Decentralized Polygeneration Energy Systems: A General Overview on the Important Aspects

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Abstract
A polygeneration system is a small-scale energy system with multiple components of different technologies. The system consists of generations and storage that is sized and configured to match a specific demand. With these decentralized energy systems, located close to the end user, local energy resources can be used easily. Different technologies for electricity and heat generation and electrical and thermal storage are presented in the report.

The objective of this thesis is to describe important aspects of polygeneration in decentralized energy systems. Interactions between environmental, economic and social aspects of life are essential when configuring a sustainable polygeneration system. Also, climate change and low levels of living standards is a driving force to provide better alternatives for energy supply.

A case study in a rural village in India has been carried out to model and optimize a polygeneration system for the community. The optimization is made in the software HOMER (Hybrid Optimization of Multiple Energy Resources) with suitable data for different input parameters, resulting in a techno-economic analysis. Additionally, a sensitivity analysis of the system has been performed in order to consider fluctuations of uncertain input parameters.

The result from the case study shows an optimized system with 79 % of renewable resources, which consists of solar PVs with a capacity of 50 kW. Moreover, the system includes a diesel generator with the capacity of 20 kW and 40 batteries of 6V each. In theory, a polygeneration system with 100 % of renewable resources would be the most sustainable configuration in regard to the environmental aspect. However, implementing that kind of system in a rural area would not be the most reliable or cost effective alternative for the end users.

An implementation of a polygeneration system is indeed a complex process as a result of multiple aspects and energy supply is rarely the only aspect to be considered. The difference between needs in developing and developed countries vary, as the first may prefer to cover basic needs such as electric lighting to a low environmental footprint.
Sammanfattning


Syftet med kandidatarbetet är att beskriva viktiga aspekter av decentraliserade polygenererande energisystem. Samverkan mellan de miljömässiga, ekonomiska och sociala aspekterna är avgörande för att skapa ett hållbart polygenererande system. Klimatförändringar och låga nivåer av levnadsstandard är en drivkraft för att skapa bättre alternativ till energiproduktionen.

En fallstudie har gjorts i en avlägsen by i Indien för att utforma och optimera ett polygenererande system för ett samhälle. Optimeringen är gjord i datorprogrammet HOMER (Hybrid Optimization of Multiple Energy Resources) med lämplig indata, vilket resulterat i en teknisk och ekonomisk analys. Utöver detta har en känslighetsanalys gjorts som tar hänsyn till fluktuationer i osäkra parametrar.

Resultatet från fallstudien visar ett system bestående till 79 % av förnyelsebara energikällor, vilket i detta fall är solpaneler med en kapacitet på 50 kW. Systemet inkluderar även en dieselgenerator med en kapacitet på 20 kW och 40 batterier med 6 V vardera. I teorin är ett system bestående av 100 % förnyelsebar energi det mest hållbara systemet ur ett miljöperspektiv. Ett sådant system i en avlägsen by är dock varken det mest pålitliga eller kostnadseffektiva alternativet för slutanvändaren.

Implementeringen av ett polygenererande energisystem är en komplex process eftersom energiförsörjningen sällan är det enda utfallet att beakta. Behoven i utvecklingsländer och industrialiserade länder skiljer sig åt. I utvecklingsländer är grundläggande behov så som elektriskt ljus av större vikt medan en liten miljöpåverkan är allt viktigare i industrialiserade länder.
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**Nomenclature**

In this section the notations and abbreviations are presented.

**Notations**

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<th>Denomination</th>
<th>Symbol</th>
<th>Unit</th>
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<tbody>
<tr>
<td>Boiler marginal cost</td>
<td>$c_{boiler}$</td>
<td>$$/kWh</td>
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<tr>
<td>Capital recovery factor</td>
<td>CRF</td>
<td>-</td>
</tr>
<tr>
<td>Derating factor of PV array</td>
<td>$f_{PV}$</td>
<td>%</td>
</tr>
<tr>
<td>Electrical efficiency</td>
<td>$\eta_{gen}$</td>
<td>%</td>
</tr>
<tr>
<td>Electrical output</td>
<td>$P_{gen}$</td>
<td>kW</td>
</tr>
<tr>
<td>Incident radiation at standard test conditions</td>
<td>$G_{T,r}$</td>
<td>1kW/m$^2$</td>
</tr>
<tr>
<td>Lifetime of project</td>
<td>$R_{proj}$</td>
<td>year</td>
</tr>
<tr>
<td>Lower heating value of fuel</td>
<td>$LHV_{fuel}$</td>
<td>MJ/kg</td>
</tr>
<tr>
<td>Mass flow rate of fuel</td>
<td>$m_{fuel}$</td>
<td>kg/h</td>
</tr>
<tr>
<td>Maximum pump power</td>
<td>$P_{pump}$</td>
<td>kW</td>
</tr>
<tr>
<td>Nonrenewable energy production</td>
<td>$E_{nonren}$</td>
<td>kWh/yr</td>
</tr>
<tr>
<td>Number of year</td>
<td>N</td>
<td>year</td>
</tr>
<tr>
<td>Power output of PV array</td>
<td>$P_{PV}$</td>
<td>kW</td>
</tr>
<tr>
<td>PV cell temperature</td>
<td>$T_{c}$</td>
<td>°C</td>
</tr>
<tr>
<td>PV cell temperature under standard test conditions</td>
<td>$T_{c,STC}$</td>
<td>25 °C</td>
</tr>
<tr>
<td>Rated capacity of PV array</td>
<td>$Y_{PV}$</td>
<td>kW</td>
</tr>
<tr>
<td>Required pump energy</td>
<td>$P_{ann,average}$</td>
<td>kWh/day</td>
</tr>
<tr>
<td>Solar radiation incident on the PV array</td>
<td>$G_{T,STC}$</td>
<td>kW/m$^2$</td>
</tr>
<tr>
<td>Temperature coefficient of power</td>
<td>$\alpha_{P}$</td>
<td>%/°C</td>
</tr>
<tr>
<td>Total annual interest rate</td>
<td>i</td>
<td>%</td>
</tr>
<tr>
<td>Total annualized cost</td>
<td>$C_{ann,tot}$</td>
<td>$$/yr</td>
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<tr>
<td>Total load served</td>
<td>$E_{served}$</td>
<td>kWh/yr</td>
</tr>
<tr>
<td>Total thermal load served</td>
<td>$H_{served}$</td>
<td>kWh/yr</td>
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<tr>
<td>Abbreviation</td>
<td>Denomination</td>
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<tr>
<td>AC</td>
<td>Alternating Current</td>
<td></td>
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<tr>
<td>CAES</td>
<td>Compressed Air Energy Storage</td>
<td></td>
</tr>
<tr>
<td>CCHP</td>
<td>Combined Cooling, Heating and Power</td>
<td></td>
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<tr>
<td>CHP</td>
<td>Combined Heat and Power</td>
<td></td>
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<tr>
<td>COP</td>
<td>Coefficient of Performance</td>
<td></td>
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<tr>
<td>DC</td>
<td>Direct Current</td>
<td></td>
</tr>
<tr>
<td>DSM</td>
<td>Demand Side Management</td>
<td></td>
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<tr>
<td>HOMER</td>
<td>Hybrid Optimization of Multiple Energy Resources</td>
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<tr>
<td>ICE</td>
<td>Internal Combustion Engines</td>
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<tr>
<td>LCOE</td>
<td>Levilized Cost of Energy</td>
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<td>NPC</td>
<td>Net Present Cost</td>
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<tr>
<td>PCM</td>
<td>Phase Change Material</td>
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<tr>
<td>PSH</td>
<td>Pumped Storage Hydropower</td>
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<tr>
<td>PV</td>
<td>Photovoltaic</td>
<td></td>
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<tr>
<td>SMES</td>
<td>Super-capacitors and Superconductive Magnetic Energy Storage</td>
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<tr>
<td>SOC</td>
<td>State of Charge</td>
<td></td>
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<tr>
<td>TCS Power</td>
<td>Thermochemical Energy Storage for Concentrated Solar Power Plants</td>
<td></td>
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<tr>
<td>UTES</td>
<td>Underground Thermal Energy Storage</td>
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</tr>
<tr>
<td>WBREDA</td>
<td>West Bengal Renewable Energy Development Agency</td>
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1 Introduction
In this chapter the main purpose and objectives with this thesis is described. Furthermore, an introduction to the subject is presented.

1.1 Background
The challenge of global warming and climate change today requires a transformation of energy production, distribution and use. Fossil fuels are limited energy resources and contributes to the global warming through emissions of greenhouse gases, thus to prevent global warming the usage of finite resources needs to be replaced by sustainable alternatives. A growing population on earth will result in increasing energy utilization. Therefore, sustainable energy solutions need to be provided for future generations in a larger scale than today.

Centralized energy is the current energy supply situation in most of the industrialized countries today. A decentralized energy system is, in contrary to a centralized power system, located close to the end consumer. As an example, electricity is generated in large power stations far from the point of demand in the United Kingdom, which results in an energy wastage of almost two-thirds of primary energy input. Most of the wastage is energy loss in transmission lines and additionally heat is wasted during the energy production (Greenpeace, 2005).

A decentralized energy system can consist of one or several micro grids, which can operate in isolation or be connected to the traditional grid. It incorporates three main components of generation, storage and demand. The micro grid provides a reliable and sustainable energy supply and focuses on the environmental resources in the local area to optimize the efficiency of the system. One of the main objectives with the micro grid is to control and balance the energy production and the local demand. The generation consists of components such as wind turbines, solar PVs, fuel cells, Stirling engines, micro turbines or internal combustion engines (ICE). The technologies can be combined in a way that allows the system to provide electricity, heating and cooling in the same system. Different types of configuration of the systems can be used to cover the energy demand for residential and commercial buildings as well as for larger communities.

In 2012, 1.2 billion people in the world lacked access to electricity (Schnitzer et. al., 2014). To electrify a number of those households unlikely to be connected to the traditional centralized energy grid, several micro grid projects has been implemented at these rural areas. It has generated income and an increased level of living standards among many underprivileged villages.

In India, more than 78.7 % of the population is living without or with poor access to electricity and reliable energy distribution (The World Bank, 2012). This thesis will include a case study on a rural village on Sagar Island, located in the west of India. The island is 224.3 km² with a population of 160 000 in 43 villages (DX News, 2015). Transmission lines from the mainland to the island have never been installed, however diesel generators run during a limited time each day and produces one part of the power supply on the island. The electricity distribution lines run through the center of the island, although the lines do not reach all villages. To provide those remote villages with power the West Bengal Renewable Energy Development Agency (WBREDA) has set up decentralized photovoltaic (PV) power plants that supplies some of the villages with electricity during six hours a day.
1.2 Problem Formulation and Objectives
The objective with this thesis is to describe important aspects of polygeneration in decentralized micro grids. The aspects can be mapped into three main categories, the technological, economic and social categories considering environmental issues and sustainability.

Firstly, technologies appropriate for generation and storage will be evaluated in terms of environmental aspects and availability of local energy resources. Moreover, different methods for optimal sizing of a polygeneration system will be considered. In addition, an operational strategy will be defined in regards to ensure reliable energy supply from the system.

Secondly, the economic aspects of a polygeneration system will be evaluated. The aim is to determine the economic influence when implementing and configuring a polygeneration system, which also includes evaluation of different energy management strategies.

Thirdly, social and political aspects, such as social benefits and potential political barriers of a polygeneration implementation will be determined. The consequences of different political energy policies and popularizing of renewable energy resources will be discussed. Finally, a case study with an implementation of a micro grid in the rural village Natendrapur located on Sagar Island in India will describe an optimized model of a polygeneration system. The software HOMER (Hybrid Optimization of Multiple Energy Resources), will generate the techno-economic optimization of the system.

To summarize the described issues, the following three questions will be answered.
- How are the economic, environmental, social and political aspects affecting the implementation and usage of a polygeneration system?
- Which generation and storage technologies are suitable for an implementation?
- Considering specified input data for the case study, what are the techno-economic optimization and configuration of the system?

1.3 Constrains
In this report, many aspects of polygeneration will be mentioned. Due to the vast areas of these aspects, they will all be discussed, though in different levels of complexity. The case study will state an example of how a system implementation can be optimized in regards to the studied aspects. Input parameters for the economic and technical calculations are either based on previous field studies or default input parameters in HOMER. The energy load in the case study will only be electrical and deferrable and not thermal since it requires a more advanced knowledge of the software.

2 Literature Study
In this chapter the literature study will be presented. It will give important and general information about the aspects of polygeneration.

2.1 Decentralized Energy
Before the early 20th century, distributed power plants provided 100% of electricity to local costumers. In 1910 the availability and feasibility of central power distribution made it possible to
meet an increasing demand, therefore the central power distribution dominated the power production until somewhere in the late 20th century, when decentralized power had its renaissance.

Several domains in society such as retail, telecommunicating, healthcare and energy are moving towards decentralization, which indicates that organizations and people are moving away from centralized systems. The movement of decentralization brings important opportunities to improve the average standard of living for all (Owens, 2014).

One of the main objectives of decentralized energy systems is the possibility of high energy efficiency. Almost all of input energy is put to use when taking advantage of waste heat. Decentralized generation implicates that large scale transmission lines are not needed and therefore a lot of energy loss in transmission are being used instead of wasted (Greenpeace, 2005).

Polygeneration is a method of applying decentralized energy systems. The economic, social, political and environmental aspects need to interact in order to obtain a sustainable generating system, which is described in Figure 1. These aspects will be discussed further on.

2.2 Economic Aspects
The economic benefits and challenges has an important role in the choice of using a decentralized or centralized energy system. Today, economic growth and competitiveness is one of the most vital factors for developing the society. There are a lot of benefits from an economic point of view with the decentralized polygeneration energy systems. These micro grids allow the consumer to choose the most cost effective configuration of the system that best suits the site.

Some of the generation technologies can produce electricity and at the same time utilize waste heat for useful heating or cooling in so called CHP (Combined Heat and Power) and CCHP (Combined Cooling, Heat and Power) systems. This leads to an overall increased efficiency in the system, which contributes to a better power output and therefore a greater economic gain. With these types of system, it is possible to avoid the investment of a separate cooling or heating
device. Many countries encourage companies and individuals to use technologies with minimal impact on the environment, which they express by making these components more affordable. In some countries it is possible to gain financial aid from the government when installing environmental friendly technologies to produce electricity. This could be a great economic advantage for setting up a polygeneration system.

In remote or rural areas an autonomous micro grid could be a more cost efficient alternative instead of extending the traditional main grid. The implementation of a polygeneration system in developing countries can not only increase the average standard of living but can also result in new business opportunities for the community. In rural areas where access to electricity is poor, many are unfamiliar with the positive outcomes electricity can bring. Both the implementation and the maintenance can create job opportunities, which generate incomes. More important there is an opportunity for individuals to start their own businesses that are in need of electricity to function. Startups, such as barbershops, hospitals, schools and cafes can then create more jobs. One of the biggest challenges is the investment cost of the equipment and the fact that the payback time on renewable generations is yet long. There is a lot of research and development in the area of renewable technologies with the aim to make the technologies more efficient and in that way more accessible and useful in the society. The costs of the system depend on several parameters such as current feedstock prices, product prices and the frequency of maintenance and replacements. Both capital costs and operating costs of the components has to be compared. By using renewable resources the fuel costs can be eliminated. Before implementing a polygeneration system the net present cost (NPC) should be calculated. The formula reveals if the investment will be profitable considering the technologies life span (Thomson, n.d.).

2.3 Social and Political Aspects
The digitalization with information and communication technologies is continuously growing thanks to the existing innovative spirit for developing our societies and ways of living. Even though the technology exists it is still not available for everyone. Most people living in rural areas in developing countries do not have access to electricity. The decentralization of energy in form of small-scale polygeneration systems could be a solution to reach out to rural communities. The access to electricity simplifies and makes the everyday life more efficient, allowing new activities to take place. It improves the standard of living significantly and covers basic social needs such as health, education and income. Higher energy consumption will raise the level of these needs, especially in developing countries. Practical beneficial examples could be extending daylight hours with lightning, having access to a refrigerator and allowing women to go to school instead of gathering wood for cooking. The job opportunities that comes with the increased usage of energy brings incomes and economic growth, which is key to the development of the communities.

With decentralized energy follows energy freedom for the consumers since configuration, location and supply are locally controlled. This increases the users independency of other stakeholders on the market and allows local adjustments to meet the current demand. It is easier to meet the growing energy demand with a decentralized system rather than a centralized one since changes can be done quickly. A challenge is to predict the future energy demand in order to balance supply and demand. Since the energy usage leads to new types of demands the future consumption growth rate should be considered while implementing a system.
An important aspect in order to succeed with an implementation of a polygeneration system is the attitude, commitment and knowledge about and towards decentralized energy and the technologies behind the system. The communities and people that could benefit from the system must be informed about the advantages it can contribute with, not only to the individual but also the whole society. People who have been unfamiliar with electricity as an asset during the main part of life can be skeptical to the implementation of such a system and even the need of electricity. The implementation and usage of decentralized energy could change the cultural view of production and usage of energy by empowering individuals and communities.

In industrialized countries it is getting more important for the individual to take responsibility for the ecological footprint on earth by reducing carbon dioxide emissions and by using renewable alternatives. Self-sustaining energy, produced from renewable sources can be an active way for the individual to contribute to this cultural change. A challenge is the esthetical perspective of the system which some claims are disturbing, in forms of noise and appearance.

Political laws and regulation also have an influence in the choice between centralized or decentralized energy distributions. Decisions about financial aid from the government on certain technologies are one aspect that can encourage people to produce their own energy. There are many powerful companies that by own interests steers the market one way or the other and decide the need of the customer. An increased usage of decentralized energy would affect the large scaled centralized energy systems and would pressure them to adjust to the market. It would reduce the vested interests for the stakeholders on the centralized market (Owens, 2014).

2.4 Environmental Aspects

The average temperature on earth has risen by 0.8 °C between 1850 and 2005 (University of Gothenburg, 2010). Although there has always been some variation in the temperature on earth, small average temperature changes like this are reasons for dangerous shifts in climate and weather. Humans have a profound responsibility of climate change since our emissions of carbon dioxide and other greenhouse gases has created a shell around earth, trapping energy in the atmosphere which are causing the heating. Some changes are inevitable, and it can be difficult to predict an exact future of the climate change, but it is clear that the way we live today are not a reliable model of the future.

Disregarding living in the industrialized or in the developing part of the world, the everyday life of all is connected and dependent on the climate. The climate change is a global issue and the greenhouse gases can never be isolated to one part of the world. However, some parts of the world are utterly exposed to the consequences of climate change. Developing countries, which already have unstable economics and social situations, are the ones most struck by the consequences of the climate change. Several countries and areas have been facing flooding, longer droughts or more intense rains and the sea level is rising. This is a direct threat for the survival of a few countries (EPA, 2016).

Most part of greenhouse gases comes from burning fossil fuels when producing energy. In order to reduce the emissions of carbon dioxides, the energy production needs to change into a more sustainable alternative. In developed countries, the need for new energy supply is limited. Thus, changes into more renewable energy production with decentralized polygeneration, can be
motivated on account of environmental benefits. The main purpose of decentralized energy systems, in this part of the world, is to increase efficiency and to reduce the waste heat with CHP and therefore provide a more environmentally sustainable alternative. In traditional centralized energy system that runs on fossil fuels, about two-thirds of input fuel is lost in transmission lines and as waste heat in the energy producing process. With CHP components, the waste heat can come to use as heat supply for homes and businesses. The total efficiency of CHP systems can be as high as 90% if all waste heat is put to use (Owens, 2014).

The environmentally related challenges of implementing a decentralized energy system involve possible disorder of local ecosystems. For example, potential effects from wind turbines on birds are discussed, such as collision impacts and disturbance effects. Moreover, bat mortality can also be connected to wind turbines (Greenpeace, 2005).

In developing countries, the power supply is often limited and unreliable and the main grid often lack possibilities to reach all potential customers. Therefore, the decentralized polygeneration can offer an environmentally sustainable supply of energy without excluding anyone. Local natural resources such as sun, wind and water are used to provide a reliable supply of electricity. Fluctuations and weather crisis of today are not as big of a challenge for the reliability of the energy production of polygeneration systems since they can be configured to match the site (Owens, 2014).

The environmentally related barriers of implementing and using of a polygeneration system in a developing country contain of competitions for natural resources, such as land and water. Though this could be seen as a problem in developed countries as well, there are most examples of such conflicts in developing countries. The use of the technology is also facing the barriers of negatively affected ecosystems, noise or odor and pollution in the local area. Further developments and life cycle analysis of the power technologies are necessary to increase the diffusion of polygeneration systems (Yaqoot et. al., 2016).

2.5 Technology Aspects
Polygeneration is the foundation of a micro grid, which is a small-scale energy system. A micro grid consists of different technologies that store and produce electricity, heating and cooling by taking advantage of the local resources close to the installation site. It is either operating autonomously as an island at all time or connects to the main grid during special occasions such as peak hours, working as a support to the traditional grid.

2.5.1 Generation
In this part the different technologies for the generation of the micro grid is presented. Each generation component can be evaluated by its controllability and dependability whereas natural factors have an impact, such as the seasonal weather changes. Data for the generation technologies can be found in Appendix 1.
2.5.1.1 Reciprocating Engines
Reciprocating engines can be divided into spark-ignited and compressed-ignited, also known as diesel engine. The theory behind the spark-ignited engine is the Otto cycle, which differs from the diesel cycle where the air itself can ignite the fuel because of the compression. The engine includes a cylinder with a piston, a spark plug and one intake and one exhaust valve. Different types of engines are defined by their number and assembling of the cylinders. The cycle to produce power consists of four steps, intake, compression, ignition and exhaust. In the first step a mix of air and fuel fills the cylinder. The intake valve closes and the gas mix compresses. The piston moves to the top of the cylinder and the spark plug ignites the mix. The mix expands and the pressure forces the piston down. The exhaust valve releases the gas and the cycle repeats. This cycle allows the engine to start quickly compared to the Stirling engine. The efficiency of the engines depends on the type, size and the fuel being used. The efficiency increases with the engines size. The Otto engine produce between 2 kW – 2 MW while the diesel engine can produce up to 50 MW (Persson & Olsson, 2002).

2.5.1.2 Stirling Engines
In a Stirling engine thermal energy is converted to mechanical energy. It is the temperature differences within the device that are producing the work. There are a lot of different configurations of Stirling engines but the most common ones are the Alpha, Beta and Gamma types. They differ from design aspects but the main principles of how they work are the same. The theory behind how the engine produces the work comes from the idealized Stirling cycle where the relationship between the pressure and volume is related to the temperature of the working gas. The gas is operating in a closed system, which means that the volume is fixed. The working gas is normally air, helium or hydrogen. Even though the two last mentioned are hard to contain they are light gases that will reduce losses (Brill, n.d.).

The engine consists of either one cylinder with two pistons, one for displacing the gas and the other for creating the work. It can also consist of two cylinders with a piston in each one. The gas in the cylinder is heated by an external source. The heated gas will produce a pressure leading to an expansion of the gas that creates a movement of the piston towards the colder side of the cylinder. In the colder part of the cylinder the gas cools, the pressure decreases, the gas contracts and the piston moves back. The high temperatures within the cylinder require it to be built with a resistant material that can handle the temperature changes. The potential efficiency is very high and it is dependent on the temperature difference. A higher temperature difference will result in a better efficiency. Compared to a combustion engine it is more efficient and not as noisy since there are no valves that are used to let the gas in and out of the cylinders (Persson & Olsson, 2002).

2.5.1.3 Micro Turbines
A micro turbine is a small-scale combustion turbine that consists of a compressor, combustion chamber, turbine and a generator that can produce both heat and electricity. There are two different types, unrecuperated and recuperated. Air goes through the compressor, which increases the pressure of the air and continues to the combustion chamber where the fuel goes in. The fuel can be natural gas, hydrogen, propane or diesel. The mix ignites in the combustion chamber. The high temperature gas enters the turbine and expands. The turbine is connected to
the generator through a shaft that begins to rotate and electricity is generated. It is possible to use waste heat with a recuperator, which increases the efficiency of the power source. The recuperated turbine uses some of the exhausted gas to boost the incoming air. The capacity is between 25 kW – 500 kW and the efficiency is 15 % and if recuperated it is between 20 – 30 %. If used as CHP cogeneration it can be up to 85 %. The turbines have few moving parts, which facilitate the maintenance work, and the small size makes it possible for the turbines to be installed close to the demand. Micro turbines are often used as a power backup to the main grid or during peak hours while the load increases significantly (Capehart, 2014).

2.5.1.4 Wind Turbines
A wind turbine transforms kinematic energy to electricity. It consists of a tall pole with a generator, controller and a rotor with blades attached to it. There are both vertical and horizontal wind turbines. The wind is stronger and less turbulent higher up, which is the reason of the high pole. The lift and drag force from the air creates a higher pressure on one side and a lower pressure on the other side of the blade which causes it to turn. The rotor is connected to a shaft that with a gearbox transmit the rotation to a generator that produces electricity. The controller measures the wind speed to make sure that the wind turbine only operates during the right conditions. An acceptable condition is a wind speed between 3.5 – 24.5 m/s in order for the wind turbine to work efficient without being damaged (U.S. Department of Energy, 2013). The best-suited locations for wind turbines are open areas, high-elevated terrain that is close to the coastline or out in the sea whereas the wind is stronger. There are small wind turbines with a capacity less than 100 kW that are used for homes and bigger wind farms with a capacity of several megawatts used for greater loads (U.S. Department of Energy, 2013).

2.5.1.5 Solar PV
The solar photovoltaic (PV) panels convert sunlight into electricity. The cells in the solar panels are made out of semiconducting materials such as silicon and the top section is made out of glass working as a protection. These cells consist of one negative, n doped, and one positive, p doped, layer of the semiconducting material, which creates an electric field. It absorbs photons from the sunlight and that energy releases electrons in the material. The electrons start moving between the layers and thereby creates a direct electrical current (DC). The DC current can then be inverted to alternating current (AC) with an inverter. The cells are packed into modules that can be combined in series or parallel arrays to increase the power output. The efficiency of the device depends on the surrounding temperature and the amount of sunlight. An increased temperature will reduce the efficiency of the device since it is decreasing the voltage. Solar panels or arrays are normally installed on rooftops or on bigger areas directly on the ground in so called solar plants (Solar Server, 2011).

2.5.1.6 Solar Thermal Collector
The solar collector absorbs sunlight transferring it to heat in a gas or liquid medium. The absorber is made out of metal strips that have a dark coating in order to increase the absorption level. There are two kinds of solar collectors, flat plated and evacuated-tube collectors. The flat plated collectors consist of a transparent cover that transmits the light and protects external factors of removing the heat, an absorber, a heat transfer medium such as water, air or solar fluid,
and an insulation material. The evacuated tube collectors on the other hand consist of several tilted glass tubes filled with vacuum connected in a series. Each tube consists of a liquid filled copper tube. When the liquid gets heated it begins to vaporize and rises to the top of the tube where the heat exchanger is situated. The solar collectors are often installed on rooftops facing the sun to be able to absorb as much sunlight as possible. They are mostly utilized to heat water and air for buildings (Solar Server, 2011).

2.5.1.7 Fuel Cells
There are many types of different fuel cells, but as a distributed power technology all sorts of fuel cells utilizes the chemical reaction with oxygen or another oxidizing agent to convert chemical energy into electrical energy. Fuel cells consist of one negative side, the cathode, and a positive side, the anode, and also an electrolyte, which enables charges to travel between the two sides without any combustion. Through an external current, electrons move from the negative side to the positive side and electricity is produced in the process. The by-products of this process are water, heat and carbon dioxide. Hydrogen, often from natural gas, or oxygen from ambient air, are two types fuel in a cell. For this this type of fuel cell, the hydrogen at the anode turns into a positively charged ion and a negatively charged electron. The ions can pass through the electrolyte and the electrons travels in wires creating an electric current. At the cathode the positively charged ions reacts with the oxygen to create water or carbon dioxide. The operational temperature varies between $80 - 1000 \ ^\circ C$, depending on the type of fuel cell. Because of exothermic reactions in fuel cells are commonly used, large amount of heat are generated within the fuel cell (Owens, 2014).

Moreover, fuel cells are commonly used to provide premium and continuous power in either stationary or mobile applications. Further usage of fuel cells require additional commercial and technical developments, due to their relatively low efficiencies and high cost in comparison to other distributed power technologies. On the other hand, despite of low emissions and high efficiencies, future fuel cells can be more competitive considering silent operating qualities and low maintenance requirements. The technology advances must consist of decreasing manufacturing and investment cost for the fuel cells to gain greater fields of application (Persson & Olsson, 2002).

2.5.1.8 Absorption Chiller
Since the beginning of the last century, absorption chiller technologies have been available and widely used as cooling system. Absorption chiller uses the refrigeration cycle in which compression, condensation, expansion and evaporation processes are incorporated. Heat is the energy source that absorption chillers use. In a polygeneration system, the waste heat from distributed power technologies are used to provide the refrigeration cycle process with thermal energy. Therefore, absorption chillers are commonly referred to as thermal efficient solutions as the overall efficiency of a polygeneration system can be improved. The ratio of heat removed to input work is expressed in terms of the cool Coefficient of Performance (COP), which are a way of measuring the energy efficiency.

There are two different mediums used in absorption chillers, one is the refrigerant and the other one is the absorbent. The combinations of ammonia and water or alternatively water and lithium
bromide are the most frequently refrigerants respectively the absorbents used in the process. The combination of water-lithium bromide, is limited by the freezing point of the refrigerant water, which is 0 °C. Whereas the combination ammonia-water can generate cool in temperatures of minimally -60 °C. However, chillers are not commonly used in large scale systems since the COP are lower and limited.

The process cycle initiates at the evaporator where the liquid refrigerant absorbs ambient heat and evaporates at a low partial pressure. In the absorber, an exothermic reaction between the absorbent and the refrigerant which causes absorption of the refrigerant. Thus, heat is generated during the reaction, which needs to be chilled to enable further absorption of the refrigerant. The absorption is necessary to create a pressure drop, which enables further absorption of the refrigerant.

To reach the pressure in the generator, the pump increases the pressure of the refrigerant-saturated liquid and external heat is added through a heat exchanger. In the generator, the different boiling points allow the refrigerant to evaporate and separate from the absorbent. The vaporized refrigerant continues to the condenser where the heat is emitted and the refrigerant can condense and the liquid is subsequently supplied to the evaporation phase (Nelson et. al., 2005).

The absorption chillers can be divided into characterizing categories, which are single effect, double effect and triple effect absorption chillers. The single effect refers to chillers that are constructed to avoid any pump work and instead the waste heat composes almost everything of the energy source. Single effect chillers have two pressure levels, a lower level at the absorber and a higher level at the generator and condenser. A double effect chiller requires a higher temperature of the waste heat in comparison with a single effect. Furthermore, a double effect chiller requires additional heat exchangers and pumps (Rydstrand et. al., 2004).

The minimum temperature of waste heat required to supply the process with an acceptable COP, is in the interval of 85 – 90 °C. Double effect chillers are in general more efficient with a higher COP, although the investment costs are higher in comparison with single effect chillers (Nelson et. al., 2005).

<table>
<thead>
<tr>
<th>Cooling Technology</th>
<th>Coefficient of Performance</th>
</tr>
</thead>
<tbody>
<tr>
<td>Absorption Chiller:</td>
<td></td>
</tr>
<tr>
<td>Single Effect</td>
<td>0.7 – 0.8</td>
</tr>
<tr>
<td>Double Effect</td>
<td>1.3 – 1.4</td>
</tr>
<tr>
<td>Vapor Compressor</td>
<td>4 – 7</td>
</tr>
</tbody>
</table>

2.5.1.9 Vapor Compressor Cooling

The vapor compressor refrigerant system contains of a refrigerant, compressor, expansion valve, evaporator and a condenser. The mechanical compression process is needs electricity to run. The process initiates at the compressor where the pressure of the refrigerant is increased. The refrigerant flows to the condenser and condenses from vapor to liquid, which is an exothermic process, thus heat is released. The refrigerant experiences a pressure drop at the expansion valve after the condenser. Thereafter, the refrigerant passes the evaporator where heat is absorbed and
the refrigerant vaporizes at low temperature and the vaporized refrigerant supplies the compressor. The COP for the described cooling technologies can be found in Table 1 (Yeh, 1999).

2.5.2 Storage
In this section, alternatives of energy storage technologies will be described. Energy storage technologies refer to different applications, which absorb and store energy for a period of time. The output of the storage can either be energy released to supply energy or to power services.

2.5.2.1 Electricity Storage
There are several ways to store electricity. The electricity storage can be categorized in mechanical, electrochemical, electrical and chemical storage.

Mechanical
The aim of mechanical energy storage is to convert electricity to potential or mechanical energy and to store the converted energy for later use as electricity. There are three central methods of mechanical energy storage, which are pumped storage hydropower (PSH), compressed air energy storage (CAES) and flywheels.

Pumped storage hydropower systems use elevation to convert off-peak electricity into potential energy. During off-peak periods electricity, water is pumped from a reservoir to a reservoir at a higher elevation. Consequently, when water flows back down during peak hours electricity generates.

Together with compressed air energy storage, pumped storage hydropower is the most developed method for energy storage and also 99% of installed energy storage capacity. Compressed air energy storage systems compress ambient air through off-peak electricity and store the compressed air in storage tanks or in underground caverns. During peak-hours the compressed air is heated and expanded in a turbine driving a generator for electricity production. When the air is compressed from atmospheric pressure to a storage pressure in the interval of 50 – 100 bar, the air is heavily heated. Also, air compressors use multistage coolers to reduce discharge temperatures and the heat of compression is extracted during compression process or removed by a cooler. The heat loss is being compensated for during expansion phase by heating the air in combustors, which would be using natural gas fuel in most cases. The turbines capacity in diabatic CAES allows generation of three times the output for the same natural gas input, and if the heat loss during compression phase is used to heat air in a recuperator, the power-to-power efficiency is approximately 42% without waste heat utilization, and 55% with. The adiabatic method has a much higher efficiency, up to 70%, which can be reached if the heat during compression is used to reheat the air during turbine operations.

Flywheels are the third system in which electricity is stored as mechanical energy. The flywheels consist of a rotor, which spins in a nearly frictionless enclosure to store electricity. When energy is needed, the rotor is slowing down to convert resulting kinetic energy into electricity (International Energy Agency, 2014).
Electrochemical
Chemical reactions with two or more electrochemical cells in electrochemical batteries enable the flow of electrons. Lithium-based batteries consist of lithium metals or lithium compounds, for example lithium-ion and lithium-polymer batteries, which are commonly used in mobile applications. For stationary applications, sodium-sulphur batteries are frequently used, in which liquid sodium and sulphur are typically used. Furthermore, lead-acid batteries consist of two lead-based plates and use and electrolyte to produce electric current. The main utility areas for lead-acid batteries are stationary applications as backup power sources.

Moreover, another example of electricity storage is the vanadium redox flow batteries, which use electrodes and an electrolyte that can endure more charges and discharges without being subject to deterioration. Through the oxidation-reduction reactions of vanadium or other ions in redox flow batteries, the system charges and discharges. A current is either applied or delivered in a central reaction unit, through which the electrolyte is pumped from a storage tank. The power of the battery is determined by the size of the reaction unit (cell stack) and the energy capacity of the battery is determined by the size of the tank (International Energy Agency, 2014).

Electrical
Static electricity or magnetic fields are used in electrical energy storage technologies to directly store electricity. Super-capacitors and superconductive magnetic energy storage (SMES) are examples of electrical energy storage methods. To store energy, the super-capacitors utilize large electrostatic fields between two conductive plates. In this manner, electricity is quickly stored and released. The superconductive magnetic energy storage technologies store energy in magnetic fields, which are created by the flow of direct current electricity into a super cooled coil. Electric currents can cycle through the coil of superconducting wire without losing energy thanks to the negligible resistance that low-temperature superconductive material has.

In general, these system technologies have high cycle lives and power densities though the energy densities tend to be much lower. Therefore, often these type of technologies supply applications with short bursts of electricity into the energy system. A development of improved energy density in these storage systems would decrease the overall cost and increase the fields of application as well (International Energy Agency, 2014).

Chemical
To store electricity, chemical energy storage uses chemical energy carriers, for example electrolysis. The electricity is firstly converted, then stored and lastly re-converted into the end-use form, which can e.g. be electricity, heat or liquid fuel (International Energy Agency, 2014).

2.5.2.2 Thermal Energy Storage
The storage of thermal energy can be divided into sensible heat, latent heat and thermochemical storage, which are all presented in this section.

Sensible Heat
Without the use of a phase change or a chemical reaction, sensible heat storage use change in temperature of a medium. Several technologies of sensible heat storage have already achieved high levels of deployment, thus this method is considered the most mature method of thermal energy storage. Worldwide, hot and cold-water tanks as sensible heat storage can be found in
residential, commercial and in industrial facilities. Furthermore, pit storage, molten salts and solid media storage are other sensible heat storage examples. Underground thermal energy storage (UTES) preserve underground pumped and heated or cooled water to provide heating or cooling resources. The water is pumped into and out of thermal storage systems, which can be either an existing aquifer or man-made boreholes.

On the other hand shallow pits system can be used as storage with gravel and water frequently used as storage mediums. The pit storage systems are dug and filled with the medium and covered with a layer of insulating materials. To provide a heating or cooling resource, water is pumped in and out of these pit systems. Molten salts are a solid thermal storage medium at room temperature and at atmospheric pressure. The salt is commonly used to store heat in concentrating solar power plants. To meet heating or cooling demand, hot- and cold-water storage in tanks are frequently used in domestics. Hot water storage in this form is the most common, which includes insulated water tanks (International Energy Agency, 2014).

**Latent Heat**
Latent energy can be stored when decreasing the enthalpy of a system and consequently energy can be released by increasing the enthalpy again. Medium used for latent heat storages are commonly water, sodium acetate trihydrate and paraffin. The storage medium in latent heat storage systems undergoes a phase change during store and release process. In such way, the enthalpy of the medium system can be changed. Thus, the freezing and melting of a medium is the latent heat storage and respectively the energy release. With this type of storage method, energy densities can be 3 to 15 times greater than sensible storage and moreover, the discharge temperature can be more adapted to the desired application.

A form of latent heat storage is ice storage, where energy is stored in frozen water and melted to release energy. Other forms of latent heat storage are phase change material (PCM) slurries, which have an advantage in comparison to water, since the mixtures have higher thermal energy storage capabilities, it has approximately twice the storage density of liquid water (International Energy Agency, 2014).

**Thermochemical**
Heating or cooling capacity can be stored in the form of chemical compounds in thermochemical storage systems. Endothermic reactions store energy and then released via exothermic reactions. This type of reversible chemical reactions results in energy densities 5 to 20 times higher than sensible heat. Uncoupled from phase change critical temperatures, the thermal energy can be discharged at different temperatures depending on the properties of the thermochemical reaction. As an example, thermochemical energy storage for concentrated solar power plants (TCS Power), stores energy in reversible gas solid reactions, using calcium oxide or hydroxide at a temperature of 400 – 550 °C and manganese oxide at a temperature of 750 – 900 °C (International Energy Agency, 2014).

**2.5.3 Demand**
One key attribute of a micro grid system is to balance supply with a desirable load. This consists in forming a control system that in an effective and safe way can match demand with available
supply. In this section the importance of energy management strategies, operational strategy and sizing of the polygeneration system are described.

The ability to control energy usage is called demand side management (DSM). The DSM strategy can be categorized in demand response (DR), energy efficiency and strategic load growth. The goal is to make the system more efficient or make the end consumers aware of their energy consumption. This enables them to adjust their usage pattern in a way that it benefits the environmental, social and economic aspect (Davito et. al., 2010).

There are several methods to balance the supply and demand in micro grids. The energy efficiency consists of permanently minimizing the use of energy while obtaining the same service outcome. Changing old technology devices to modern more efficient ones can be one solution. In contrary to demand response it does not depend on the end users energy consuming behavior. The strategic load growth has the aim to increase the overall load. As seen in Figure 2 there are four different methods of demand response that by changing the end users consumption pattern will be beneficial for the system. Peak clipping has the objective to reduce peak demand, valley filling increases the consumption during off peak periods, load shifting meaning that load moves from peak to off peak time and dynamic energy management induct demand variations.

The polygeneration system has to be sized to meet the peak demand. Challenges are that the peak demand increases electricity cost, it requires more generation capacity and it raises the risk of a shortage of supply. Due to high costs as a result of the need of extra capacity during peak hours there are an incentive to flatten the critical load. By being aware of the peak hours on daily and annual bases, consumers load can be shifted to off peak periods.

The key to have a successful demand side management is to provide the consumers with helpful information about their consumption through smart displays. This could be done by real time displays that show analyzed data from the energy system. By gathering useful information, the display could show recommendations for energy reduction (Davito et. al., 2010).

![Figure 2: Demand response methods that affect energy consumption (Chuang & Gellings, 2008).](image)
2.5.3.1 Energy Management Strategies

There are many different energy management strategies including demand side management as mentioned above but also dispatch methods, which are mentioned in this section. The micro grid is being controlled by dispatch methods that determine the different operations and limitations in the system. The objective with the dispatch strategy is to provide the desirable energy supply with certain constraints and aims, for example with minimized carbon emissions or costs. The method coordinates a schedule for how and when the polygeneration technologies will generate power and if or where it should be stored and used (Deckmyn et. al., n.d.). In a micro grid there are several operational strategies that determines which operations the system should priorities. A CHP micro grid is most commonly heat- or electricity led. If the system is heat led it will meet the heat demand first and use the excess power for the electricity demand. If it is electricity led it will work the other way around prioritizing electricity demand in first hand (Sobh & Elleithy, 2015). These operational strategies are based on the technologies characteristics such as start up time, discharging time and efficiency. The software HOMER, that will be used in the case study, use two different dispatch methods, load following and cycle charging. The system generate just enough power to meet the demand with load following. The cycle charging on the other hand let the generators produce maximum power and allows the excess power charge the batteries. Setpoints can be established for the batteries. When a setpoint is reached it tells the system that the batteries can start discharging (HOMER Energy, 2010).

Loss of power supply can be devastating both in a social and financial context. Therefore, it is extremely important for the micro grid system to have an intelligent operational strategy that can coordinate supply, storage and demand. The energy supply for the system can be divided into reliably, intermittent or non controllable. Whereas reciprocating engines and fuels cells counts as more reliable supply and renewable energy classifies as intermittent to non-controllable. The range of intermittency can reach from the solar PVs more predictable supply to wind turbines more irregular supply. A system with many renewable sources increases the supply irregularity. To moderate this, the non-critical loads can be restricted until the supply is stable again. Another thing to keep in mind is minimizing conversion and distribution losses in the system. For example, by feeding a DC load from a DC source, such as solar PV.

The energy loads can be dived into critical loads, such as data systems, adjustable loads, like heating and cooling, and sheddable loads. How sensible the loads are to different changes is a key characteristic for the operational strategy. Storage is used to be able to meet demand at all time. It is a vital part of supporting the system. The capacity and the amount of time it can be used are two main points from the storage perspective. Supply, demand and storage can all be evaluated from its controllability and dependability, which can be used to configure the micro grid (Thompson, n.d.).
3 Case Study

Natendrapur is a village on Sagar Island, located in West Bengal in India. The island is 224.3 km$^2$ and belongs to the Ganges delta. About 43 villages are located on the island and the distance to the main land is about 3 km (DX News, 2015). A hypothetical implementation of a polygeneration system in the village will compose the foundation of this case study. A techno-economic analysis and a configuration will be presented.

![Map of Sagar Island](image)

Figure 3. Map of Natendrapur in West Bengal, India (Google Maps, 2016).

Sagar Island is isolated from the main land, see Figure 3, and extensions of the main electricity grid to the island have never been implemented. Between 1996 and 2006, WBREDA installed ten different solar PVs in remote sites on the island. The ten solar PV power plants have the total capacity of more than 300 kW and are powering 2000 families during six hours a day. The solar plant in Natendrapur produces 28.5 kW and was built in 2000 (Mondal & Mandal, 2013).

![Access to electricity](image)

Figure 4. The electricity access in Natendrapur, India (Mondal & Mandal, 2013).
In 2011 the village had a population of 1179 and 236 households (Mondal & Mandal, 2013). As seen in Figure 4 there are 29.41 % of the households that have access to the grid electricity, 47.06 % having access to the solar electricity and 23.30 % are without any electricity (Mondal & Mandal, 2013). The total amount of workers in the village is 37.26 % where most of them are classified as main workers, working more than 6 months. Of the main workers the majority works with agriculture (Census, 2011).

On the island, in almost all locations, the people who does not have access to the electricity grid or solar panels uses kerosene for lightning and the monthly consumption varies from 4-7 liters per household. Approximately, the demand per household is about 30 units per month with duration of supply for at least 8 hours. The use of electricity for domestic activities is mostly between 4 am to 6 am and during 6 hours in the evening, between 6 pm to 12 pm (Mondal & Mandal, 2013).

Sagar Island has a tropical climate and the summers are much rainier than the winters. The average temperature is 26.6 °C and the average annual rainfall is 1720 mm, where the greatest amount of precipitation occurs in August (Climate Data, n.d.).

![Figure 5. The daily temperature, radiation and average wind speed on Sagar Island, India (HOMER Energy, 2016).](image-url)
There are an average of 250 sunny days and 55 overcast days in a year and the average solar radiation is about 1600 kWh/m² on horizontal surface (Mondal & Mandal, 2013). The daily radiation, daily temperature and the average wind speed for the area are presented in Figure 5.

To estimate the electricity demand for the village, the data have been estimated from the demand profile in another rural village in India called Devari Bharat. That village has a population of 1258 and 238 numbers of households (Census, 2011), which is very similar to the population of Natendrapur. The daily demand for Devari Bharat is 160 kWh (Sreedharan et. al., 2014), which allows the usage of utilities such as fans, lightning, mobile charging and TVs.

### 3.1 Optimizing with HOMER

HOMER is a software used to design and optimize micro grids taking in account both technical and economic aspects. It works as a tool to compare different configurations of generation, storage and load in the system. It can be used for remote micro grids as well as systems connected to the main grid. The software evaluates technology costs, electrical and thermal load and resource availability. With its sensitivity analysis methods, it can also define potential future influences of factors that are uncertain, such as fuel or capital prices (HOMER Energy, 2015).

### 3.2 Economic Analysis

Homer uses the net present cost (NPC) and the levelized cost of energy (LCOE) as financial measure to produce an economic analysis of each energy system. The cost of extending the main grid from the mainland to the island can also be estimated and the breakeven point between the options calculated.

The program calculates the NPC for each configuration, which is utilized to rank different feasible configurations in order to find the optimized one. It consists of the total costs of the system over its lifetime including capital costs, replacement costs, operating and maintenance cost, fuel costs, emission penalties and costs for buying power from the main grid. It also includes the total revenues for the system lifetime, which includes the potential salvage value at the end of the lifecycle and revenues from selling power to the grid. The salvage value shows the values of the components at the end of the life cycle. By using the real interest rate instead of the nominal interest rate, the inflation considered. The NPC can be calculated with the following equation:

\[
NPC = \frac{C_{ann, tot}}{CRF(i, R_{proj})} ,
\] (4.1)

where \( C_{ann, tot} \) is the total annualized cost, \( i \) is the annual real interest rate, \( R_{proj} \) is the projects life time and \( CRF \) is the capital recovery factor which is a function calculated as follows:

\[
CRF(i, N) = \frac{i(1-i)^N}{(1+i)^N-1},
\] (4.2)

where \( N \) is the number of years.

The LCOE is the cost of useful electrical energy that the system produces. It is calculated by dividing the annual cost of electricity produced divided by the total annual electrical load served,
$E_{served}$. Since the configuration does not include a thermal load it can be left out of the equation, which results in

$$LCOE = \frac{C_{ann, tot} - c_{boiler} H_{served}}{E_{served}} = \frac{C_{ann, tot}}{E_{served}},$$

where $C_{ann, tot}$ is the total annualized cost of the system, $c_{boiler}$ is the boiler marginal cost and $H_{served}$ is the total thermal load served.

The results of hundreds of power systems modeled in HOMER have been compiled into a diagram showing how the LCOE varies with the renewable penetration (Lilienthal, 2013).

As seen in Figure 6 the modeling results in a visualizing of the LCOE and renewable penetration for a system. The LCOE increases significantly for a system that consists of 100% renewable resources.

To be able to compare the grid extension option with the autonomous micro grid the capital costs, maintaining costs and the electricity price from the main grid need to be determined. The cost of the grid extension is represented in parameters of capital cost [USD/km], O&M cost [USD/year/km] and the grid power price [USD/kWh]. The break-even grid extension distance is the total NPC of the grid extension distance that is equal to the total NPC of the stand-alone system.
3.3 Modeling
Without risking instability or an excessive LCOE, the micro grid is configured and modeled in HOMER. This is to achieve a feasible system with as much renewable power sources as possible. The renewable fraction of the system is calculated by the following equation:

\[
f_{\text{ren}} = 1 - \frac{E_{\text{nonren}}}{E_{\text{served}}} \tag{4.4}
\]

where \(E_{\text{nonren}}\) is the nonrenewable electrical production and \(E_{\text{served}}\) the total served electrical load.

The applied components and the outline of the model are shown in Figure 7. The data for the electrical load of the village is based on previous surveys and approximations (Sreedharan et. al., 2014). The software provides a method to specify a load profile from templates with default magnitudes corresponding to user profiles for communities and residential profiles.

![Figure 7. Schematic outline of model.](image)

![Figure 8. Daily electrical load profile of Natendrapur, India (Sreedharan et. al., 2014).](image)
The hourly values of the template suitable for a community is scaled to fit the village of the case study, see Figure 8.

![Figure 8. Scaled load profile (HOMER Energy, 2016).](image)

Some random variability is added to the daily load profile in order to make it more realistic. This yields a scaled annual load profile as shown in Figure 9, with the annual average of 163 kWh/day. Moreover, a deferrable load is added to the model. Deferrable loads are electrical loads that normally have some storage associated with them and water pumping is one type of a deferrable load (HOMER Energy, 2015). The village in this case study requires a water purifier, i.e. a deferrable load, hence an approximation of the deferrable load of the villages is essential.

Approximately one inhabitant consumes two liters of water a day. A suggested water purifier pump can have an output rate of 500 l/h and an additional storage tank of 2 000 l. The required annual average, $P_{\text{ann,average}}$, is therefore

$$P_{\text{ann,average}} = P_{\text{pump}} \frac{V_{\text{load}}}{V_{\text{capacity}}} = 3\text{kW} \cdot \frac{2l/\text{day} \cdot 1179}{500l/\text{h}} = 14.148 \text{ kWh/day}$$

as the village has 1 179 inhabitants and the maximum pump power, $P_{\text{pump}}$ is 3 kW. The scaled annual average, which is the input used in HOMER, is reduced to 12 kWh/day since the water storage tank is considered to be used as well.

There is a search space for each technology in the software, which is a set of decision variable values that the program uses to find the optimal system. The search space can either represent the power in kW or the quantity for the particular component. Additionally, each component requires cost input parameters, which are the capital cost per kW or per quantity, the replacement cost per kW or quantity and the operating and maintenance cost per kW or quantity.

<table>
<thead>
<tr>
<th>Power Application</th>
<th>Capital</th>
<th>Replacement Cost</th>
<th>Operating &amp; Maintenance Cost</th>
</tr>
</thead>
<tbody>
<tr>
<td>Diesel Generator</td>
<td>500 $/kW</td>
<td>500 $/kW</td>
<td>0.030 $/kW/year</td>
</tr>
<tr>
<td>Solar PV</td>
<td>3000 $/kW</td>
<td>3000 $/kW</td>
<td>10 $/kW/year</td>
</tr>
<tr>
<td>Battery</td>
<td>900 $/Battery</td>
<td>900 $/6V/1231Ah</td>
<td>10 $/Battery/year</td>
</tr>
<tr>
<td>Converter</td>
<td>300 $/kW</td>
<td>300 $/kW</td>
<td>0 $/kW/year</td>
</tr>
</tbody>
</table>

Table 2. Cost parameters for technical components (HOMER Energy, 2016) (Renewable Energy Battery Source, 2016).
The software can provide the model with both dispatchable power sources, such as generators, and with renewable power sources, such as solar and wind power. For this model, a diesel generator is added with possible capacity rates that in this case are the search space. It is set to vary from 0 to 30 kW. The generators cost parameters are shown in Table 2.

Furthermore, the lifetime of the generator is assumed to 15 000 hours and the minimum load ratio is set at 40 % of its rated capacity which implicates that the efficiency of the power output will never drop under a certain level, see Figure 10. The electrical efficiency is calculated with the following equation:

\[
\eta_{\text{gen}} = \frac{3.6 \cdot P_{\text{gen}}}{m_{\text{fuel}} \cdot LHV_{\text{fuel}}},
\]  

(4.6)

where \( P_{\text{gen}} \) is the electrical output, \( m_{\text{fuel}} \) is the mass flow rate of the fuel and \( LHV_{\text{fuel}} \) is the lower heating value.

Additionally, the model is configured with solar flat plate PVs whose cost properties are presented in Table 2. The size range of the PV panel is set to vary from 0 to 65 kW in the search space. The PV cell temperature in full incident radiation increases the ambient temperature by 30 degrees or more. In standard test condition the increased ambient temperature is not considered and the PV manufactures rate the power output at 1 kW/m² and at a cell temperature of 25 °C. The increased ambient temperature is considered when calculating the PV array power output of the model. The PV array power output in real condition is calculated with the following equation:

\[
P_{\text{PV}} = Y_{\text{PV}} f_{\text{PV}} \left( \frac{\bar{G}_T}{\bar{G}_{T,\text{STC}}} \right) \left[ 1 + \alpha_p \left( T_c - T_{c,\text{STC}} \right) \right],
\]  

(4.7)

where \( Y_{\text{PV}} \) is the rated capacity of the array. The PV derating factor is \( f_{\text{PV}} \), \( \bar{G}_T \) is the solar radiation incident on the PV array in the current time step and \( \bar{G}_{T,\text{STC}} \) is the incident radiation at standard test conditions. The temperature coefficient of power is \( \alpha_p \), \( T_c \) is the PV cell temperature in the current time step and \( T_{c,\text{STC}} \) is the PV cell temperature under standard test conditions.
A wind turbine is another potential renewable power source to a micro grid. Considering the low rate of average wind resources, the model in this case study is unlikely to gain any economic or power profit from a wind turbine, as the minimum wind speed for wind turbines to generate acceptable output is between 3.5 m/s (U.S. Department of Energy, 2013). Consequently, the wind turbine will not be considered as a potential power source for the model.

Moreover, the micro grid requires a storage technology. Considering the rural area and limited resources of manpower in the village, battery is a supposable storage application and also a mature technology for this kind of utility area. Several batteries of different manufactures and different properties can be considered in the software as potential storage applications. Nominal voltage [V] and nominal capacity [Ah], the suggested life throughput [kWh] and maximum charge respective discharge current [A] are properties of the battery. Furthermore, the quantity of batteries per string is a specific input parameter, which needs to be set to the standard values such as 24 V or 48 V, in order to be consistent with other standard components which are connected to the bus. The search space that is the possible quantity of batteries must be modified for each battery option since the properties of the potential batteries vary heavily in size, thus the search space needs to be changed for different types of batteries. For this case study the storage technology consists of a lead-acid battery with a nominal voltage of 6 V, which means 4 batteries per string and the cost parameters of the batteries can be found in Table 2.

Furthermore, a converter is required to convert the DC current into AC. The costs of the converter are seen in Table 2. The converter is sized to be able to meet the peak load of 23 kW, which can be seen in Figure 9.

To consider a grid extension as an alternative to a stand-alone system, the applied software compares the cost of the grid extension with the cost of each stand-alone system configuration.

<table>
<thead>
<tr>
<th>Grid Cost</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Capital Cost [$/km]</td>
<td>5 000.00</td>
</tr>
<tr>
<td>O&amp;M Cost [$/year/km]</td>
<td>160.00</td>
</tr>
<tr>
<td>Grid Power Price [$/kWh]</td>
<td>0.10</td>
</tr>
</tbody>
</table>

The estimated input variables are shown in Table 3. The breakeven distance shows when the total NPC are the same between the alternatives and demonstrates the profitable distance for the extension. The capital cost parameter presented in Table 3, are based on estimation for developing countries and does not include site specific transportation costs (NRECA, 2000). The O&M cost and the grid power price is based on default options in HOMER.

The possible dispatch strategies in the software are either load following or cycle charging. Cycle charging means that whenever the diesel generator needs to run to serve the primary load, it will operate at full output power. Excess electricity is then provided to the lower priority objects such as the deferrable load and the battery bank. The parameter, setpoint state of charge (SOC), are
applied to the strategy, which means that once the system starts to charge the battery bank it will not stop until the bank reaches the state of charge. This means that the battery is not allowed to discharge until it has reached the setpoint. For a load following system there are no more parameters to be set.

A sensitivity analysis can be performed in the software by adding multiple values for particular input variables. Thereby, the optimization process is repeated for each value of the variable.

**Table 4. Sensitivity variables.**

<table>
<thead>
<tr>
<th>PV Capital Cost Multiplier</th>
<th>Battery Price Multiplier</th>
<th>Diesel Price Multiplier</th>
<th>Setpoint SOC [%]</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.7</td>
<td>0.7</td>
<td>1.20</td>
<td>60</td>
</tr>
<tr>
<td>0.8</td>
<td>0.8</td>
<td>1.30</td>
<td>70</td>
</tr>
<tr>
<td>-</td>
<td>-</td>
<td>1.50</td>
<td>80</td>
</tr>
</tbody>
</table>

The parameters evaluated in the sensitivity analysis were the capital cost for solar PVs and batteries as well as the diesel price and the setpoint percentage. In Table 4, the exact multipliers of each parameter are presented. The multipliers were chosen to reflect possible future events. The LCOE and the NPC in polygeneration systems are strongly affected by the capital cost of renewable power technologies and also of the cost of the storage technologies. Current technical development can cut cost of the investment capital, which is likely to be shown in the LCOE and NPC values of the sensitivity analysis. Lastly, a potential additional load was added to the optimized system. This was carried out since the load profile in the rural village is likely to increase in the near future. After implementing a polygeneration system and so continuous power supply to the rural area, the demand profile is often increased due to new needs and behavior patterns. It is therefore interesting to investigate if the system configuration is compatible for any additional load. The load profile for the system was change into 190 kWh/day and to 220 kWh/day.

### 3.4 Results and Discussion

The optimized configuration made in HOMER consists of a solar PV, a diesel generator, batteries and a converter.

**Table 5. Optimized results for the system (HOMER Energy, 2016).**

<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>50</td>
<td>20</td>
<td>40</td>
<td>25</td>
<td>0.407</td>
<td>337 457</td>
</tr>
</tbody>
</table>

The choices of the technologies for the system can be motivated by the environmental surroundings on the island and the affordability for the population. The use of solar PVs is a good way of taking advantage of the many sun hours. The high amount of daily radiation is more important than the decrease in efficiency for the PVs caused by the increased temperature. Considering the small fluctuations in the amount of sun hours on the island, the renewable resources are well suited even though they are classified as non-controllable energy supply. Due to the small amount of buildings in the area there are also enough space for a solar plant. The lack of high wind speed made it non-profitable to use wind power in the system. The choice of
complementing the renewable solar power with a diesel generator is to make the system more reliable. Diesel generators are commonly used in polygeneration systems in rural areas because of its low cost. The batteries were chosen because of its suitability for the rural area with the low need of maintenance and simplicity of installation. Moreover, batteries as storage are a mature and frequently used type of storage in rural areas.

The result of the LCOE is 0.407 USD/kWh and the NPC is 337 457 USD when the diesel price is set to 1 USD/l. Moreover, the capacities for the technologies are presented in Table 5. The system consists of 79 % renewable energy production and the operational strategy is controlled by load following.

![Figure 11. Capital cost for technologies in the optimized system (HOMER Energy, 2016).](image)

The capital cost for each component is visualized in Figure 11, where the solar PV has the highest capital cost.

<table>
<thead>
<tr>
<th>Component</th>
<th>Capital Cost [$]</th>
<th>Replacement Cost [$]</th>
<th>O&amp;M Cost [$]</th>
<th>Fuel Cost [$]</th>
<th>Salvage Value [$]</th>
<th>Total [$]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Solar PV</td>
<td>150 000</td>
<td>-</td>
<td>6 463</td>
<td>-</td>
<td>-</td>
<td>156 464</td>
</tr>
<tr>
<td>Diesel Generator</td>
<td>10 000</td>
<td>8 889</td>
<td>11 728</td>
<td>68 461</td>
<td>1 149</td>
<td>97 928</td>
</tr>
<tr>
<td>Batteries</td>
<td>36 000</td>
<td>33 106</td>
<td>5 171</td>
<td>-</td>
<td>3 142</td>
<td>71 135</td>
</tr>
<tr>
<td>Converter</td>
<td>7 500</td>
<td>3 182</td>
<td>-</td>
<td>-</td>
<td>560</td>
<td>10 083</td>
</tr>
<tr>
<td>Emission Penalties</td>
<td>-</td>
<td>-</td>
<td>1 847</td>
<td>-</td>
<td>-</td>
<td>1 847</td>
</tr>
<tr>
<td>System</td>
<td>203 500</td>
<td>45 177</td>
<td>25 210</td>
<td>68 461</td>
<td>4 891</td>
<td>337 457</td>
</tr>
</tbody>
</table>
The initial capital cost of the system with all its components is 203 500 USD with and operating cost of 25 210 USD/year. The CO₂ emission from the diesel generator is 13 945 kg/year. Further on, Table 6 shows all calculated costs and salvage values for the components as well as the system for the project lifetime of 25 years.

The cash flow chart, as seen in Figure 12, shows the time perspective of when different costs are appearing during the life cycle of the system. This includes replacement, operating, fuel and capital costs. The salvage value appears at the end of the life cycle showing the remaining value of the assets. Considering that the salvage value is positive, the system still holds an economic value.

The diesel generator is utilized in combination with the use of solar PVs. The use of the diesel generator increases during the peak season from June to September, which is seen in Figure 13. In theory, a polygeneration system with 100 % renewable resources would be the ideal configuration since it would eliminate the CO₂ emissions. The problem with implementing this kind of system at the island would be the increased LCOE since one of the most important aspects for a rural village is to cut costs. The configured system consists of 79 % solar PVs which is probably as high as it can be considering elevating costs and reliability of supply. The possibility to store the energy from the solar PVs is vital to have such a high percentage of renewable resources in the system, though it is often an expensive solution. One critical aspect of using HOMER as a tool to configure the system is that all the different technologies presented in the literature study was not available in the software, especially for storage options. Increasing the number of different technologies secures the system by spreading the risk for a system shut down.
if a component needs to be replaced or repaired. This way the electricity supply is not as dependent on only one source.

![Figure 14. Grid extension cost (HOMER Energy, 2016)](image)

The breakeven distance for extending the main grid in comparison to using the isolated microgrid is 36.01 km, which is presented in Figure 14. The distance from the island to main land is approximately 3 km and it is about 26 km from Natendrapur to main land. The result from the grid extension evaluation shows that it could be more profitable to extend the main grid to the village of Natendrapur. An essential assumption for this statement is that there are any main grid extension possibilities in the area of the main land coast close to Sagar Island. Otherwise, a longer distance would be required and that would result in additional costs, which can motivate an implementation of a polygeneration system in Natendrapur.

### 3.5 Sensitivity Analysis

To investigate the case study further, a sensitivity analysis of the optimization was carried out. The sensitivity analysis is based on reasonable future fluctuations of those input parameters that the user cannot control. The analysis contributes to the evaluation of the uncertainty in the system. The result of the varied sensitivity parameters of the original model assessed changes in the cost parameters.

<table>
<thead>
<tr>
<th>Sensitive SOC [%]</th>
<th>PV Capital Cost Multiplier</th>
<th>Battery Price Multiplier</th>
<th>Diesel Price Multiplier</th>
<th>LCOE [$/kWh]</th>
<th>NPC [$]</th>
</tr>
</thead>
<tbody>
<tr>
<td>-</td>
<td>0.7</td>
<td>0.7</td>
<td>1.30</td>
<td>0.365</td>
<td>302,195</td>
</tr>
<tr>
<td>-</td>
<td>0.8</td>
<td>0.8</td>
<td>1.20</td>
<td>0.379</td>
<td>313,949</td>
</tr>
<tr>
<td>-</td>
<td>1</td>
<td>1</td>
<td>1.50</td>
<td>0.448</td>
<td>371,688</td>
</tr>
</tbody>
</table>

In Table 7, some of the different sensitivity states that were optimized in HOMER are presented. As stated in the previous section, the original solar PV capital cost and the battery capital cost of the optimized model yields relatively high LCOE and NPC. The LCOE and NPC of different sensitivity cases with lower capital costs are presented. When the capital costs of the PV and the batteries are decreased by 30% and by 20%, both the LCOE and NPC are decreased, even
though the diesel price is increased with the same percentages. In Table 7 there are no alternatives of setpoints, which is because each sensitivity case is controlled by load following. Due to small changes of cost parameters, the system size remained the same. Lastly, the original model was not able to work with any of the increased load profiles.

A reasonable prediction for the near future would be an increased diesel price and that the load would increase. The configured model is not suitable for an increasing load if not the capacity of one or more components are increased. The sensitivity cases are therefore foremost a base for a discussion of cost changes. The capital cost of solar PVs or any renewable generator will probably decrease in the future since the research and product development in this field is advancing and the amount of stakeholders on the market is increasing. The system life cycle is predicted to 25 years but the load profile will probably not be the same for that amount of time. The unpredictable future demand from the village makes it difficult to size the system. There is a conflict between oversizing the system to meet future demand or to design a system that covers the current demand, in the implementation phase. The system should not be oversized in order to keep low costs for the population. At the same time, it is important to have the possibility to meet an increased load in the near future. The increased amount of startup business and improved standard of living will definitely challenge the system capacity. An alternative to oversizing could be a system design with the ability to easily add components to the micro grid. The estimated load profile of today consists of an electrical load but the need of a thermal load could also be required in the future.

4 Conclusions and Future Work
An implementation of a polygeneration system is a complex process of multiple aspects. The outcome of energy supply is rarely the only consequence to be considered when implementing a polygeneration system, regardless of implementing it in a developed or developing country. Desirable outcomes and results vary between a developed and developing country. However, the related aspects of the implementation need to be considered and studied to accomplish the desired results. It is essential to elaborate the end users’ needs of power. In a developing country, it is not only a reliable source of energy that needs to be promoted. Also, possibilities and benefits connected with electricity access such as job opportunities, simplified health care and educational opportunities are the kind of outcomes that brings value for a customer in a developing country. On the other hand, these kinds of promotions are not the most suitable for customers in a developed country, since the basic needs tend to already be covered. The focus of promotion should rather be on environmental responsibility of each individual and a cost effective energy system. Community, country and stakeholders must all be approached with the beneficial outcome from their point of view. In other words, each party can gain from an implementation despite that the outcomes may have different values for each of them.

In conclusion, the configuration of a polygeneration system is strongly dependent on the economic situation of the target group. The choice of technologies is anyhow controlled by all aspects that affects the target group. Power technologies in polygeneration systems are therefore more often from renewable sources in developed countries than in developing countries. Therefore, the results from this case study are likely to have different outcomes if additional and more accurate data were evaluated. In addition, surveys of the actual situation in the specific village, such as the willingness to pay, would be helpful to elaborate the model. This kind of
surveys would clarify the situation of the customers and make it easier to predict future demand. Further analyses of laws, the influence of certain power companies, and possible financial aids in India would provide more useful information for the optimization.

Additional future work in this area is to evaluate future demand and load profiles in order to configure a long-term sustainable polygeneration system. Also, technologies that were not available in HOMER could be possible components, which could have decreased cost or added sustainability to the system.
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<table>
<thead>
<tr>
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</thead>
<tbody>
<tr>
<td>Typical Size Range</td>
<td>20 kW - 20 MW</td>
<td>4 - 25 kW</td>
<td>30 - 250 kW</td>
<td>200 kW -</td>
<td>1 kW -</td>
<td>(Heat exchange/collector)</td>
<td>5 kW – 5 MW</td>
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<tr>
<td>Representative Power Efficiency Range (%)</td>
<td>28 - 49</td>
<td>10 - 25</td>
<td>18 - 20</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>35 - 60</td>
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<tr>
<td>Thermal Efficiency (%) / Power to Heat Ratio</td>
<td>- / 0.9 - 2</td>
<td>40 - 80/3 - 3.3</td>
<td>50/1.6 - 2</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>- /0.9 - 1:1</td>
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<td>Total Efficiency (%)</td>
<td>75 - 85</td>
<td>70 - 90</td>
<td>80</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>75 - 85</td>
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<td>Fuel Options</td>
<td>Diesel Natural Gas Alternatives</td>
<td>Natural Gas Alternatives</td>
<td>Natural Gas Alternatives</td>
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<td>Renewable Resource</td>
<td>Renewable Resource</td>
<td>Hydrogen Natural Gas</td>
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<td>Thermal Outputs</td>
<td>Heat Hot Water Low Pressure Steam</td>
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<td>Heat Hot Water Low/High Pressure Steam</td>
<td>-</td>
<td>-</td>
<td>Heat in Liquid medium/ Gas</td>
<td>Hot Water Low/High Pressure Steam</td>
</tr>
<tr>
<td>Power Density (kW/MW)</td>
<td>35 - 50</td>
<td>3-15</td>
<td>5 - 70</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>5 - 20</td>
</tr>
<tr>
<td>Min Start Time</td>
<td>10 s</td>
<td>30 s</td>
<td>60 s</td>
<td>Immediate</td>
<td>Immediate</td>
<td>Immediate</td>
<td>Immediate</td>
</tr>
<tr>
<td>Required Fuel Pressure (psig)</td>
<td>1 - 45</td>
<td>1-50</td>
<td>50 - 80 (compressor)</td>
<td>NA</td>
<td>NA</td>
<td>NA</td>
<td>0.5 - 45</td>
</tr>
<tr>
<td>Noise</td>
<td>Moderate</td>
<td>Low</td>
<td>Moderate</td>
<td>Low</td>
<td>None</td>
<td>None</td>
<td>None</td>
</tr>
<tr>
<td>Preferred Applications</td>
<td>Power CHP Mechanical Drive</td>
<td>Power CHP</td>
<td>Power</td>
<td>Power</td>
<td>Power</td>
<td>Heat</td>
<td>Power</td>
</tr>
</tbody>
</table>