collector.

$$\eta = \frac{\dot{Q}_{useful}}{\dot{G}_g} \qquad (3.4)$$

The thermal efficiency of the collector is variable to the conditions at any time. It can be calculated based on the equation 2.5 and takes into account the ambient temperature Ta, the inlet fluid temperature T_i, and the radiation H. The optical efficiency η_o is the the efficiency of the collector at the point where the average collector temperature is equal to the ambient temperature. k_1 and k_2 are the heat loss coefficients.

$$\eta = \eta_o - k_1\frac{T_i - T_a}{H} - k_2\frac{(T_i - T_a)^2}{H} \qquad (3.5)$$

According to EU regulations the collector ‘s efficiency on the aperture area must be at least, to the following conditions: optical efficiency at least 0.75, k1 heat loss not more than 1.18 W/m2°C, k2 heat loss not more than 0.010 W/m^2 $°C^2$. Optical efficiency is directly related with the cover’s. absorbance, emittance and transmittance, the materials that are used for the absorber and last the incident angle. Figure 3.9 shows the characteristic efficiency curves of flat plate collectors.

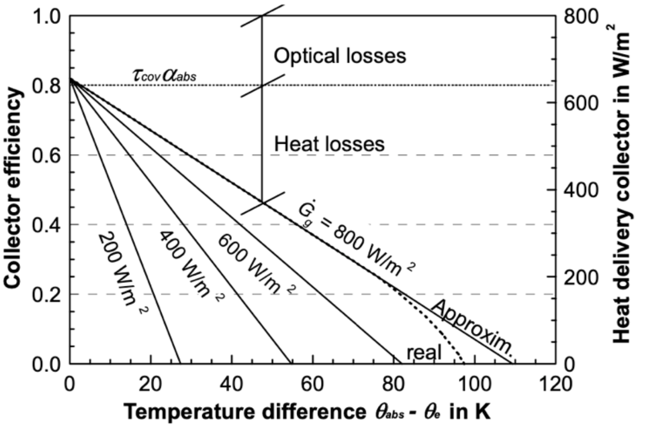


Figure 3.9: Efficiency curves of flat plate collectors

The design of the collector has to combine the material parameters and the environmental parameters in order to achieve highest efficiency when the temperature difference will be at the lowest value.

Chapter 4
Stirling Engine

4.1 Overview

The Stirling engine was designed by Robert Stirling in 1816 and its purposed was for water pump specific for mining operations. It was a different way to pump water to steam pumps, which had the unfortunate tendency to occasionally blow up. In later years the thermodynamic principles behind the engine were worked out. Since that time, Stirling engines have continued to capture the imagination of engineers, and many investors. They are interested due to potential of high efficiency rates, low volume operation, decrease emissions, and the variety of fuels that can be used.

Stirling engines have been used with solar-dish concentrators, cryogenic coolers, for residential heat and for producing electricity. Additionally, they were used in submarine propulsion systems, and various distributed generation systems concepts. Nowadays , a s more than 50 companies design and produce Stirling engines; but there has been little, if any, commercial use to date in power generation or combined heat and power (CHP) applications.

Stirling engines are heat engines that utilize the Carnot cycle – the Carnot cycle is the most efficient heat engine cycle allowed by physical laws. However, the practical translation of this theory into hardware has resulted in only modest electrical generation efficiencies – equivalent to microturbines – and slightly less than reciprocating engines. Hot water can be produced from the engine cooling and lubrication system and the exhaust gas – and can result in overall thermal efficiencies approaching 80%. This would make these systems attractive in residential or small industrial and commercial applications. The models currently under development are in the 1 to 55 kW range. The lower end of the range is usually fitting for residential purposes, and at the higher end for a small commercial application. The packages can be installed in multiples to obtain larger outputs.

The engine package uses a separate combustion chamber, which can be engineered to a low-emissions combustor. This also allows the use of a wide range of fuels, like natural gas, propane, oil, biomass, waste fuels, etc. Stirling engines also can use any source of high-temperature heat: The engines have been combined with solar-dish concentrators in 1 to 7 kW systems. Surplus heat from industrial processes can be used, but it must be at least 850oC for the engine to function. So far prototypes have achieved very low NOx levels.

While Stirling engines are worthy candidates for distributed generation and combined heat and power applications, they face formidable hurdles to establishing a lodgment in the marketplace. Reciprocating engines or gas turbines – have been the recipients of heavy investments and many years of development.

An application where the central and advantaged characteristics of Stirling engine produce a benefit/cost ratio unmatched by the competition has yet to be accomplished. Most of the companies promoting Stirling engines for distributed generation have not progress enough and field-test results are not being offered to the public.

Stirling engines are prime movers, and therefore can be used to supply shaft power for pumps, electric generators, or other mechanical drive applications. The technology so far is being developed to serve the following power applications:

Stationary Power Generation, Distributed Generation

- Peak shaving and base-load power
- Microgrid implementations.
- Stand-alone power
- Resource recovery (e.g., landfill gas)
- Backup/stand by power

A significant and popular usage of development is the application for solar-energy dish concentrators.

The Stirling engine’s advantage to utilize different sources of heat makes them suitable for use as heat-recovery devices in industrial units. The source of heat, (e.g., from a furnace or kiln flue), must be between 700 and 900oC, noncorrosive, and have a heat content of at least 93,000 W for a 24 kW unit. Under design models will be able to operate with heat sources between 980 and 1100oC and achieve electric conversion efficiencies approaching 55%.

In a typical Stirling engine, approximate 30% of the heat input is converted to electric power, and 70% of the heat input is rejected to the cooling system and exhaust gases, so there is a great opportunity for water heating design or other low-temperature heating application that can be implement taking advantage the heat rejection. Because Stirling engines are liquid-cooled, it is relatively easy to capture heat for CHP applications through a simple liquid-to-liquid heat exchanger. The only difference between a "power only" package and a CHP package is the addition of the heat exchanger and related control elements. Stirling engines can achieve CHP thermal efficiencies approaching 80% at competative reasonable costs with a suitable thermal host. Potential applications would include small commercial building heating/cooling systems, hotels or laundries.

Nowadays, the Stirling engine is being on the front again, and many are arguing that it is the technology of the future. Many power plants are already being used to use Stirling models tailored to the needs of consumers. There are many examples around the world, many application are seen by the United States. In Europe there are several manufacturers, most of them of German descent, building Stirling engine applications for more than a decade and in recent years their also focusing on exploiting renewable energy sources.

4.2 Stirling Thermodynamic Cycle

The Stirling engine operates by alternatively heating and cooling a working gas. Heat is provided at a temperature at the one end of a cylinder (the red end), while heat is rejected at constant temperature at the other end (the blue end). Work is created as the expanding gas pushes against a piston. The working gas is transferred back and forth between the two chambers, often with the help of a "displacer piston." The working gas is generally compressed in the cold chamber and expanded in the hot chamber to produce power. A regenerator is used between the hot and cold chambers of the machine to increase the energy-conversion efficiency.

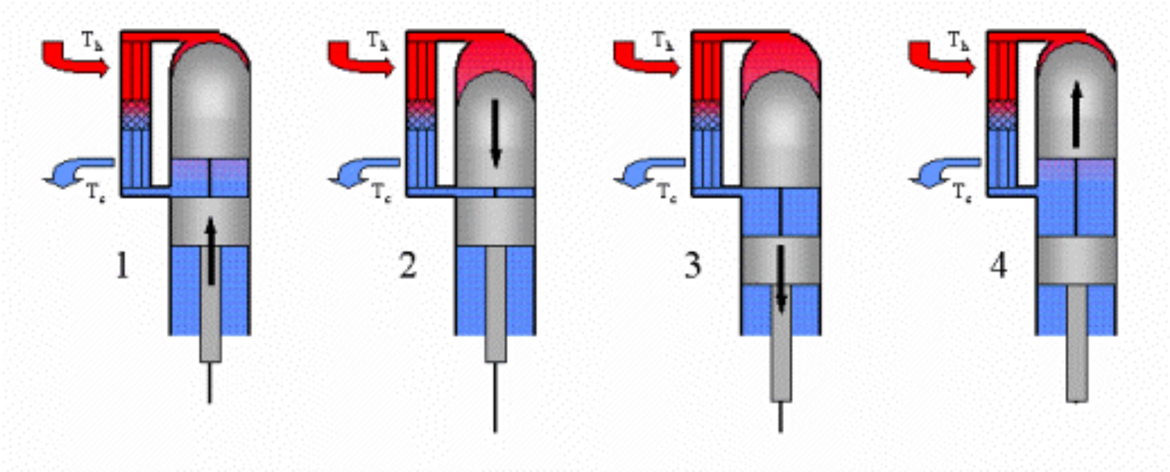


Figure 4.1: Single cylinder Stirling Engine System.

The Stirling machine is a closed gas machine, ie it produces work by heating and cooling the same mass of gas and does not exchange gas with either the cold or the hot source, but only heat. It has two pistons, the power piston (yellow), which is hermetically sealed, and the separation piston (green), which is porous and partially allows gas flow through it. The theoretical cycle of the Stirling machine includes the successive phases of operation which are as follows:

A: (4-1) during indoor heating the gas is heated by the hot source and limited by the separation piston increases its pressure.

B: (1-2) the hot gas is released producing a projectile and pushes the power piston to the maximum volume value.

C: (2-3) the gas cools evenly since the separation piston limits it in contact with the cold source.

D: (3-4) the gas is compressed isothermally to finally be limited to the space of the hot source by the power piston due to the momentum provided by the movement of the wheel (crankshaft).

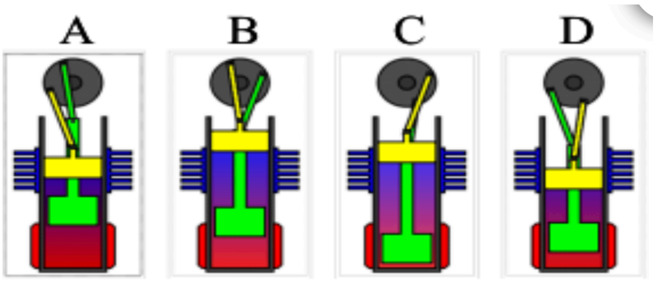


Figure 4.2: Working faces of Stirling Engine cycle.

When converting thermal energy into mechanical work, the Stirling machine theoretically has the potential to achieve maximum efficiency, from any other heat engine, where W is the generated mechanical work, Q the heat offered, TH and TC the temperatures of the isothermal transitions 1-2 and 3-4 respectively.

$$n = W/Q = 1 - T_C/T_H$$

However, practical factors such as the properties of non-ideal real gases, friction, heat loss and the mechanical properties of the machine's construction materials cause the machine's performance to deviate to lower levels.

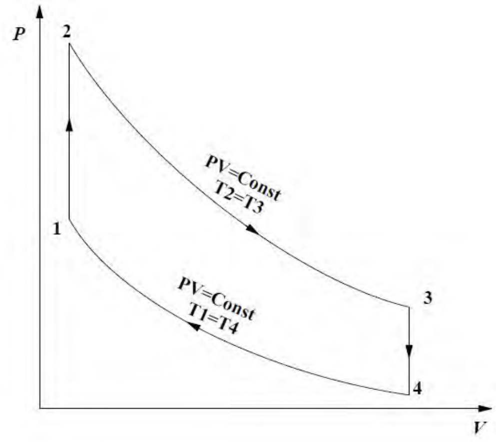


Figure 4.3: ideal Stirling cycle PV diagram.

4.3 Stirling Thermodynamic Cycle Phases of operation.

When the gas is closed in a cylinder and moved to the warm part of the cylinder, its pressure increases, and it seeks to expand. So, it can produce energy through work. On the contrary, when the gas is forced to go to the cold part of the cylinder, it cools and contracts, consuming energy. The gas produces more energy through work during the expansion than what is needed during its compression the sum of these two energies during a cycle is the net energy produced per cycle by the machine (in J / cycle) which if we then multiply by the frequency. operation of the machine (in cycles / s) we calculate its power (in W). The following is a detailed analysis of the Stirling cycle inside a machine based on the image showing the four stages of the cycle.

According to figure 4.3 we have the four thermodynamic phases of the cycle.

Isothermal expansion (T = const):
Most of the working gas inside the closed system is driven into the hot cylinder. The gas is heated and discharged by driving both pistons inwards (in our figure the piston of the hot cylinder to the right while the cold cylinder to the bottom). The angular deflection of the crankshaft measured from the vertical and clockwise direction at the beginning of the phase is zero. At the end of the first phase the crank at 90 °.

Colling (V = const):
The gas has dissipated. Most of the gas (about 2/3) is still in the hot cylinder and one third in the cold cylinder. The volume in the hot cylinder is maximum. As a large volume of gas is transferred from the hot to the cold cylinder, a amount of heat is stored in the regenerator.

Isothermal compression:
Now most of the hot working gas, which has been released, has been transferred to the cold cylinder. The gas is cooled and shrinked, collecting both pistons inside their cylinders (in the lower left cylinder to the left while in the upper cylinder upwards). The

regenerator continues to absorb heat from the working gas as it passes from the hot to the cold cylinder.

Heating (V=const)

The gas that has already been collected is mainly in the cold cylinder. The crankshaft is also turned 90o, forcing the gas to return to the hot cylinder and complete the cycle. As a cold volume of gas is transferred from the cold to the hot cylinder, the regenerator delivers heat to the working medium, preheating it. If the regenerator is considered perfect then it only gives off as much heat as it had absorbed.

4.4 Types of Stirling Engines.

The two major types of Stirling engine are known as the "kinematic" and "free piston." In the former, the piston(s) are connected by means of connecting rods and crankshaft, or with a swash plate (also known as a wobble plate). A swash plate is commonly used to control the pitch of helicopter rotor blades. In the kinematic Stirling engine, the swash plate controls the stroke, and thus the output. The swash plate allows for variable output while maintaining the thermal input, allowing faster response to changes in demand.

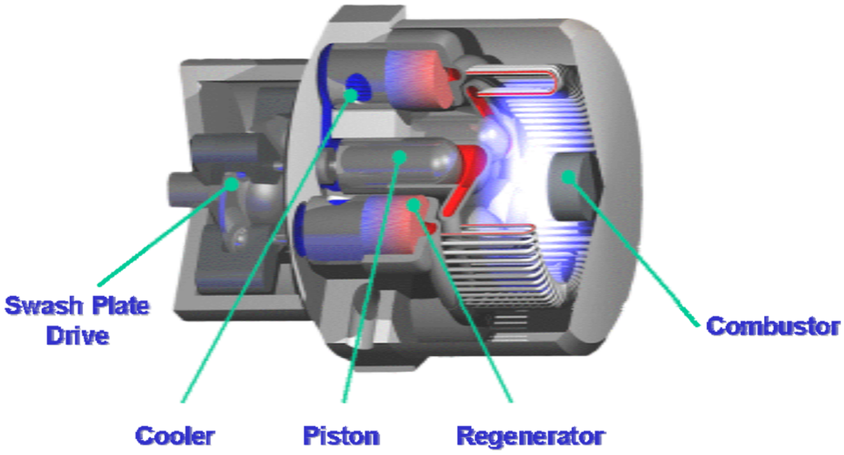


Figure 4.4: Kinematic Stirling engine.

Kinematic Stirling engines can be designed as either single- or double-acting engines. Single- acting kinematic Stirling engines can have one or more cylinders, with varying designs for mechanical linkage. Double-acting kinematic Stirling engines require several cylinders. The working gas in a double-acting configuration operates on opposite faces of the piston. The Stirling Thermal Motors (STM) design for its 4-120 engine (see Figure 4.4) involves four parallel cylinders, where the reciprocating piston motions are linked to a swash plate via one rotating shaft.

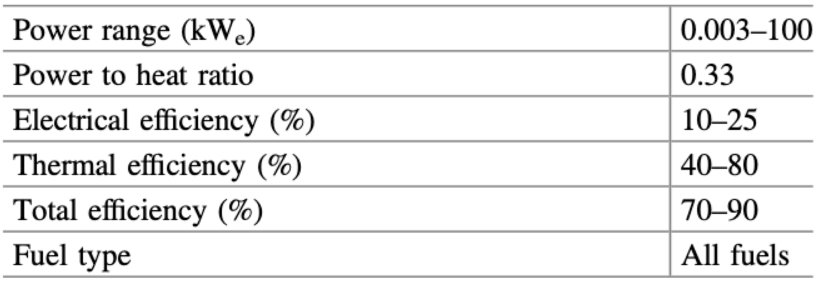
Free-piston Stirling engines do not have any mechanical linkage between the piston and the power output. The pistons are mounted in flexures and oscillate freely. Flexures are springs that are flexible in the axial direction, but very stiff in the radial direction. A fluid or a linear alternator receives the reciprocating output via pneumatic transfer. The free-piston engine is a single-acting engine. Since the working gas in the single-acting design only operates on one face of a piston, two pistons are required in each cylinder – one for displacement and one for power. Free-piston configurations have to-date been limited to small sizes (below 12.5 kW).

An important element of a Stirling engine is the working fluid. In theory, any fluid could be used, but given the heat transfer characteristics of the candidates, hydrogen or helium are typically preferred. However, the use of hydrogen introduces several design issues, e.g., engine seals, corrosion and embrittlement, and working fluid makeup.

One of the reasons that Stirling engines do not more closely approach Carnot efficiencies is the practical fact that engine components need to be cooled and lubricated. In a Stirling engine, 30% of the heat input is converted to electric power, almost 50% goes to the coolant, with the remaining power dissipated as exhaust or other losses. Power-only systems are typically equipped with a radiator and fan to dissipate the coolant heat into the air.

4.5 Stirling Engines and CHP systems

Stirling engines are well established and a mature technology to be implement for a micro Combine Heat and Power (mCHP) system. This scale is for residential and portable energy generation. As mentioned, the electrical efficiency of the Stirling engine varies from 10% – 30%. In case of Stirling engine used in a CHP system where the lost heat is used the overall efficiency of the system can increase significantly. Table 4.1 shows the main characteristic of a CHP system with Stirling engine.



Power range (kW$_e$)	0.003–100
Power to heat ratio	0.33
Electrical efficiency (%)	10–25
Thermal efficiency (%)	40–80
Total efficiency (%)	70–90
Fuel type	All fuels

Table 4.1: Energy characteristics of the CHP Stirling Engine System.

The heat loss from the Stirling engine can be “collected” by a heat exchanger in the cold source of the engine as well as by using the heat exchanger through which the burnt gases are exhausted into the atmosphere. Figure 4.5 shows this exploitation of heat loss in a biomass CHP based on a Stirling engine.

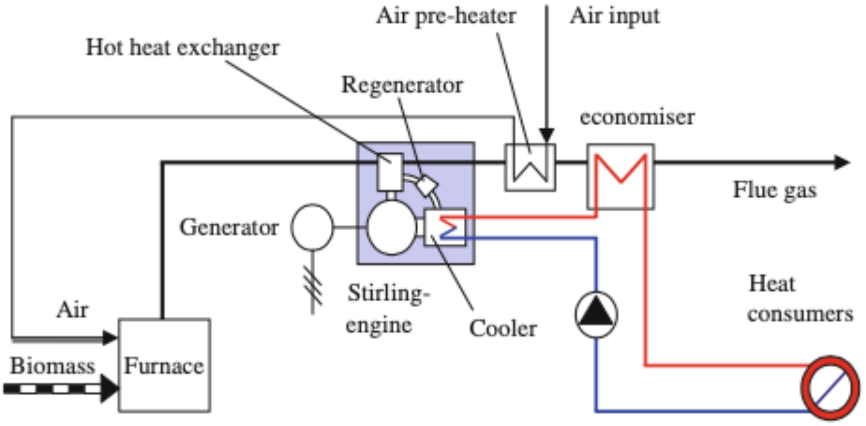


Figure 4.5: Biomass CHP with recovery of Stirling's engine heat loss.

Chapter 5
System Evaluation

5.1 Thermodynamic analysis of the System.

As a simple approach we consider the system under thermodynamic analysis. The problem involves efficiency, power that is delivered under a quasi-static thermodynamic process. The aim is to estimate the power output. The thermal efficiency of the vacuum tubes collectors is estimated and taking into account. Between the solar collector and the environment there is heat transfer that is very important to the overall system thermal efficiency, these values have taken form literature [5].

The T-S diagram is given, taking into account the solar collector system that is the heat source of the system. The collector is connected to the expansion chamber of the heat engine. The surface of the collector is rising but also Heat is lost via convection, radiation and natural advection.

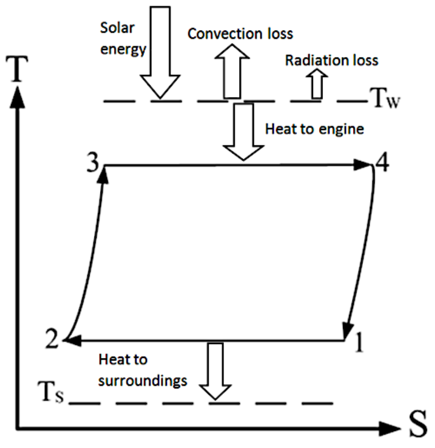


Figure 5.1: Heat Transfer of the Stirling engine connected to Solar collector system.

Taking account, the heat losses from the vacuum tube system the input energy is given by:

$$q_{in} = \omega I_{sun} A_c - h_n (T_w - T_s) A_c - \varepsilon \sigma (T_w^4 - T_s^4) A_c \qquad (5.1)$$

The efficiency of the collector based on the absorption is estimate,

$$\eta_{collector} = \frac{q_m}{I_{sun} \times A_c} \qquad (5.2)$$

As heat is transferred to the expansion chamber there is a very thin wall separating the collector to the expansion chamber of the engine. The conduction coefficient is negligible, and the temperature is considered to be the same and any exact time. As mentioned, Stirling engines can utilize any working fluid, in this example we consider the working fluid as air and is approached as an ideal gas. Heat Transfer is this case is consider following Newton's linear transfer law.

The engine's heat cycle is consisting of the heat that is absorbed by the working fluid Q_{in} and the heat transfer to the surrounding environment Q_{out}. Estimating Q_{in} and Q_{out} the time needed to accumulate heat t_{ac} and time needed to reject heat t_{rj} are consider in the analysis.

$$Q_{in} = h_f A_c (T_w - T_3) t_{ac} \qquad (5.3)$$

and

$$Q_{out} = a_k (T_1 - T_s) t_{rj} \qquad (5.4)$$

The working fluid is considered as an ideal gas, so the relation that defines it is the ideal gas relation,

$$PV = nRT \qquad (5.5)$$

and considering that the process is isothermal and endothermic the entropy terms of the figure 5.1 are described by,

$TdS = T\left(\frac{dP}{dT}\right)_v dV$ (5.6). substituting Equation 5.5 to 5.6 we derive

$TdS = \frac{nRT}{V}dV$ (5.7) which is applied at 3-4 process of the T-S diagram

$\int_3^4 TdS = \int_3^4 \frac{nRT}{V}dV$ (5.8)

The entropy is the prosses is defined by

$S = \left(\frac{\delta Q}{T}\right)_{int,rev}$ which transforms equation 5.8 to

$Q_{in} = nRT_3 ln\frac{V_4}{V_3}$ (5.9)

During the engine's cycle the entropy is increased by a quantity S_{gen} added to as an incremental addition and given as $\Delta S = \oint \frac{\delta Q}{T} + S_{gen}$ and since the process is reversible under the process assumptions we get

$\Delta S = \oint \frac{\delta Q}{T} + S_{gen} = \frac{Q_{in}}{T_3} - \frac{Q_{out}}{T_1} + S_{gen} = 0$ (5.10)

Based on the thermodynamic analysis we know that $S_{gen} \geq 0$ and $\oint \frac{\delta Q}{T} \leq 0$

Combining it into to equation 5.10 we derive $\frac{Q_{in}}{T_3} - \frac{Q_{out}}{T_1} \leq 0$

To approach the real process, we need to take account the engine's heat losses by introducing the heat losses property l. This is what justifies an increase of the entropy in each cycle. So as

$Q_{out} = l\ x\ Q_{out}^{rev}$ (5.11)

At the Stirling engine the heat that is released to low temperature thermal storage at a reversible isothermal step is given by

$Q_{out}^{rev} = nRT_1 ln\frac{V_1}{V_2}$ and when taking into account the heat losses we have

$$Q_{out} = lnRT_1 ln\frac{V_1}{V_2} \qquad (5.12)$$

Knowing that the compressive ratio is defined as $r_v = \frac{V_4}{V_3} = \frac{V_1}{V_2}$ we can substitute into (5.9) and considering the mathematical relations for Q_{in} and Q_{out} the endothermic and exothermic time of the Stirling engine are calculated,

$$h_f\, A_c(T_w - T_3)t_{ac} = nRT_3 ln\frac{V_4}{V_3} \quad \rightarrow \quad t_{ac} = \frac{nRT_3 ln r_v}{h_f A_c(T_w - T_3)} \qquad (5.13)$$

$$a_k(T_1 - T_s)t_{rj} = lnRT_1 ln\frac{V_1}{V_2} \quad \rightarrow \quad t_{rj} = \frac{lnRT_1 ln r_v}{a_1(T_1 - T_s)} \qquad (5.14)$$

To keep the analysis analytical, we assume that heat transfer process of the working fluid has a linearly time change, expressed as $\frac{dT_{air}}{dt} = \pm K_l$ where K > 0, the average rate of temperature change and is a material depended property. When K is positive the temperature increases and when K is negative the temperature decreases over time. This period of time that is the heat regenerative process is happening at stage 2-3 and 4-1 of the T-S diagram and given by

$$t_{23} = \frac{(T_3 - T_2)}{K_l} \qquad (5.15)$$

and

$$t_{41} = \frac{(T_4 - T_1)}{K_l} \qquad (5.16)$$

For a full Stirling circle description, we add all time intervals $t_{sc} = t_{rj} + t_{23} + t_{ac} + t_{41}$ and get

$$t_{sc} = \frac{lnRT_1 lnr_v}{a_1(T_1 - T_s)} + \frac{(T_3 - T_2)}{K_l} + \frac{nRT_3 lnr_v}{h_f A_c (T_w - T_3)} + \frac{(T_4 - T_1)}{K_l} \qquad (5.17)$$

So for each Cycle the energy in the collector is

$$Q_{in} = q_{in} \times t_{sc} \qquad (5.18)$$

Substituting equation (5.3) and (5.17) we get

$$q_{in} = \frac{h_f}{\frac{1}{A_c(T_w - T_3)} + \frac{h_f l T_1}{a_1 T_3 (T_1 - T_s)} + \frac{2h_f (T_3 - T_1)}{nRT_3 \ln r_v K_l}} \qquad (5.18)$$

The efficiency of the Stirling engine can expressed as

$$\eta_{st} = \frac{P_{st}}{Q_{in}} = \frac{Q_{in} - Q_{out}}{Q_{in}} = 1 - \frac{T_1}{T_3} l \qquad (5.18)$$

The heat that is rejected from the Stirling Cycle is given by

$q_{out} = \frac{Q_{out}}{t_{sc}}$ (5.19). and the output power of the Stirling engine cycle is estimated by

$$P_{St} = \eta_{st} \times q_{in} \qquad (5.20)$$

5.1 Analysis of the Vacuum Solar collector.

This thesis covers the energy analysis of a boiler assisted vacuum tube solar collector system, the production of which was done in a way having an indirect working principle. This is why we consider that is a closed loop water system that utilized a heat exchanger at the connection with Stirling's engine chamber.

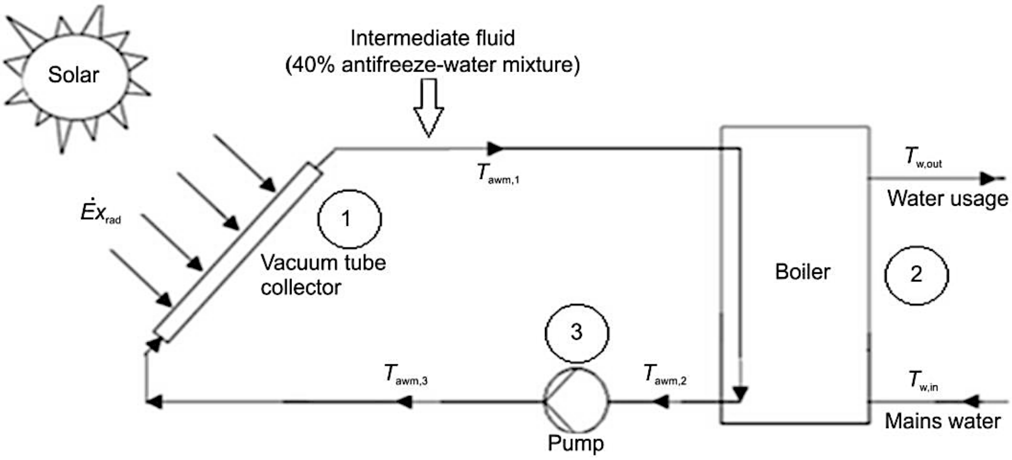


Figure 5.2: Energy flow in the system,

.

The performance of the solar collector is directly dependence from the instant irradiance, and the heat losses due to conduction, convection and radiation factors. The efficiency is calculated by equation 5.21

$$\eta = \eta_o - k_1 \frac{(T_i - T_a)}{H} - k_2 \frac{(T_i - T_a)^2}{H} \qquad 5.21$$

Where

Ti is the temperature of the inlet fluid; Ta is the ambient temperature; H is the irradiance [W/m2];

η_o is the optical efficiency. The optical efficiency is the efficiency of the collector at the point where the average collector temperature is equal to the ambient temperature.

k_1 and k_2 are the heat loss coefficients.

The efficiency of the collector, as defined by the EN 12975 on the aperture area of the collector shall meet, or exceed the following conditions: optical efficiency at least 0.75, k_1 heat loss not more than 1.18 W/m2°C, k_2 heat loss not more than 0.010 W/m^2 °C.

The collector power output can then be calculated as

$\dot{Q}_{ST} = A_{st}\,\eta_{st}\,H$ 5.22

where:

g —collector efficiency [%];

Q_{ST}—power output from the collectors [W];

A_{ST}—collector area [m2];

H—irradiance on the collector surface [W/m2]

Having done an ideal Adiabatic analysis on a Stirling engine, we would like to calculate the heat transfer and the friction flow results of the three heat exchangers for engine performance. This will allow us to make a parametric sensitivity analysis as required to optimize it. Forced heat transfer by convection is essential for the operation of the Stirling engine. The heat transferred from the external heat source to the working gas in the hot part is stored in a circular manner and recovered in the regenerator, and is disposed of by the working gas in the outer container of the cold part. All this is done in solid heat exchangers (large wet surface in the empty volume), in order to limit the "dead space" to an acceptable value and therefore it is possible to reason the engine output power. We find that the efficient heat exchange has the price of increased flow friction, resulting in so-called "pumping loss". This loss refers to the mechanical power required to "pump" the working gas through heat exchangers, thus reducing the production of pure engine power.

The theory and analysis of these results are extremely complex, and we believe that we can invoke the plethora of documented experimental and empirical studies (eg Kays & London, Compact Heat Exchangers). Almost all of this huge body of work. It is based on fixed flow conditions, and therefore does not apply directly to the oscillating flow conditions applicable to Stirling engines. gas behaves as if it is in a steady flow. So, we have called this analysis "Simple" because it is a gross simplification of an extremely complex process. At this stage there is still significant disagreement about this approach, and one must deal with the results of this analysis with a sound measure of skepticism. The only alternative to the design is the recent "Similarity and Scale" approach developed by Allan Organ and presented in his book "The Regenerator and the Stirling Engine".

To compare the heat output of different solar collectors, the product (A_{ST} g_{ST}) of aperture area and efficiency at the operating condition considered should be compared rather than efficiency alone. The choice of collector type depends on several factors such as price, efficiency, operating temperature, and location (available solar radiation, ambient temperatures).

In order to evaluate the performance of the heat pipe evacuated tube solar collector, typical solar radiation and meteorological data should be available. Figure 5.3 shows the measurements data of solar irradiance based on the experimental solar and meteorological station available at Cyprus on July, 2016. The figure shows variations of the direct normal irradiance (DNI), diffuse horizontal irradiance (DHI) and global horizontal irradiance (GHI) with the local time for a selected clear-sky day. An 8 hours period of exposure is assumed for solar radiation calculations.

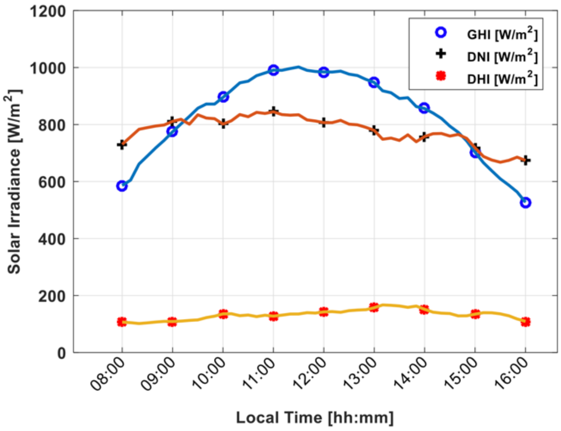
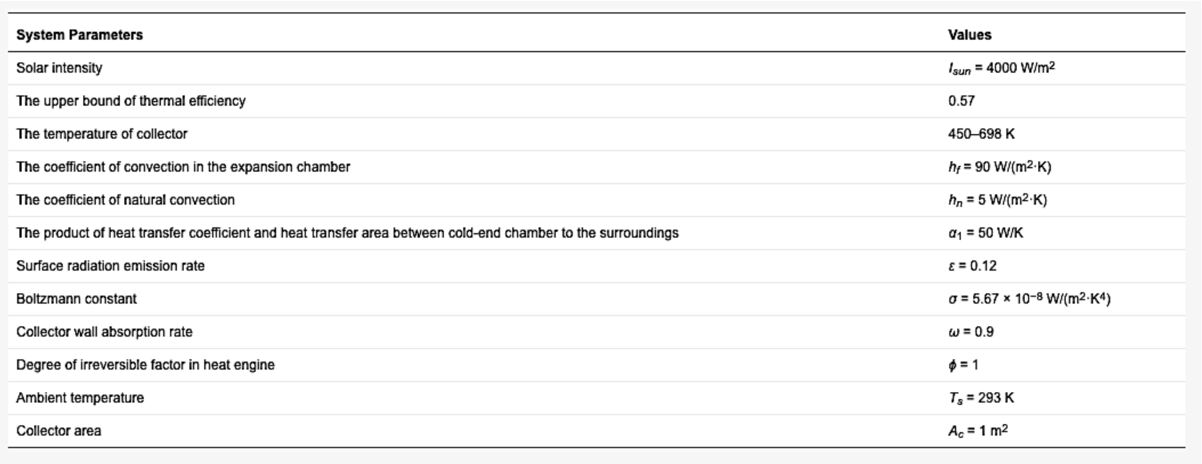


Figure 5.3: Variation of the direct, diffuse and global solar irradiance for the sample testing day.

8:00:00 AM	30.6	75.4
10:00:00 AM	38.2	97.9
12:00:00 PM	43.5	94.2
2:00:00 PM	50.1	88.2
4:00:00 PM	47.1	89.3
5:30:00 PM	30.2	77.5
8:00:00 AM	32.2	70
10:00:00 AM	44.8	90.9
12:00:00 PM	50.6	89.7
2:00:00 PM	50.1	84.2
4:00:00 PM	39.4	90.9
5:30:00 PM	29.9	71.5
8:00:00 AM	30.4	75.2
10:00:00 AM	44	99.7
12:00:00 PM	50.2	95.9
2:00:00 PM	51.8	94
4:00:00 PM	47.8	92.1
5:30:00 PM	30	70.3
8:00:00 AM	30.2	77.7
10:00:00 AM	42.7	90.3
12:00:00 PM	53.9	87.5
2:00:00 PM	52	98.1
4:00:00 PM	40.7	96.6
5:30:00 PM	33.1	73.8
8:00:00 AM	32.5	81.1
10:00:00 AM	48.2	97.6
12:00:00 PM	53	100.8
2:00:00 PM	53.9	103.3
4:00:00 PM	45.4	97.5
5:30:00 PM	35	80.7

Table 5.1: The input and output temperatures of the working fluid through the vacuum tube solar collector



System Parameters	Values
Solar intensity	$I_{sun} = 4000$ W/m^2
The upper bound of thermal efficiency	0.57
The temperature of collector	450–698 K
The coefficient of convection in the expansion chamber	$h_f = 90$ W/(m^2·K)
The coefficient of natural convection	$h_n = 5$ W/(m^2·K)
The product of heat transfer coefficient and heat transfer area between cold-end chamber to the surroundings	$\alpha_1 = 50$ W/K
Surface radiation emission rate	$\varepsilon = 0.12$
Boltzmann constant	$\sigma = 5.67 \times 10^{-8}$ W/(m^2·K^4)
Collector wall absorption rate	$\omega = 0.9$
Degree of irreversible factor in heat engine	$\phi = 1$
Ambient temperature	$T_s = 293$ K
Collector area	$A_c = 1$ m^2

Table 5.2: System parameters for study.

The engines system parameters that are modeled are given by the Table 5.3

5.2 Calculations of the System.

From the above thermodynamic analysis, we can estimate the efficiency of the engine, given the solar intensity. Table 5.2 gives the basic parameters for a single piston Stirling engine that is examined. The system is designed to operate with moderate-temperature heat input that is consistent with solar-thermal collectors.

5.2.1 P-V diagram and Power

This diagram enables us to know the work of the circular process followed by a thermal engine, such as the Stirling machine based on what we have developed in theory. Examples we see of the volume pressure diagram are shown in the figure below for different DT conditions as well as the amount of power in each diagram, which is of course calculated from the area of the graph. A useful diagram proves the following, as depending on the differential temperature it gives us the amount of power that the P-V diagram gives us. We result that as the temperature difference increases, the power generated in each cycle of the process performed by a Stirling machine increases.

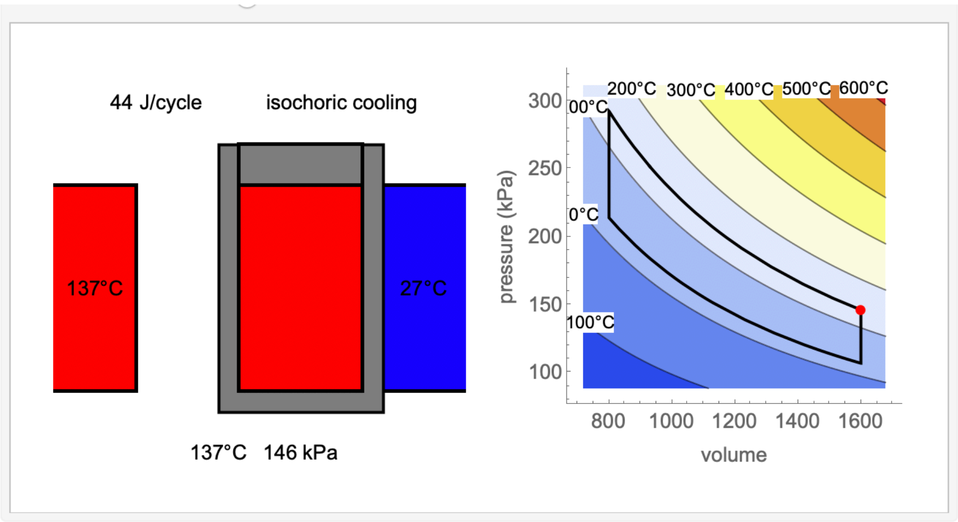


Figure 5.4 Calculated P-V diagram for engine mode is shown at that operating point, for a specific temperature differential.

Implementing the analysis to calculate the work in engine based on the temperature difference ΔT that occurs at a given moment. For some ΔT we got the fowling

WORK OF THE ENGINE	
ΔT °C	CALCULATED POWER W
20	50.69
30	63.23
40	71.94
50	122.41

Table 5.5: Calculated Engines work.

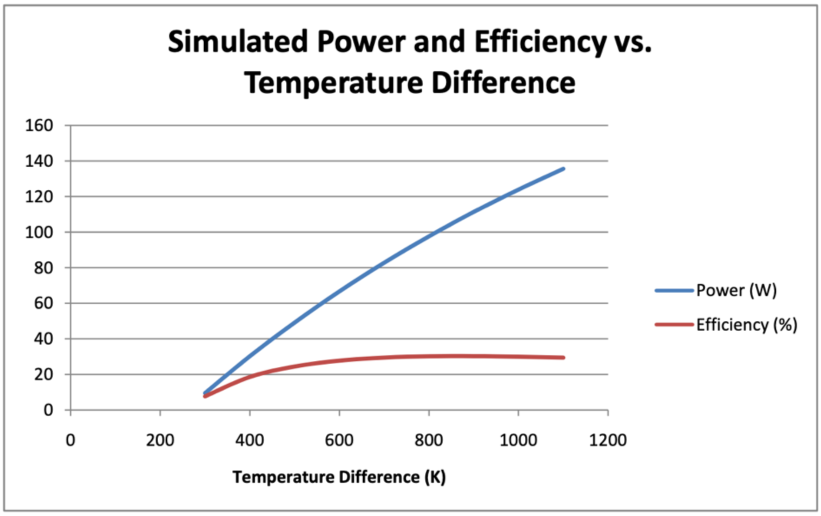


Figure 5.5: Power and efficiency of the system calculated based on the thermodynamic analysis.

5.3 Results and Discussion.

A new approached to micro generation system is examined. An "old" engine, the Stirling engine powered by a solar thermal collector system for thermal-electric generation. The Stirling engine is based on low-temperature differentia process window with relative modest efficiency but simple and low cost manufacturing.

The thermal efficiency of the system can be improved by increasing the input temperature thus improving the efficiency of the solar collector subsystem. This can be done by more efficient collector materials, or specialized tracking system of the solar tubes. On the other hand, this kind of improvements always increase the cost of the system. Reducing the T_1 temperature could also have the same effect. This could be done with the use of better heat exchanger materials and geometry.

Additional, calculations show that the efficiency of an ideal Stirling cycle can reach 60%. However, in real cycles this figure is much lower, due to the leakage of the coolant, the friction of various parts, lower temperature gradients, the heat loss on heating of metal surfaces, etc. The attractiveness of this systems that use Stirling engines together with solar collectors is most on the simplicity of design thus low-cost investment. The analysis shows that the area of the solar collectors and the temperature in the cold area can influence the efficiency of the engines. The first issue is improved by installing more number of tube collectors. The second issue can be resolved by installing heat exchangers for the heating system.

The combined benefits of electricity generation, energy storage, and heat energy are a attractive combination. The potential for this technology to play a role in decarbonizing humanity’s energy portfolio is compelling.

Appendix A

A1: B-type Stirling Engine Modeling in Maple

```
Manipulate[
 Quiet@Module[
   {mAir = 10 ChemicalData[gas, "MolarMass"], pMax1, pMin1, pMax2, pMin2, minvar = 10,
    maxvar = 800, vIsothermalExpand, v2IsothermalExpand, vIsothermalCompress,
    v2IsothermalCompress, inf3, inf4, ΔU, U, maxEff, W, Δstep = 15, d = 1.},
   vIsothermalExpand = Transpose[{(* Combines the two
       separate variables to make ordered pairs *)
      UnitSimplify[(* First variable start *)
       (* Attempts to simplify the units of the given quantity *)
       ThermodynamicData[
         gas, "SpecificVolume", { (* Specifies the property
           desired (Specific Volume) for air at each data point *)
          "Temperature" → Quantity[texp, "DegreesCelcius"],
          (* Sets additional parameters for ThermodynamicData at α°Celcius *)
          "Pressure" → Quantity[Range[minvar, maxvar, Δstep] 1000, "Pascals"]
          (* Sets additional parameters for Pressure at 10,
          000Pascals to 1,000,000Pascals *)
         }
        ] mAir],
      Quantity[(* Second variable start *)
       Range[minvar, maxvar, Δstep] 1000, "Pascals"
      ]
     }
    ];
   (* Define the variable IsothermalCompress as ordered pairs representing
    volume reduced by the isothermal compression of the engine *)
   vIsothermalCompress = Transpose[
     {(* Combines the two separate variables to make ordered pairs *)
      UnitSimplify[(* First variable start *)
       (* Attempts to simplify the units of the given quantity *)
       ThermodynamicData[
         gas, "SpecificVolume", { (* Specifies the property
           desired (Specific Volume) for air at each data point *)
          "Temperature" → Quantity[tComp, "DegreesCelcius"],
          (* Sets additional parameters for ThermodynamicData at β°Celcius *)
          "Pressure" → Quantity[Range[minvar, maxvar, Δstep] 1000, "Pascals"]
          (* Sets additional parameters for Pressure at 10,
          000Pascals to 1,000,000Pascals *)
         }
        ] mAir],
      Quantity[(* Second variable start *)
       Range[minvar, maxvar, Δstep] 1000, "Pascals"
      ]
     }
```

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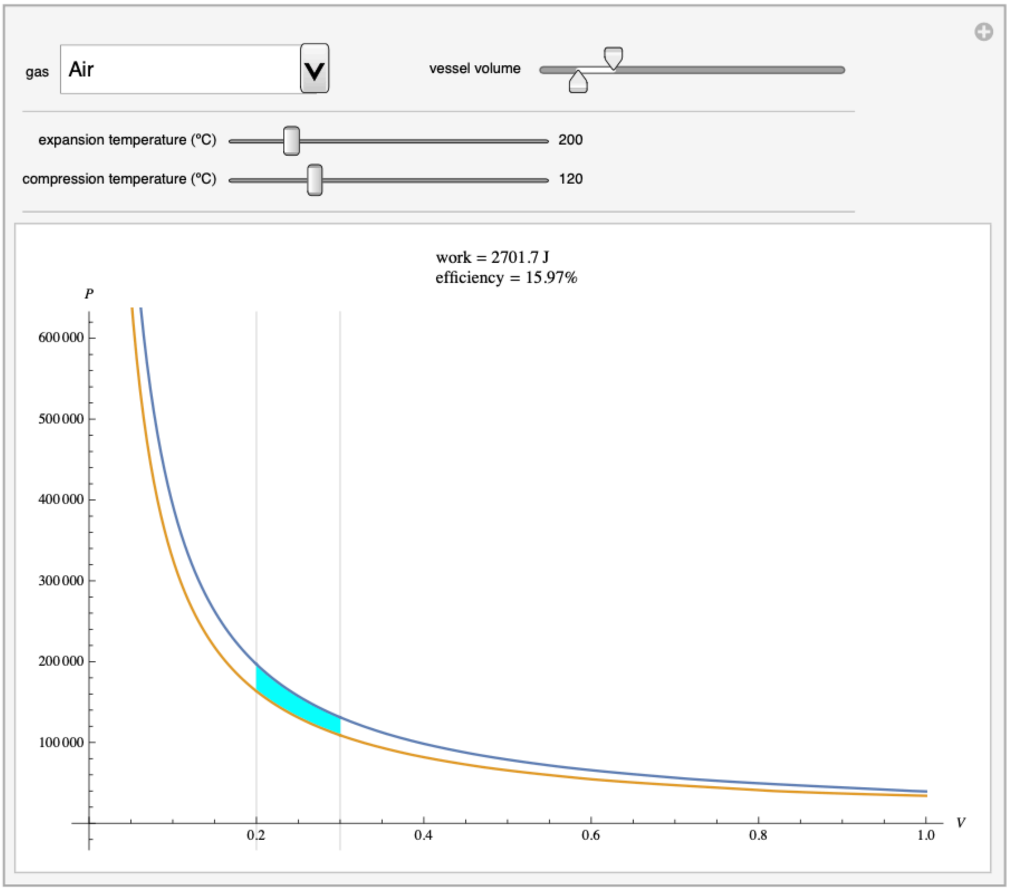
```
   ];
  v2IsothermalExpand = QuantityMagnitude[UnitConvert@vIsothermalExpand];
  v2IsothermalCompress = QuantityMagnitude[UnitConvert@vIsothermalCompress];
  inf3 = Interpolation[v2IsothermalExpand];
  inf4 = Interpolation[v2IsothermalCompress];
  W = Quantity[
    NIntegrate[Evaluate[inf3[V]], {V, λ[[1]], λ[[2]]}] -
     NIntegrate[Evaluate[inf4[V]], {V, λ[[1]], λ[[2]]}], "Joules"];
  {pMax1, pMin1} = (Quantity[inf3[#], "Pascals"] & /@ λ);
  {pMax2, pMin2} = (Quantity[inf4[#], "Pascals"] & /@ λ);
  U[T_, p_] := ThermodynamicData[gas,
     "InternalEnergy", {"Temperature" → T, "Pressure" → p}] * mAir;
  ΔU = U[ Quantity[texp, "DegreesCelcius"], pMax1 ] -
    U[ Quantity[tComp, "DegreesCelcius"] , pMin2];
                UnitConvert[Quantity[tComp, "DegreesCelcius"], "Kelvins"]
  maxEff = 1. - ──────────────────────────────────────────────────────────;
                UnitConvert[Quantity[texp, "DegreesCelcius"], "Kelvins"]

  Show[
   Plot[{Tooltip[inf3[V], "expansion curve"], Tooltip[inf4[V], "compression curve"]},
    {V, 0, λ[[1]]}, AxesLabel → {V, P}, PlotRange → All],
   Plot[{Tooltip[inf3[V], "expansion curve"], Tooltip[inf4[V], "compression curve"]},
    {V, λ[[1]], λ[[2]]}, AxesLabel → {V, P}, PlotRange → All,
    Filling → {1 → {2}}, FillingStyle → RGBColor[0, 96, 99]],
   Plot[{Tooltip[inf3[V], "expansion curve"], Tooltip[inf4[V], "compression curve"]},
    {V, λ[[2]], d}, AxesLabel → {V, P}, PlotRange → All],
   PlotRange → {{0, d}, {0, 600 000}},
   PlotLabel → Column[{Row[{"work = ", W}], Row[
       {"efficiency = ", NumberForm[QuantityMagnitude[W / ΔU] * 100, {4, 2}], "%"}]}],
   AxesOrigin → {0, 0},
   ImageSize → Large,
   GridLines → {λ, {}}
  ]

 ]
,
Row[{Control[
   {{gas, "Air", "gas"}, {"Acetone", "Air", "Ammonia", "Argon", "Benzene", "Butane",
     "Butene", "CarbonDioxide", "CarbonMonoxide", "CarbonylSulfide", "CisButene",
     "Cyclohexane", "Cyclopropane", "Decane", "Deuterium", "DimethylEther",
     "Dodecane", "Ethane", "Ethanol", "Ethylene", "Fluorine", "HeavyWater",
     "Helium", "Heptane", "Hexane", "Hydrogen", "HydrogenSulfide", "Isobutane",
     "Isobutene", "Isohexane", "Isopentane", "Krypton", "Methane", "Methanol",
     "Neon", "Neopentane", "Nitrogen", "NitrogenTrifluoride", "NitrousOxide",
     "Nonane", "Octane", "Oxygen", "Parahydrogen", "Pentane", "Perfluorobutane",
     "Perfluoropentane", "Propane", "Propylene", "Propyne", "R11", "R113",
     "R114", "R115", "R116", "R12", "R123", "R124", "R125", "R13", "R134a",
     "R14", "R141b", "R142b", "R143a", "R152a", "R21", "R218", "R22", "R227ea",
     "R23", "R236ea", "R236fa", "R245ca", "R245fa", "R32", "R365mfc",
     "R41", "RC318", "SulfurDioxide", "SulfurHexafluoride", "Toluene",
```

```
     "TransButene", "Trifluoroiodomethane", "Water", "Xenon"}}], Spacer[60],

   Control[{{λ, {0.2, 0.3}, "vessel volume"}, QuantityMagnitude[0.1],
     QuantityMagnitude[1.0] - 0.05, ControlType → IntervalSlider}]}],
 Delimiter,
 {{texp, 200, "expansion temperature (°C)"},
  180, 300, 10, ControlType → Slider, Appearance → "Labeled"},
 {{tComp, 120, "compression temperature (°C)"}, 100, 180,
  10, ControlType → Slider, Appearance → "Labeled"},
 Delimiter,
 {{variselect, 2, "variable selector"},
  {1 → " gas volume ", 2 → " Δtemperature "}, ControlType → None},
 SynchronousInitialization → False, SynchronousUpdating → False, ControlPlacement → Top
]
```



gas Air

vessel volume

expansion temperature (°C) 200

compression temperature (°C) 120

work = 2701.7 J
efficiency = 15.97%

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