“Commercialization possibilities of Small scale biomass power plant in Japan”

Ryo Nakakido
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Abstract

After the great east earthquake in 2011, Japan has been under strong pressure for a restructuring of the energy supply structure. The Fukushima nuclear power plant accident, caused by an earthquake triggered giant tsunami, brought force to the shutdown of almost all nuclear plants in Japan and a national discussion on future energy structure arose. In 2012, a revised feed-in tariff was enforced, and Japanese energy policy has changed its direction to promote the introduction of renewables. Against the background, the aim of the thesis is to do a feasibility study of small-scale biomass power plant in Japan.

Small scale biomass plants are expected to play an important role in the future expansion of distributed generation. It has been developed with its great advantages over other renewable resources for power generation such as high stability of power generation and high total energy conversion efficiency with CHP or tri-generation technology. In 2015, the Japanese government increased the purchase price of electricity from wood chip fueled small scale (< 2 000 kW) biomass power plants to 40 JPY/kWh (0.29 Euro) to promote implementation of small scale biomass plant.

In this study, three electricity generating technologies were chosen as promising options: Steam cycle, ORC (Organic Rankine Cycle) and gasification connected to an internal combustion engine.

NPV and IRR method were used to evaluate the feasibility of projects with the technologies, and it is found that none of the projects can be feasible in power only generation mode even under the high FIT price in Japan. In CHP mode, all technologies are feasible in specific ranges. Steam cycle plant is feasible in 1000 kW or larger plant and NPV reaches around 983 million JPY in 2000 kW plant. IRR is 12.4 % in the plant, but the steam cycle plant is susceptible to input parameters change especially fuel cost and the selling price of heat. As the values can fluctuate over the plant operation period, it poses a great risk to the project. ORC plant is also feasible in 1000 kW or larger plant, and NPV reaches 1,592 million JPY in 2000 kW plant. The IRR of the plant is 13.2 %, and it is the best values among the plants examined in this study. ORC plant is relatively insusceptible to parameter changes, but changes in fuel cost, capacity factor, and capital cost still has a measurable impact on the project’s feasibility. Gasification plant is feasible in all capacity ranges, and it is relatively competitive in smaller than 1000 kW plants. In 360 kW plant, NPV is around 43.6 million JPY and IRR is 6.5 %. In gasification, capacity factor is the critical factor which has the largest impact on the feasibility of the project.


**Acknowledgement**

I would like to express the deepest appreciation to my supervisor Dr. Anders Malmquist at the Department of Energy Technology at KTH for consistent guidance and support to complete this study.

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In closing, I would like to thank my parents for their continuous support.
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Nomenclature

ANRE – Agency for Natural Resource and Energy, Japan
BFB – Bubbling fluidized bed
CFB – Circulating fluidized bed
CHP – Combined Heat and Power
EIA – U.S. Energy Information Administration
EPCOs – Japan’s ten vertically integrated electricity power companies
FBC – Fluidized bed combustion
GEU – General Electricity Utilities
IRR – Internal Rate of Return
JPY – Japanese Yen
JREF - Japan Renewable Energy Foundation
MAFF – Ministry of Agriculture, Forestry and Fisheries, Japan
METI – Ministry of Economy, Trade and Industry, Japan
NEDO – New Energy and Industrial Technology Development Organization
NPV – Net Present Value
OCCTO - Organization for Cross-regional Coordination of Transmission Operators, Japan
PPS – Power Producer and Supplier
RET – Renewable Energy Technology
RPS – Renewable Portfolio Standard

LHV_{gas} – Low Heating Value of the gas
LHV_{biomass} – Low Heating Value of the biomass
V_{gas} – volume of the gas
V_{biomass} – volume of the biomass
CF_k – Cash flow of year k
C_{capital} – Capital cost of the project
C_{capital,tot} – Total capital cost
C_{capital,unit} – Unit cost of the capital
PC_{installed} – Installed capacity of the power plant
m_{fuel} – Mass of consumed biomass fuel
LHV_{fuel} – Low heating value of the fuel
CapacityFactor - Capacity factor of the plant
Eff_{el} - Electrical efficiency of the plant
C_{fuel} – Cost of fuel
C_{fuel,unit} – Unit cost of fuel
C_{labor} – Cost of labor
N_{labor} – Number of labor
C_{labor,capita} – Cost of labor per capita per year
C_{maintenance} – Cost of plant maintenance
C_{utility} – Utility cost of the power plant
C_{operating} – Total operating cost
R_{el} – Revenue from electricity sales
P_{el} – Produced amount of electricity from the plant
\varepsilon_{Auxiliary} – Auxiliary power ratio in the power plant
P_{el,unit} – Unit price of electricity
R_{thermal} – Revenue from heat sales
P_{thermal} – Produced amount of heat from the plant
P_{thermal,unit} – Unit price of heat
1 Introduction

After the great east earthquake in 2011, Japan has been under strong pressure for restructuring of the energy supply structure. The Fukushima nuclear power plant accident, caused by an earthquake triggered a giant tsunami, brought force to the shutdown of almost all nuclear power stations in Japan and a national discussion on future energy structure arose. In 2012, a revised feed-in tariff was enforced and Japanese energy policy has changed its direction to promote the introduction of renewables.

Small scale biomass plants are expected to play an important role in the future expansion of distributed generation. It has been developed with its great advantages over other renewable resources for power generation such as high stability of power generation and high total energy conversion efficiency with CHP or tri-generation technology. This market has already been rapidly growing in many countries such as Sweden, Finland and Germany with strong political support and geographical advantages and is contributing to an increased share of renewable energy based power generation. In 2015, the Japanese government increased the purchase price of electricity from wood chip fueled small scale (< 2 000 kW) biomass power plants to 40 JPY/kWh (0.29 Euro) to promote the implementation of the small-scale biomass plant. However, the Japanese small scale biomass business is in an early stage and is facing many challenges such as lack of biomass supply chain, no infrastructure for district heating supply and low energy conversion efficiency because of undeveloped biomass energy technology. To overcome the issues, establishment of a representative model case of small-scale biomass power plant optimized for Japanese environment is critically needed. The aim of this study is to do a feasibility study of a wood chip fueled small scale biomass plant in Japan.

2 Methodology

To conduct the feasibility study of small-scale biomass plant in Japan, this thesis will include the following steps:

In the first step, all background information such as Japanese energy structure, relevant regulations and basic classification of available technology for small-scale biomass power generation will be corrected to get a big picture of existing small-scale biomass-based power generation in Japan.

After that, actual and more detailed data will be collected by several study visits in Japan. The study visits will be taken place at in-service small-scale biomass plants to get to know actual situation of small-scale biomass power generation in Japan. The information will be obtained by collecting local input at in-service plants and actual available energy technologies information from manufacturers. Interviews with key persons in Japan’s biomass power generation industry will also be done.

After the all information collecting, several candidate technologies will be chosen and a detailed evaluation of the technologies will be carried out from both technical and economic perspectives. The evaluation will also include a sensitivity analysis of the project.
3 Background

3.1 Current energy situation in Japan

3.1.1 Japan’s power sector today

Figure 1 shows total primary energy source trend in 1972 – 2012. In early 1970’s, a large part of the total primary energy was supplied by oil and coal. After oil shocks of the 1970’s, Japan has started to diversify the energy resources and began to increase the use of nuclear energy and natural gas. The total primary energy supply had been keeping increasing from early 1970’s to end of 1990’s and then had been stable around 500,000 ktep until Fukushima nuclear power plant accident occurred in 2011 and all nuclear power plant was shut down.

![Figure 1: Total primary energy source trend in 1972 – 2012 (IEA 2014)](image)

Japan’s power sector is characterized by an extremely low self-sufficient rate of primary energy supply. Owing to the inadequacy of its domestic energy resources, Japan is a country which heavily depends on overseas fossil fuels. It is the world’s largest importer of liquefied natural gas, the second largest coal importer and the third largest crude oil and oil products importer in the world (EIA 2014). In 2008, the self-sufficient ratio was only 4% which results from hydropower, geothermal power, solar power, biomass power and so on. 99.6% of petroleum supplies, 96.7% of natural gas supplies and 100% of coal supplies were supplied by importing (Goto et al. 2012). In 2013, the total energy consumption in Japan was 361 billion liters of crude oil equivalent and 25% of the total consumption was electricity and the rest was heating, gasoline, natural gas, etc. (METI 2015). The amount of energy imported stays around 85% of the total amount (EIA 2014).

The following points have been claimed as structural issues of the power sector faced by Japan (ANRE 2014):

- Fundamental vulnerability of the energy supply system due to high dependency on overseas energy resources.
- Profound economic impact by the instability of resources price due to increased energy demand in emerging countries, regional conflicts and changes in economic conditions, etc.
- High greenhouses gas emissions due to high oil dependent energy structure.
In addition to the situation, the great east earthquake and Fukushima nuclear power plant accident occurred in March 2011 and all nuclear power plant was shut down. It arouses national discussion for future energy supply structure, and some policies had been set for structural reforms. This will be described in following sections.

3.1.2 Electricity generation

Japan’s electricity market is mainly consisting of ten vertically integrated electricity power companies which are called EPCOs. Figure 2 shows the electricity distribution system overview of Japan. One of the unique characteristics of Japan’s electricity distribution system is the regional monopoly by EPCOs. Each EPCO is located in different region – Hokkaido, Tohoku, Tokyo, Hokuriku, Chubu, Kansai, Shikoku, Chugoku and Kyushu, and it almost dominates the electricity market in their located region. Total market volume in 2013 was 982.4 TWh, and ten big EPCOs accounted for 86 % (848.5 TWh) of the total. The electricity market is open for over 50 kW customers (62 % of the total in 2013) but the share of non-EPCOs in 2013 was only 4.2 %, and there is almost no competition between each EPCO (ANRE 2015).

The other unique characteristic of Japan’s electricity distribution system is the fact that the country is divided into two regions each running at a different frequency. This occurred because of a lack of communication between EPCOs in Tokyo and Kansai. The first generator in Tokyo was purchased from AEG in 1985, and the first generator in Kansai was purchased from GE in 1896.

![Figure 2: Japan's electricity distribution system overview](ANRE 2015)

The problem regarding the frequency difference came up to the surface after the great east Japan earthquake in 2011. The Fukushima nuclear power plant accident caused by an earthquake triggered giant tsunami brought a severe lack of electricity supply in Tohoku and Tokyo region. However, electric power interchange from other region was very limited because of limitations in the capacity of the frequency conversion facilities between Tokyo and Chubu, and it created a situation that the disaster victims were facing an electric power crisis even if the other region in Japan had sufficient ability to supply the electricity. This fact became one of the strong driving forces of deregulation of Japan’s electricity market, and it will be described in the next section.

3.1.3 Deregulation of Electricity Market

After the great east Japan earthquake, the following negative aspects caused by vertical integration of EPCOs raised up to surface: lack of a system to transmit electricity beyond regions, little competition and
strong price control and limitations in handling the change in energy mix including the increase of renewables (ANRE 2015).

On April 2, 2013, the cabinet voted for the “policy on electricity system reform” which contains three objectives: securing a stable supply of electricity, suppressing electricity rates to the maximum extent possible and expanding choices for consumers and business opportunities and the following three steps to achieve this objective was presented from the cabinet (ANRE 2015). Figure 3 shows the roadmap for electricity market reform in Japan.

1st step: Establish the organization for cross-regional Coordination of Transmission Operators (April 2015)

The Organization for Cross-regional Coordination of Transmission Operators (OCCTO) was established in April 2015. OCCTO will work as a coordination institution for EPCOs supply-demand and grid plan sector, and it can order EPCOs to change the plans to make transmission line more efficient and well-coordinated (OCCTO). Another main function of OCCTO is to order EPCOs to reinforce generations and power interchanges under a tight supply-demand situation (ANRE 2015).

2nd step: Full retail competition (April 2016)

A current business license under the Electricity Business Act is divided into three categories: GEU (General Electricity Utilities), PPS (Power Producer and Supplier) and Wholesale Electricity Utilities, etc. While GEU (10 EPCOs) supplies electricity to customers, including those in the regulated sector with the obligation to supply, PPS is allowed to supply electricity only for customers in liberalized sector which have more than 50kW capacity. From April 2016, the retail market in the residential sector will be opened for PPS in addition to GEU. For full retail choice, business license categories under the electricity business act will also be revised. The licenses will be divided into Generation, Transmission & Distribution, and Retail categories, and each company will get required licenses depend on their business area. (ANRE 2015)

3rd step: Unbundle the transmission/distribution sectors of EPCOs

The transmission/distribution sectors in EPCOs will be unbundled by 2020. There are mainly two main aims for the unbundling. One of these is to ensure neutral transparent power transmission and distribution to decrease entry barriers for new generating company and boost competition in the market. It will also encourage the diversification of business at the retail level. The other is to ease transmission functions across a border area. It is expected to promote the implementation of renewable energies which vary from region to region (Itoh 2012).

Figure 3: Roadmap for Electricity Market Reform (ANRE 2015)
3.1.4 Feed-in tariff

After the Fukushima nuclear power plant accident, all nuclear power plants in Japan were forced to shut down and the deficiency was covered by thermal power generation. The share of thermal power generation reached around 90% in total electricity generation in 2012, and it made Japanese energy system as a high cost, high CO₂ emission and more vulnerable to an overseas condition such as a conflict in the middle east. The situation arouses national discussion on current and the future energy demand and supply system and reduces its dependency on nuclear power and greatly expansion of renewable energy supply has been set as a long-term target for future energy demand and supply system.

In July 2012, Feed-in tariff (FIT) scheme was enforced by replacing RPS (Renewable Portfolio Standard) law and existing solar FIT. In the feed-in tariff scheme, electricity utility supplies renewable energy sourced electricity which is purchased at a fixed price for government fixed period to electricity consumers and collect surcharge together with the electricity charge. The surcharge price, tariffs and its durations is decided by the Ministry of Economy, Trade and Industry, Japan (METI). The surcharge price, tariffs and its durations will be revised every fiscal year (METI 2013). Table 1 shows the time series of FIT price in Japan.

Table 1: Time series of FIT price in Japan (IEA 2015)

<table>
<thead>
<tr>
<th></th>
<th>Purchase price (JPY/kWh) (tax excluded)</th>
<th>Purchase period</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>FY2012</td>
<td>FY2013</td>
</tr>
<tr>
<td>Solar</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Less than 10 kW</td>
<td>42</td>
<td>38</td>
</tr>
<tr>
<td>10 kW or more</td>
<td>40</td>
<td>36</td>
</tr>
<tr>
<td>Double generation system (Less than 10 kW)</td>
<td>34</td>
<td>31</td>
</tr>
<tr>
<td>Wind</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Onshore Less than 20 kW</td>
<td>55</td>
<td>55</td>
</tr>
<tr>
<td>20 kW or more</td>
<td>22</td>
<td>22</td>
</tr>
<tr>
<td>Offshore</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Geothermal</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Less than 15,000 kW</td>
<td>40</td>
<td>40</td>
</tr>
<tr>
<td>15,000 kW or more</td>
<td>26</td>
<td>26</td>
</tr>
<tr>
<td>Fully new facilities</td>
<td>Less than 200 kW</td>
<td>34</td>
</tr>
<tr>
<td>200-1,000 kW</td>
<td>29</td>
<td>29</td>
</tr>
<tr>
<td>1,000-30,000 kW</td>
<td>24</td>
<td>24</td>
</tr>
<tr>
<td>Hydro</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Less than 200 kW</td>
<td>25</td>
<td>25</td>
</tr>
<tr>
<td>200-1,000 kW</td>
<td>21</td>
<td>21</td>
</tr>
<tr>
<td>1,000-30,000 kW</td>
<td>14</td>
<td>14</td>
</tr>
<tr>
<td>Biogas</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Wood (forest thinning) Less than 2,000 kW</td>
<td>39</td>
<td>39</td>
</tr>
<tr>
<td>2,000 kW or more</td>
<td>32</td>
<td>32</td>
</tr>
<tr>
<td>Wood (others), Crop residue</td>
<td>24</td>
<td>24</td>
</tr>
<tr>
<td>Wood (recycled waste materials of buildings)</td>
<td>13</td>
<td>13</td>
</tr>
<tr>
<td>Waste materials</td>
<td>17</td>
<td>17</td>
</tr>
</tbody>
</table>

* FY2015 (1): from April 1 to June 30, (2): from July 1
* When generators are required to install output control equipment, 35 JPY/kWh
* Photovoltaic generation + storage battery or fuel cell
* When generators are required to install output control equipment, 29 JPY/kWh

When the FIT was enforced on July 2012, the speculative bubble in solar PV market occurred as the settled FIT price of solar PV (42 JPY/kWh) was much higher than market expectation. As shown in Table 2, operational capacity of solar PV had increased drastically from July 2012, and it accounted for around 95% of total renewable energy capacity in March 2015. The FIT price of solar PV has gradually lowered and the price was settled as 27 JPY/kWh which is only 2/3 of the first solar PV FIT price in July 2012. On the contrary, implementation of other renewable energies especially biomass have not well promoted by
FIT and still shows quite a low share in electricity generation. From April 2015, FIT price for under 2MW biomass generation with unused (waste) wood was revised from 32 JPY to 40 JPY, and it is expected to be a strong driving force to expand biomass power generation in Japan.

Table 2: Operational Renewable Energy Capacity under FIT (Japan Renewable Energy Foundation 2015)

<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Photovoltaic &lt;10kW</td>
<td>969.21 MW</td>
<td>1307.2 MW</td>
<td>820.63 MW</td>
</tr>
<tr>
<td>Photovoltaic ≥10kW</td>
<td>704.05 MW</td>
<td>5735.44 MW</td>
<td>8571.46 MW</td>
</tr>
<tr>
<td>Wind</td>
<td>62.63 MW</td>
<td>46.93 MW</td>
<td>221.13 MW</td>
</tr>
<tr>
<td>Small hydro</td>
<td>1.73 MW</td>
<td>3.87 MW</td>
<td>83.77 MW</td>
</tr>
<tr>
<td>Geothermal</td>
<td>0.05 MW</td>
<td>0.09 MW</td>
<td>4.65 MW</td>
</tr>
<tr>
<td>Bioenergy</td>
<td>30.4 MW</td>
<td>91.94 MW</td>
<td>101.6 MW</td>
</tr>
<tr>
<td>Total</td>
<td>1768.06 MW</td>
<td>7185.46 MW</td>
<td>9803.23 MW</td>
</tr>
</tbody>
</table>

3.2 Biomass as a fuel

3.2.1 Biomass power generation in Japan

Biomass power generation is expected to play an important role in Japan’s future energy supply system. It has advanced characteristics compare to other renewable resources such as stable energy supply and high overall efficiency with co- or tri-generation technology. Regarding biomass resources, Japan is relatively biomass resources-rich country. Total forest area is around 25 million hectares, and it is 66% of land area. Growing stock is 4.9 billion cubic meters, and it indicates 195 m$^3$/hectares and 38.5 m$^3$/person (FAO 2014). As it is explained in the previous sections, feed-in tariff scheme was enforced in 2012. The purchase price of electricity is revised every fiscal year, and from 2015, 40 JPY/kWh has been set to less than 2,000kW plant with forest thinning wood to promote utilization of unused wood in small-scale biomass power generation.

Map of biomass power generation plants in Japan is shown in Figure 4. Currently, 46 biomass power plants are in operation in Japan, and 58 plants are under construction or planning (FT carbon 2015). Most of the biomass power plants are relatively big as almost all plant are over 2MW, and it is reported that some conflicts are already happening in some region such as Miyazaki, where 4 of more than 5 MW plants are located.
Summary of the changes in wood demand and supply in Japan is shown in Figure 5. The modern forestry industry and wood demand/supply changes in Japan are roughly divided into three periods (MAFF 2015):

- **Demand expansion period (after World War II to around 1973)**

  During the recovery period after the World War II, Japan was in a rapid economic growth period and domestic wood demand expanded rapidly due to the rapid increase of new housing starts and paper and paperboard production. The wood demand reached 117.6 million m$^3$ in round wood equivalent which is about 2.1 times of that in 1976 while a number of new housing starts reached 1.91 million which is about 4.3 times of that in 1960, and production of paper and paperboard was reached 13 million tons which are about 2.6 times of that in 1960. Although domestic wood supply was increased in the beginning by following the demand expansion, the increasing peaked out in 1967 because of forest resource constraint which was available at that time. In that situation, wood importing was liberalized partly in 1960 and fully in 1964 to meet the wood demand, and the importing wood had become the mainstream in wood market.

- **Stagnant Demand Period (from around 1973 to around 1996)**

  After 1973, although the paper and paperboard production was still keep increasing, the number of new housing starts had begun to decrease and thus the total wood demand stayed around 100 million m$^3$. During the period, the wood price had declined continually while forest management costs increased by contrast. It made it difficult to make a profit from forestry, and domestic wood supply had started decline and the decline continued until 2002.

- **Demand Decline Period (from around 1996 - )**

  In addition to new housing starts, the wood demand for wood chip and pulp were also on decline trend from around 1996 and thus the total wood demand had begun to decline. In 2009, total wood demand dropped below 70 million m$^3$ for the first time in 46 years, and it was almost only 60 % of peak amount of that in 1973. Although the supply of domestic wood turned to upward trends since 2002 and keeps increasing along with decreasing of round wood and wood products importing, the total supply of domestic was around 21 million in 2014 which was less than half of that in 1967.
3.2.2 Energy conversion technologies for woody biomass

Biomass, especially from an energy perspective, is defined as organic matter, especially plant matter that can be converted to fuel. It consists of 45-55 % carbon, 40-50 % of oxygen, 5-7 % of hydrogen and nitrogen (0-0.5%) and sulfur (0-1.0%) on dry mass basis (RET 2014). Although atomic components of biomass are same, other important parameters such as moisture content and ash content are quite varied and thus heating value in different biomass material is varied over a wide range. Thus, energy engineering application of the biomass is the varied and technical choice for the proper process on specific biomass material is of great interest for maximizes utilization of biomass resources.

Figure 6 shows the main biomass conversion techniques and processes.
Energy conversion technologies for biomass are mainly divided into two processes: thermochemical conversion and biochemical conversion.

**Thermochemical conversion**

Thermochemical conversion processes include three technologies - Direct combustion, Gasification, and Pyrolysis.

**Direct combustion**: Direct combustion is the oldest biomass energy conversion process. With high temperature (around 800 degrees or more) in the direct combustion process, biomass reacts with oxygen in the atmosphere and is decomposed into several substances. Generated heat in the process is used for heating or further energy conversion processes for electricity generation.

**Gasification**: The aim of gasification is to generate a combustible gas called product gas. It consists of combustible gasses such as H₂, CO₂ and CH₄ and the composition is adjusted for further processes such as using for combustion in a gas turbine or gas engine, or as fuel for fuel cells.

**Pyrolysis**: The aim of pyrolysis is to obtain a charcoal and liquids such as oil. In this process, decomposition of the biomass occurs at a high temperature in the complete or nearly complete absence of oxygen atmosphere and various substances are generated as a product such as charcoal, oil, and combustible gas. Gasification is a type pyrolysis and the conversion technology is chosen on the basis of required product.
Biochemical conversion

Biochemical conversion processes include digestion and fermentation.

Digestion:

The aim of this process is to obtain a product gas from biomass with high water content. Anaerobic digestion is a microbial conversion method, and thus, all biomass containing high water levels such as organic waste, manure, and straw except wood can be processed without any pre-treatment. The product gas typically consists of 65% CH₄, 35% CO₂ and trace gases such as H₂S, H₂, and N₂ (Appels et al. 2011).

Fermentation:

The aim of this process is to produce ethanol by microorganism’s activity such as yeast or bacteria. The main difference from anaerobic digestion is the final product, energy-rich gas from anaerobic digestion and ethanol from the fermentation process.

For small scale woody biomass application, thermochemical, especially combustion and gasification are the most suitable technology in general. Therefore, further examine of both technologies will be done in the following section.

3.2.3 Biomass combustion

Biomass combustion is one of the oldest biomass conversion systems. It has been used for a wide range of applications such as heating, lighting, cooking, chemical and charcoal production and generation of steam and electrical power.

In biomass combustion, there are three types of combustion: perfect combustion, complete combustion, and incomplete combustion. Perfect combustion is achieved when all the fuel is burned with only the stoichiometric amount of air. Complete combustion is achieved when all fuel is burned with only a minimal amount of air above the stoichiometric amount of air needed for the combustion. Incomplete combustion occurs when all the fuel is not burned (Teir & Teir 2002).

The basic stoichiometric equation for the biomass combustion, which represented by the empirical formula of cellulose (C₆H₁₀O₅), is illustrated by following equations (Donald L. Klass 1998).

\[
(C₆H₁₀O₅)_n + 6nO₂ → 6nCO₂ + 5nH₂O
\]  \hspace{1cm} (3.1)

In the ideal case, a stoichiometric amount of oxygen is reacting with biomass so that complete combustion occurs. The stoichiometric combustion of 1 kg of dry wood at standard temperature and pressure needs about 1.4 kg of oxygen and produce 1.8 kg of CO₂, and release about 20 MJ of heat (RET 2014).

However, perfect combustion will not occur in reality. Providing of just a stoichiometric amount of oxidizer cannot complete the reaction with fuel within limited combustion time. Therefore, providing of excess air is necessary for complete combustion within a reasonable time limit (Compedu). Figure 7 shows the theoretical flame temperature for wood combustion with various moisture contents and excess air.
As it can be seen from the figure, flame temperature is drastically changed by an increase of moisture content and excess air. The increase of excess air result an increasing of flame temperature, and which leads a risk of hazardous NO\textsubscript{x} formation. The temperature rise also depends on combustion technology type, so the proper selection of combustion technology and also excess air control is the key factor for proper combustion with hazardous material emission control.

In principle, combustion technologies for biomass are distinguished into following three technologies: Fixed bed combustion, Fluidized bed combustion and pulverized fuel combustion. Figure 8 shows a schematic of the principle combustion technologies.

Figure 7: Theoretical flame temperature vs. wood moisture content and excess air (Donald L. Klass 1998)

Figure 8: Principal combustion technologies for biomass (Koppejan & van Loo 2012)
Fixed bed combustion:

Fixed bed combustion includes grate furnaces and underfeeds stokers. In fixed bed combustion, primary air is fed from the bottom of the fixed bed and drying, gasification and charcoal combustion will occur on the bed. The produced combustible gases are burned after secondary air is fed in the middle of the furnace.

Grate furnace technology has many variations: fixed grate, moving grates, traveling grates, rotating grates and vibrating grates, and technology selection need to be done carefully by considering specific advantages and disadvantages of each technology depend on fuel type. The main advantages of grate furnace are it can be used for biomass fuels with high moisture content, various particle sizes, and high ash content. Moreover, it can be operating well even at partial load and also insensitive to slugging compared to fluidized bed combustion. Although special technologies are needed for efficient NOx reduction and also high excess oxygen (5 – 8 vol %) decrease efficiency, grate furnace technology is common in small to medium size applications with its low investment and operating cost with a capacity of under 20MWth.

Underfeed stokers represent a cheap and operationally safe technology for small and medium scale system, up to a nominal boiler capacity of 6MWth (Koppejan & van Loo 2012). It is suitable for biomass fuels with low ash content and small particle sizes as melted ash particle may cause problems in underfeeding stokers by covering the upper surface of the fuel bed. The advantage of underfeeding stokers is good partial load behavior and their simple load control due to continuous fuel feeding and low fuel mass in the furnace. It enables to operate the system more easily and flexibly with load changes.

Fluidized bed combustion:

Fluidized bed combustion (FBC) technology is distinguished in bubbling fluidized beds (BFB) and circulating fluidized bed (CFB). Fluidized bed consists of small particles such as silica sand and dolomite and creates a fluidized state by the upstream flow of air. The bed material represents 90 – 98 % of the mixture of fuel and bed material and the intense heat transfer and mixing provides good condition of combustion with low excess air ratio (1.1 – 1.2 for CFB and 1.2 – 1.3 for BFB plants) with high flexibility concerning moisture content and kind of biomass fuel used (Koppejan & van Loo 2012). In addition to the efficiency increases, the efficient heat transfer between bed material and biomass fuel allows complete combustion of the biomass fuel at low temperatures, and it results lowering of formation of thermal NOx. In BFB, the velocity of air into the bed is maintained the solid particles in suspension and the velocity is increased in CFB so that the particle move up and out from the bed and circulate. Because of the system complexity, FBC has high investment and operating cost, it is interesting only for the plant for large scale (>20MWth for BFB and >30MWth for CFB) (Koppejan & van Loo 2012).

Pulverized fuel combustion:

In pulverized fuel combustion systems, small particle size fuels such as sawdust and fine shavings are injected into the furnace with air. The quality of the fuel in the system has to be quite constant as the particle size of the system is limited to less than 10 to 20 mm and moisture content of the fuel normally not exceed 20%. Transportation air is used as primary air, and the auxiliary burner is used for start up the furnace. In pulverized fuel combustion system, fuel gasification and charcoal combustion take place at the same time because of the small particle size, and thus the system has excellent control and fast alteration of load possible.

3.2.4 Biomass gasification

Biomass gasification is a thermo-chemical conversion process of solid biomass fuels into a high calorific product gas. During the process, biomass fuel reacts with gasifying agents such as oxygen, steam or CO2 to provide oxygen for the process. The composition of the gas heavily depends on the type of biomass fuel, reaction conditions and the gasifying agent. Its main composition is H2, CO and a small amount of
CH₄, CO₂ and in the case of the gasifying agent are air, N₂ is also included. Calorific value of the gas depends on gasifying agent, and net calorific values of the product gas with each gasifying agent are 4 - 6.5 (MJ/m³, dry) for air, 7 – 9 (MJ/m³, dry) for enriched air (80% O₂) and 12 – 17 (MJ/m³, dry) for steam. Besides the product gas, char and ash with varying carbon contents and condensable low molecular hydrocarbons are produced.

The gasification process consists of four stages: Drying, Pyrolysis, Oxidation, and Reduction:

**Drying:**

Moisture contents requirement of the biomass fuel for gasification process is usually 10 – 20 %. In the drying zone, the heat supplied from oxidation zone will dry fuels for next step. The temperature of the process usually under 200 degree (Osowski & Fahlenkamp 2006).

**Pyrolysis:**

After the drying, the biomass fuels move to the pyrolysis zone. As it is cloth oxidation zone, the temperature of the biomass increases over 200°C and pyrolysis will occur in the absence of oxygen. In the process, char and volatile gasses such as CO₂, H₂ and CO will be released by thermal degradation. (RET 2014)

**Oxidation:**

In oxidation process, pyrolysis gasses and char will react with provided oxygen or air to provide required energy in other stages. In this stage, the following reactions will occur (Compedu).

**Combustion of gasses:**

\[
\begin{align*}
\text{H}_2 + 0.5 \text{O}_2 & \rightarrow \text{H}_2\text{O} \quad \Delta H_R = -241 \text{ kJ/mol} \\
\text{CO} + 0.5 \text{O}_2 & \rightarrow \text{CO}_2 \quad \Delta H_R = -281 \text{ kJ/mol} \\
\text{CH}_4 + 2\text{O}_2 & \rightarrow 2\text{H}_2\text{O} + \text{CO}_2 \quad \Delta H_R = -802 \text{ kJ/mol} \\
\text{C}_2\text{H}_4 + 3\text{O}_2 & \rightarrow 2\text{H}_2\text{O} + 2\text{CO}_2 \quad \Delta H_R = -1326 \text{ kJ/mol}
\end{align*}
\]

**Total and partial combustion of char:**

\[
\begin{align*}
\text{C} + \text{O}_2 & \rightarrow \text{CO}_2 \quad \Delta H_R = -390 \text{ kJ/mol} \\
\text{C} + 0.5\text{O}_2 & \rightarrow \text{CO} \quad \Delta H_R = -109 \text{ kJ/mol}
\end{align*}
\]

**Methane production:**

\[
\begin{align*}
\text{CO} + 3\text{H}_2 & \rightarrow \text{CH}_4 + \text{H}_2\text{O} \quad \Delta H_R = -205 \text{ kJ/mol} \\
\text{C} + 2\text{H}_2 & \rightarrow \text{CH}_4 \quad \Delta H_R = -71 \text{ kJ/mol}
\end{align*}
\]

**Reduction:**

In the reduction process, char is converted into product gas. The Boudard reaction is an endothermic reaction and thus, it reduces the process temperature. (Compedu)

\[
\begin{align*}
\text{C} + \text{CO}_2 & \rightarrow 2\text{CO} \quad \Delta H_R = 172 \text{ kJ/mol}
\end{align*}
\]

In steam gasification, following reactions will also occur (Compedu).
\[
C + \text{H}_2\text{O}(g) \rightarrow \text{CO} + \text{H}_2 \quad \Delta H_R = 130 \text{ kJ/mol} \quad (3.12)
\]
\[
C + 2\text{H}_2\text{O}(g) \rightarrow \text{CO}_2 + 2\text{H}_2 \quad \Delta H_R = 88 \text{ kJ/mol} \quad (3.13)
\]

The production of hydrogen from steam and carbon monoxide called water-gas shift reaction is also an important reaction in this process. (Compedu)

\[
\text{CO} + \text{H}_2\text{O}(g) \rightarrow \text{CO}_2 + \text{H}_2 \quad \Delta H_R = -41 \text{ kJ/mol} \quad (3.14)
\]

There are different basic concepts regarding biomass gasification technologies: the fixed bed gasification process, the fluidized bed gasification process and the entrained flow gasification process (Obernberger & Thek 2008). For small to medium scale applications, only the fixed bed gasification process is usually selected and thus the fluidized bed and entrained flow gasification process is not further considered in this paper.

Figure 9 shows the scheme and operating principle of updraft and downdraft gasifier. In the updraft gasifier, gasifying agent enters at the bottom of the gasifier and the product gas exits at the top of the gasifier. The advantages of updraft gasifier are that it is relatively insensitive towards varying particle size (5-100 mm) and moisture content (up to 55 wt% (w.b.)) (Obernberger & Thek 2008). Another advantage is that it is easy to operate stably, and it has good partial load behavior.

In the downdraft gasifier, the gasifying agent is injected into oxidation zone and the pyrolysis products flow co-currently through the hot combustion and gasification zone. After the gasification in reduction zone, the product gas exits at the bottom of the gasifier. The advantages of downdraft gasifier are the lower tar content in the product gas as most of the tar are decomposed and oxidized in hot oxidation area. (Compedu) For this reason, the downdraft gasifier allows a simple design of the gas cleaning and tar removal systems for utilization in an internal combustion engine. Compare to updraft gasifier, downdraft gasifier is sensitive towards varying particle size of the fuel (20-100mm) and fuel moisture contents (moisture content > 20 %), and their partial load behavior is rather poor (Obernberger & Thek 2008).

![Figure 9: Scheme and operating principle of conventional fixed bed gasifiers (left: updraft gasifier, right: downdraft gasifier)](Obernberger & Thek 2008)
The efficiency of the gasification process is given by the following equation.

$$\eta_{CG} = \frac{\text{LHV}_{\text{gas}} \cdot V_{\text{gas}}}{\text{LHV}_{\text{biomass}} \cdot V_{\text{biomass}}} \cdot 100\%$$

(3.15)

It is called cold gas efficiency and it measures how much of the energy in biomass fuels transfer to product gas. The cold gas efficiency is usually an order of 50 % to 85 % and it is not taking into consider the temperature of the gas (RET 2014). Therefore, for thermal applications, consideration of the product gas temperature and specific heat is also important to evaluate the total gasification process efficiency. (Compedu)

### 3.2.5 Heat and power generation technologies

International Energy Agency summarized biomass energy conversion technologies and their current development status in their report called technology roadmap for biomass in 2012. The summary of the technologies and its current development status is shown in Figure 10. From their report, potential technologies will be:

- Direct combustion or gasification and steam cycle
- Direct combustion with ORC
- Gasification with engine

As co-firing is generally for huge scale biomass power plant and most of them are existing coal plants with supplemental facilities for biomass feeding, it is excluded from further discussion. In following section, each of the potential technologies will be discussed.

![Figure 10: Overview of biomass energy conversion technologies and their current development status (IEA 2012)](image-url)
3.2.5.1 Steam Cycle

Figure 11 shows a flow and T/S diagrams of back-pressure plants based on Rankine cycle. At first, biomass fuel is combusted in the boiler and steam is generated and superheated by the heat (2→3→4→5). The generated steam enters steam turbine thereafter, and the turbine transforms most of the energy in the steam into mechanical energy (5→6). The mechanical energy is converted into electricity by a generator which is mechanically connected to the turbine. In condensing turbines, exited low energy steam after the turbine is condensed in the condenser and rest of the energy which was contained in the steam is released as heat (6→1). Finally, the condensed water is pumped up to the boiler and the cycle continues. (1→2)

![Figure 11: Flow and T/S diagrams of back-pressure plants based on Rankine cycle(Koppejan & van Loo 2012)](image)

In the steam cycle, steam temperature and pressure are the main determinants of the electrical efficiency. In a conventional steam boiler, the pressure range is from a few bars to 100 bars and the temperature reaches around 540 degrees, and the well-designed and pertinently constructed boiler is necessary to generate high pressure and temperature steam (Malin 2012). Another important factor which determines the electrical efficiency is the pressure and temperature of the condenser. The differences of the pressure and temperature between before and after the turbine, which means the differences between boiler and condenser determines the energy conversion efficiency of a steam turbine, and thus lower pressure and temperature in the condenser increase the electrical efficiency of the cycle.

In CHP plant, back pressure turbine is used instead of condensed turbine. In the back pressure steam turbine, all exhaust steam from the turbine is extracted to heat utilization purpose. As it is not condensed in the condenser, the steam does not expand completely inside the turbine and the energy conversion efficiency is lower than the condensing steam turbine in the same condition. Although the lower electrical efficiency compares to condensing steam turbine, back pressure steam turbine can achieve higher overall efficiency (70 – 80%) by utilizing the exhaust heat. (RET 2014). Figure 12 shows the thermal efficiency of the Rankine cycle as a function of live steam parameters and backpressure. For small turbines, since the backpressure steam needs to be saturated as droplets are not allowed, the thermal efficiency is lower than bigger plants. To maximize the overall efficiency of the plant, the heat utilization system needs to be carefully designed and the turbines have to be optimized for the heat requirements.
3.2.5.2 Organic Rankin Cycle

The principle of ORC process corresponds to the conventional Rankin cycle process which is used in steam cycle. The substantial difference between ORC and steam cycle is that ORC uses organic working medium with favorable thermodynamic properties instead of water. Figure 13 shows the thermodynamic cycle and components of an ORC unit. For biomass power generation, ORC process is connected with biomass thermal oil boiler via thermal oil cycle. The hot temperature thermal oil from the biomass boiler is used to preheat and vaporize the organic working medium in the evaporator (8 → 3 → 4). The organic medium vapor enters turbine and the energy in the organic medium vapor is transformed into mechanical energy while passing the turbine (4 → 5). An electric generator is directly connected to the turbine and the mechanical energy of turbine is converted to electricity. The exhausted vapor flow through the regenerator (5 → 9) and heats the organic medium (2 → 8) which enters to the evaporator. The vapor after the regenerator is condensed in water cooled condenser (9 → 1) and pumped up to the regenerator and then to the evaporator. (1 → 2 → 8 → 3). The ORC process is operated in complete closed-loop circuit and the recovered heat in the condenser (hot water feed temperature around 80 to 100 degrees) can be utilized for district or process heat. (Obernberger et al. 2003)
The ORC process has following favorable characteristic. (Andrea Duvia & Alessandro Guercio 2009) (Obernberger et al. 2003)
- High turbine efficiency with relatively low input pressure and temperature compare to steam cycle
- Low mechanical stress of the turbine
- No erosion of the turbine blades
- Enable direct connection of the electric generator to the turbine without gears.
- Long operational life of the machine
- Low operating cost
- Insensitive to load changes and has good partial load performance

As the organic working mediums which are used for the ORC process have relatively low boiling temperature and heavier math per unit volume, ORC process can achieve relatively higher turbine efficiency with low pressure and temperature input compare to steam cycle. As the rotation speed of the turbine is slower than the steam cycle because of the heavier math of the organic medium, mechanical stress of the turbine is low and electric generator can be directly connected to the turbine without gears to avoid the losses in the gears and save the equipment cost for the gears. The organic working medium can avoid erosion of the turbine blades which is a serious problem in the steam turbine and it helps lower maintenance cost for the turbine and longer machine lifetime. With the superior characteristics, the typical lifetime of ORC unit are greater than 20 years, as has been proven by geothermal applications (Obernberger et al. 2003). Since the cycle of the ORC process is closed and no additional working medium or water treatment system is required, the operating cost is low. In Europe, allowance of automatic operation of plants without the need of onsite attendance by licensed operators also contributes to decrease the operating cost.

### 3.2.5.3 Internal Combustion Engines

Overview of biomass gasification system with an internal combustion engine is shown in Figure 14. In the gasification system, biomass resources are gasified in the gasifier and ash is removed from the gas. After the ash removing, gas is cooled down, and other impurities such as tar and char are removed in a filter. After the purifying, the product gas is sent to IC engine and generates electricity.
Otto engine and Diesel engine are the representative internal combustion engines which are widely used nowadays. Figure 15 shows the ideal cycle of the both engines.

The Otto engine uses spark ignition for ignition process. In the Otto cycle, gasoline vapor and the air is enter to the engine in intake stroke (5→1). The gasoline vapor and the air are compressed by compression stroke and both pressure and temperature of the mixture gas increase (1→2). By spark ignition, the gas mixture is combusted at constant volume and the pressure increases till maximum point (2→3). The high-pressure gas expands in power stroke phase (3→4), and the exhaust valve opens and the exhaust gas escapes at the end of the expansion (4→1). The piston pushes remaining combustion gas from the chamber (1→5) to for new gas vapor and air intake.

The Diesel cycle uses compression ignition for ignition process. In Diesel engine cycle, only the air is enter to engine chamber and compressed until the temperature gets above the ignition temperature of the fuel (1→2). After the compression, fuel is injected into the chamber and combustion is occurred (2→3). The gas mixture pushes the piston and gives work to outside (3→4). The exhaust valve opens and the exhaust gas escapes at the end of the expansion (4→1) and the piston push remaining gas from the chamber.
Otto engines can be run with gasification syngas alone and electrical efficiency and overall efficiency is around 35 % and 40 % when the exhaust gas temperature is set to 150 degrees. The values are compatible with the real-life performance of gas engines whose size ranges from 0.5 to 3MW total output fed by gasification syngas (Baratieri et al. 2009). The use of Otto engine for small scale CHP applications is widely used in Europe, and it is competitive especially under the 2MW_e plant. The advantages of using Otto engine for biomass CHP application are relatively higher electrical and overall efficiency especially for small scale up to 2MW, long mechanical lifetime and high flexibility of operation with short start-up and good partial load operation.

The Diesel engines cannot be run on gasification syngas alone without converted to Otto engine by installing spark ignition system, and thus it must be run in dual fuel mode. In the dual fuel mode, some amount of diesel is supplied into the engine with the syngas to help the ignition of the gas and air mixture when it is compressed. In the best case, 90% of the power output can come from producer gas (Malin 2012). Although the dual fuel mode operation in the diesel engines decrease the CO2 emissions reduction compare to the Otto engines, it offers the advantage of high flexibility operation. As the biomass gasification process is not perfectly stable, the stop of gasification process directly affects the yielding ability of the plant, the high flexibility of operation is a significant advantage to secure stable power supply and avoid the economic risk of the project.

Since the diesel engines can achieve higher compression ration than Otto engines, the electrical efficiency of the diesel engines is higher than the one of the Otto engines, and it reaches around 40 – 45 % (Klaus & Helmit 2010). In contrast to Otto engines, as the syngas is directly injected into compressed air in the diesel engines, complete combustion easily occurs even with a lean gas such as gasification syngas and the emission of CO and hydrocarbons is relatively small. The characteristic also brings an advantage of good partial load operation compare to the Otto engines.

4 Economic calculations

4.1 Discount Cash Flow of the Systems

4.1.1 Net Present Value and Internal Rate of Return of the systems

Net Present Value (NPV) is the differences between the sum of the present value of cash flows and initial capital cost. It is calculated with equation below where \( t \) refers estimated plant life which is assumed 20 years in this study as same as price guaranteed period by FIT scheme, \( CF_k \) refers a cash flow of year \( k \), \( d \) refers discount rate of the project which is assumed to 5 % a year, and \( I_{capital} \) refers total capital cost of the project. In NPV method, the capital should be taken place only when NPV is positive, and project with negative NPV is not acceptable.

\[
NPV = \sum_{k=1}^{t} \frac{CF_k}{(1 + d)^k} - I_{capital} \tag{4.1}
\]

Internal Rate of Return is the discount rate that makes the NPV of the projects equal to zero. IRR fulfill the following equation.

\[
\sum_{k=1}^{t} \frac{CF_k}{(1 + IRR)^k} - I_{capital} = 0 \tag{4.2}
\]
To evaluate the project by IRR, hurdle rate has to be set which is a minimum rate of return a business operator will accept the project. For a project to be accepted, the IRR should be bigger than or equal to the hurdle rate, and higher IRR is preferable. In the case of biomass power generation business in Japan, 8% is a rough standard for the value.

### 4.1.2 Capital cost

Capital cost is calculated with following equation where $C_{\text{capital,unit}}$ refers total capital cost and $PC_{\text{installed}}$ refers installed capacity of the power plant.

$$C_{\text{capital,tot}} = C_{\text{capital,unit}} \cdot PC_{\text{installed}}$$  \hspace{1cm} (4.3)

Capital cost for the power plant is varying wildly depending on the type of technology used, the scale of the plant, the geographical and social environment around the plant, etc. For steam turbine technology, Yanagida conducted a research of specific capital cost of steam turbine power plant by collecting both Europe and Japan’s actual working power plants data. The equation which shows the relationships between specific plant cost and plant capacity is shown in Table 3. For ORC plant, Andrea and Alessandro conducted ad research on existing ORC plants in Europe and found relationships between capital cost and the size of the plant. In addition, Japan Woody Biomass Association conducted a hearing research to several companies planning to built ORC plants in Japan and found that the current capital cost of 1MW ORC plants cost around 2.1 times more than the same size ORC plants in Europe. Thus, in this study, the equation of capital cost and plants size of ORC plants which is found on Andrea and Alessandro’s research is modified to current Japanese condition by multiply 2.1 to the each capital cost. The capital cost of the gasification unit per kWh is set to 0.92 million JPY which is reported on JWBA’s hearing research to several Japanese companies which are more than double of same size gasification plants in Europe (JWBA 2015).

### 4.1.3 Operating and other costs

The operating cost includes the cost of fuels, labor, maintenance, utility and ash disposal.

Fuel consumption of the plants are calculated from following equation where CapacityFactor is a capacity factor of the plants which is set to 85% in this study, and LHV$_{\text{fuel}}$ refers lower heating value of the fuel and Eff$_{\text{el}}$ refers electrical efficiency of the plant. Yanagida found that there is a strong scale merit for steam turbine efficiency and the electrical efficiency for steam turbine can be express as $5.762*\ln(PC_{\text{installed}}(kW)) – 26.65$ (Yanagida et al. 2015) and the equation is used in this study.

$$m_{\text{fuel}} = \frac{PC_{\text{installed}} \cdot \text{CapacityFactor} \cdot 8760}{\text{LHV}_{\text{fuel}} \cdot \text{Eff}_{\text{el}}}$$  \hspace{1cm} (4.4)

Thus, the cost of fuel is calculated by following equation where $C_{\text{fuel,unit}}$ refers unit cost of the biomass fuels. The cost of the wood chip with 40% moisture content for Steam turbine and ORC plants is set to 12,000 JPY (NEDO 2015) and the cost of wood pellet with 10% moisture content for gasification plant is set to 35,000 JPY (MAFF 2013).
\[ C_{\text{fuel}} = m_{\text{fuel}} \cdot C_{\text{fuel,unit}} \] (4.5)

The labor cost is calculated by multiply the numbers of labors and the cost of the labor per capita. Yanagida conducted research on existing steam turbine plants and found that the required number of operators can be express as \( 0.005 \times \text{Plant capacity} \) in the range of 250 – 1000 kW plants and \( 0.000778 \times \text{Plant capacity} + 4.222 \) in over 1000 kW plants (Yanagida et al. 2015). ORC process is basically automated and technically only need 1 – 2 labor for plant operation. However, ORC is regarded as the same category with steam turbine according to Business electrical act in Japan, and thus the required number of labor is set to same as the number for a steam turbine. For gasification plants, the plant can be operated automatically, and only a simple working condition check is needed several times in a day (Burkhardt). Thus, the number of the labor for gasification plants is set to 0.5 as it is assumed that the plant operator works on another job in half of their working time.

\[ C_{\text{labor}} = n_{\text{labor}} \cdot C_{\text{labor,capita}} \] (4.6)

Maintenance cost is usually set to 2 – 4\% of the initial capital cost. It is set to 3\% for steam turbine and 1.5\% for ORC and gasification to modify the capital cost differences as it cost more than double of standard price in Europe.

\[ C_{\text{maintenance}} = C_{\text{capital,tot}} \cdot \epsilon_{\text{maintenance}} \] (4.7)

As it was difficult to find specific utility cost for power plants, it is assumed to 0.5\% of the initial capital cost for steam turbine and 0.25\% for ORC and gasification plant for the same reason as maintenance cost.

\[ C_{\text{utility}} = C_{\text{capital,tot}} \cdot \epsilon_{\text{utility}} \] (4.8)

Ash disposal cost it calculated by the following equation. The amount of ash is estimated to 1\% of total fuel consumption, and unit cost of the ash disposal is set to 20,000 JPY/ton.

\[ C_{\text{ash}} = m_{\text{fuel}} \cdot 0.01 \cdot C_{\text{ash,unit}} \] (4.9)

The total operating cost is calculated by the following equation.

\[ C_{\text{operating}} = C_{\text{fuel}} + C_{\text{labor}} + C_{\text{maintenance}} + C_{\text{utilities}} + C_{\text{ash}} \] (4.10)

4.1.4 Depreciation

To calculate the cash flow of the project, depreciation has to be considered. In this study, depreciation period is set to 20 years as same as price guaranteed period by FIT scheme.
Depreciation = \( \frac{C_{\text{capital tot}}}{20} \) \hspace{1cm} (4.11)

**4.1.5 Revenues**

The unit price of electricity from biomass resources within FIT scheme depends on the type of biomass resources and plant scale as shown in Table 1. As it is assumed that all cases are fuelled by unused wood, the unit price of electricity is 40 JPY/kWh for under 2MW plant and 32 JPY/kWh for over 2MW power plant. Total revenue from electricity selling is calculated by following equation where \( R_{el} \) refers the revenue from electricity, \( P_{el} \) refers total amount of generated electricity, \( \varepsilon_{\text{Auxiliary}} \) refers Auxiliary power ratio and \( p_{el, \text{unit}} \) refers unit price of electricity.

\[
R_{el} = P_{el} \cdot (1 - \varepsilon_{\text{Auxiliary}}) \cdot p_{el, \text{unit}} \hspace{1cm} (4.12)
\]

Revenue from the thermal supply is calculated by multiply the amount of generated thermal by thermal unit price. Thermal unit price is set to 5.1 JPY/kWh which is equal to the heat unit price of current A heavy oil in Japan (METI 2016).

\[
R_{\text{thermal}} = P_{\text{thermal}} \cdot p_{\text{thermal, unit}} \hspace{1cm} (4.13)
\]

**4.1.6 Cash flow**

Cash flow of each year in the project is thus calculated by the following equation. Corporation tax depends on the size of the plant, but it is assumed to 35% in this study which corresponds to Japan’s tax law (NEDO 2015). Fixed property tax rate is set to 1.4 % of depreciation.

\[
\text{CashFlow} = (R - C_{\text{operating}} - \text{FixedPropertyTax}) \cdot (1 - \text{CorporationTax}) + \text{Depreciation} \hspace{1cm} (4.14)
\]

Summary of all input parameters is shown in Table 3.

**Table 3: Summary of input parameters**

<table>
<thead>
<tr>
<th></th>
<th>Steam turbine</th>
<th>ORC</th>
<th>Gasification</th>
</tr>
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<tbody>
<tr>
<td><strong>Electrical efficiency (%)</strong></td>
<td>( \text{El only case:} ) 5.762*ln(CP_{\text{installed}}(kW)) – 26.65</td>
<td>17.6 (Turboden)</td>
<td>30 (Burkhardt)</td>
</tr>
<tr>
<td></td>
<td>( \text{El + Thermal case:} ) 50 % of El only case</td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Thermal efficiency (%)</strong></td>
<td>70 – Electrical efficiency</td>
<td>68 (Turboden)</td>
<td>45 (Burkhardt)</td>
</tr>
<tr>
<td><strong>Capital cost (million JPY/kW)</strong></td>
<td>$(8.35 \times (CP_{\text{installed}}(kW))^{0.673}) / CP_{\text{installed}}(kW)$</td>
<td>$-0.89 \times \ln(CP_{\text{installed}}(kW)) + 7.77$</td>
<td>0.92</td>
</tr>
<tr>
<td>----------------------------------</td>
<td>-------------------------------------------------</td>
<td>-----------------------------------------------</td>
<td>------</td>
</tr>
<tr>
<td><strong>Capacity factor (%)</strong></td>
<td>85</td>
<td>85</td>
<td>85</td>
</tr>
<tr>
<td><strong>Electricity price (JPY/kWh)</strong></td>
<td>40</td>
<td>40</td>
<td>40</td>
</tr>
<tr>
<td><strong>Heat price (JPY/kWh)</strong></td>
<td>5.1</td>
<td>5.1</td>
<td>5.1</td>
</tr>
<tr>
<td><strong>Depreciation period</strong></td>
<td>20</td>
<td>20</td>
<td>20</td>
</tr>
<tr>
<td><strong>Discount rate (%/yr)</strong></td>
<td>5</td>
<td>5</td>
<td>5</td>
</tr>
<tr>
<td><strong>Fuel type</strong></td>
<td>Wood chip</td>
<td>Wood chip</td>
<td>Wood pellet</td>
</tr>
<tr>
<td><strong>Moisture content (%)</strong></td>
<td>40</td>
<td>40</td>
<td>10</td>
</tr>
<tr>
<td><strong>LHV (MJ/kg)/(kWh/ton)</strong></td>
<td>10.2/2833 (Koppejan &amp; van Loo 2012)</td>
<td>10.2/2833 (Koppejan &amp; van Loo 2012)</td>
<td>16.4/4556 (Koppejan &amp; van Loo 2012)</td>
</tr>
<tr>
<td><strong>Unit cost (JPY/ton)</strong></td>
<td>12,000</td>
<td>12,000</td>
<td>35,000</td>
</tr>
<tr>
<td><strong>Labor cost per capita (JPY/person/year)</strong></td>
<td>5,000,000</td>
<td>5,000,000</td>
<td>5,000,000</td>
</tr>
<tr>
<td><strong>Number of labor</strong></td>
<td>Range from 250 to 1000kW:</td>
<td>Range from 250 to 1000kW:</td>
<td>0.5</td>
</tr>
<tr>
<td></td>
<td>0.005\times\text{Plant capacity} over 1000kW:</td>
<td>0.005\times\text{Plant capacity} over 1000kW:</td>
<td></td>
</tr>
<tr>
<td></td>
<td>0.000778\times\text{Plant capacity} + 4.222</td>
<td>0.000778\times\text{Plant capacity} + 4.222</td>
<td></td>
</tr>
<tr>
<td><strong>Maintenance cost (JPY)</strong></td>
<td>3% of capital cost</td>
<td>1.5% of capital cost</td>
<td>1.5% of capital cost</td>
</tr>
<tr>
<td><strong>Utility cost (JPY)</strong></td>
<td>0.5% of capital cost</td>
<td>0.25% of capital cost</td>
<td>0.25% of capital cost</td>
</tr>
<tr>
<td><strong>Ash content of fuel (%)</strong></td>
<td>1</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td><strong>Disposal cost of Ash (JPY/ton)</strong></td>
<td>20,000</td>
<td>20,000</td>
<td>20,000</td>
</tr>
<tr>
<td><strong>Fixed property tax</strong></td>
<td>1.4% of Depreciation</td>
<td>1.4% of Depreciation</td>
<td>1.4% of Depreciation</td>
</tr>
</tbody>
</table>
5 Result

5.1 Electricity only case

The calculation result of electricity only case is shown in Figure 16 and Figure 17.

Figure 16: Power generation cost share on each technology (a) Steam turbine b) ORC c) Gasification) (Electricity only case)

In steam turbine case, electricity generation cost is significantly expensive compare to other technologies, especially in smaller scale plant. Although the steam turbine technology is the most matured and widely used energy conversion technology for biomass utilization in Japan and depreciation cost is relatively low especially compare to ORC plant because of the lower capital cost, the electricity generation cost reaches more than 100 JPY/kWh when the plant capacity is 250 kW, and it is more than 2.5 times of electricity
price in FIT scheme which is set to 40 JPY/kWh for under 2MW unused wood-fired biomass power plant. Most of the cost is coming from fuel cost, which consists more than 80 % of total cost of 250 kW plant and more than 70 % even in 2 MW plants, because of the low electrical efficiency of the steam turbine which is 5.1 % in 250 kW plant and 17.1% in 2MW plant. There is clear tendency of scale merit for both fuel consumption and depreciation cost, and the total cost decreases rapidly with the increase of installed capacity of the plant and the total cost reduced by 35.6 JPY in 2MW plant.

In ORC case, the electricity generation cost varies from 57.3 JPY/kWh in 250 kW plant to 35.6 JPY/kWh in 2 MW plants. Fuel cost and depreciation consist mostly of the generation cost, and share of the depreciation is higher in smaller scale plant. The depreciation is 18.7 JPY/kWh in 250 kW plant, and which is around three times expensive compare to a steam turbine and gasification plant. This is mainly because of relatively higher capital cost than steam turbine case and lower efficiency than gasification case. ORC case also has a clear tendency of scale merit for capital cost, and the decrease of the generation cost with an increase of plant capacity almost match to the cost reduction of depreciation.

In gasification case, the electricity generation cost is nearly constant regardless of the size of the plant, and the generation cost is around 35 JPY/kWh which is almost same value with the minimum cost in both steam turbine and ORC cases. As it is assumed that the gasification units are installed parallel with other units to increase the installed capacity in this study, and thus major parameters such as fuel cost and depreciation which represent a large part of the generation cost are almost constant, the gasification case results in a quite constant cost per unit electricity generation. Although the electrical efficiency of the gasification system is 30 % and which is around 1.7 times higher than the best case in the steam turbine and ORC case, fuel cost per unit electricity generation is slightly higher compare to the technologies. This is mainly because of high fuel price, around 1.8 times higher per unit LHV than the wood chips used for steam turbine and ORC, as the gasification system requires high-quality wood pellet with less than 10 % moisture content.

Because of several factors which push up electricity generation cost in each technology as described above, the NPV of the each technology is all negative in the overall range of plant capacity. Thus, it is obvious that the small-scale biomass power plant under 2 MW is not feasible with only electricity sales to the grid.

### 5.2 Combined Heat and Power case

Calculation result in combined heat and power case will be discussed in this section.
The calculation results of power generation cost share on each technology are shown in Figure 18. The result is basically same as electricity only case for ORC and gasification case as input parameters for cost calculation are same. In steam turbine case, fuel cost increase compares to electricity only case to cover the decrease in electrical efficiency. As a result, the total cost varies from 187.1 JPY/kWh in 250 kW plant to 60.7 JPY/kWh in 2 MW plant, and it is more than 1.7 times higher compare to electricity only case.

![Steam cost share per kWh](image1)

**Figure 18: Power generation cost share on each technology (a) Steam turbine b) ORC c) Gasification)**

Revenue and cost comparison of each technology is shown in Figure 19. In steam turbine case, thermal revenue is more than electricity revenue in all range. As electrical efficiency with back pressure steam turbine is lower than condensing steam turbine and huge amount of fuel is consumed in the plant, the generated amount of heat is more than 8 times of electricity generation, and the thermal revenue gets higher than the electricity revenue even the unit price of heat is only about 12 % of the electricity unit price. In ORC case, the thermal revenue is around 55 % of electricity revenue, and it is less than 20 % in gasification case as the gasification system has high electrical efficiency, and thus, the heat/power ratio is relatively smaller than the steam turbine and ORC.
NPV and IRR comparison with each power generation technologies is shown in Figure 20 and Figure 21. For steam turbine and ORC case, there is clear tendency of scale merit and the NPV and IRR on both steam turbine and ORC cases improves rapidly with the increase of plant capacity. For both cases, NPV is negative in smaller scale, and it turns positive around 1000 kW installed plant capacity. At 2MW installed capacity, the NPV reaches around 1600 million JPY in ORC case and 990 million JPY in steam turbine case. Although ORC case has higher NPV value in the range of over 1000 kW compare to steam turbine case, there is almost no difference in IRR comparison. The NPV of gasification system increases proportionally with an increase of installed capacity, and it reaches around 380 million JPY at 1980 kW installed capacity and the value is relatively lower compare to other technologies. The IRR of gasification case is almost constant and it keeps around 7 % in all range, and it is slightly lower than the standard hurdle rate for biomass power plant in Japan.
Figure 20: NPV comparison with each power generation technologies

Figure 21: IRR comparison with each power generation technologies
6 Sensitivity analysis

It is important to conduct a sensitivity analysis to evaluate the feasibility of the projects deeply as many of parameters used in this study are either assumed or estimated and have some fluctuation from the actual plant. The values will also vary in each actual plant with different external constraint in each place.

In this section, sensitivity of IRR on each parameter: Fuel cost, Capital cost, Heat price, Capacity factor, Ash cost, Labor cost, Maintenance cost and Utility cost, is examined by changing the each value from 0.8 to 1.2 of its original value and calculate the changes of IRR from original IRR value. Plant scale for the sensitivity analysis is set to 2 MW for steam turbine and ORC as it showed maximum IRR in the previous result, and 360 kW for gasification as gasification is competitive in smaller scale plant under 1000 kW.

The changes of IRR in the steam turbine case are shown in Figure 22. In steam turbine case, change of fuel cost has a potent influence on IRR. The 1.2 times higher fuel cost result in more than 9 % of IRR reduction. It means that only because of 20% changes in fuel price, the IRR of 2MW steam turbine plant decrease from 12 % to 3 % and the project becomes unfeasible. Capacity factor and thermal revenue changes have an almost same impact on IRR. In 20% changes of the values, the project IRR will decrease around 6% and the impact is also considerable. Capital cost has a relatively lower impact on IRR compare to previous factors, and the 20 % increase of capacity factor result around 2.2 % decrease of IRR. The other parameter has a relatively low impact as the IRR change are less than 0.5 % with a change of the parameters.

![IRR sensitivity analysis](image1.png)

**Figure 22: Change of IRR with varying input date (Steam turbine 2000kW)**

The changes of IRR in ORC case are shown in Figure 23. The impact of the parameters change on IRR is relatively lower than steam turbine case as almost all IRR changes are in the range of -4 % to 4%. In ORC case, capacity factor has the largest impact on IRR. With 20 % decrease of capacity factor, IRR will decrease around 4.2 %. Capital cost is a second largest impact factor as 20% increase of capital cost decreases IRR about 2.5 %. However, as the current capital cost of ORC is more than double of European standard, there is a huge potential for capital cost reduction. If the capital cost decrease 20 %, which is still more than 1.5 times higher than European standard, the IRR will increase around 3.6 % and the IRR of the project (2MW ORC) will reach to 16 %. Fuel cost is the third impact factor and 20 % increase of the fuel cost decrease IRR around 3 %, and the impact is much lower than steam turbine case. Thermal revenue is the 4th impact factor, and other parameters have an ignorable impact on IRR.
The changes of IRR in gasification case are shown in Figure 24. In gasification case, capacity factor has a great impact on IRR. With 20% decrease of capacity factor, the IRR will decrease around 6%. As the IRR of gasification case is around 7% as calculated in the previous section, 6% decrease of IRR means a failure of the project. Fuel cost is a second impact factor and 20% increase in fuel cost decrease IRR around 4%. The impact of capital cost changes is relatively lower compare to other technologies, as 20% increase of capital cost results in only 1.9% decrease of IRR. For the same reason in ORC, capital there are huge possibilities of capital cost reduction, and in that case, IRR will increase up to 2.2% with the 20% reduction of the capital cost. Compare to other technologies, thermal revenue change has quite a low impact in gasification case as 20% decrease of thermal revenue result only 1.2% decrease of IRR. The other parameters have an ignorable impact on IRR as same as other technologies.
7 Discussion

It is found that in the selected condition, under 2 MW unused wood fueled biomass power plant in Japan, any of the projects cannot be feasible if the plants are operated in power only mode even the electricity price is set to 40 JPY/kWh by FIT scheme. Although there is a scale merit in the steam turbine and ORC plant, the cost cannot be reduced enough to make the projects feasible under 2MW, and thus, the plants need to be operated in CHP mode.

In CHP mode, the NPV is positive for over 1 MW steam turbine and ORC plants, and for all gasification plants. Especially because of the scale merit, steam turbine and ORC plant reach high IRR, which is around 12 % when the installed capacity is 2 MW. However, sensitivity analysis shows that the risk of the projects is quite high and the feasibility of the project is greatly affected by several factors such as fuel cost and capacity factor. Especially future fuel cost is not easy to predict and there is no guaranty of 20 years secure wood supply, the risk of fuel cost increase has to be carefully considered. The gasification system is competitive under 1000 kW plant capacity from IRR perspective, and also it has relatively insulated from the influence parameter changes except capacity factor change. In Japan, there are only a few succeeded biomass gasification plants and the reason of the failure of the most of the plants is reported to because of unexpected stop of gasifier or engine system. Thus, it is the most important factor to select stable and high capacity factor gasification technologies to make the project success.

In this study, heat utilization system has not been examined and it is simply assumed that the all generated heat can be sold to outside network. However, district heat infrastructure is not well developed in Japan and the average ambient temperature is higher than many of European countries where biomass utilization infrastructure is well developed, it is not easy to find heat supply destination in Japan especially if a significant amount of heat needs to be sold. As the thermal revenue is vital for small-scale biomass power plant as it is demonstrated in result section, the investigation of heat utilization system in Japan should be examined in future work.

In small scale biomass plant which is focused on this study, economic, environmental and social sustainability have to be considered in terms of sustainability of the projects. Economic sustainability is the main concern of this study and deeply examined in this paper. The social implications of the projects have also not been discussed in this study, and it should be further investigated. To achieve social sustainability, the plant needs to maximize positive impact on sincerity such as creations of new jobs and utilization of unused biomass resources in the society, and minimize negative impacts such as issues regarding noise from plant operation or biomass transport truck. Investigation of heat utilization system may contribute to social sustainability as well. Environmental implications of the projects have also not been examined in this study. Regarding environmental sustainability, the combined heat and power operation of the plant will have a great positive impact on sustainability as it can save an enormous amount of CO2 emission from conventional fuels which are for both electricity generation and heating purpose.
8 Conclusion

This thesis aimed to do a feasibility study of under 2 MW woody biomass-fueled plants in Japan under new FIT scheme for biomass power generation. The current Japanese power sector and forestry industry were studied in order to gather necessary background information. Different biomass energy conversion technologies were also studied and three technologies are chosen for in-depth discussion: Steam cycle, ORC, and gasification with internal combustion engines. After the study, all necessary information for economic calculation of the technologies was corrected.

The economic calculation revealed that none of the plants under 2 MW can be feasible in power only production mode. The electricity generation cost is more than 35 JPY/kWh even in best cases for each technology, and NPV showed negative values in all range. A large part of the cost was fuel cost as it consists around 70-80% of total cost in each plant. CHP mode operation greatly contributed to the improvement in the feasibility of the projects, and it is found that Steam turbine and ORC plants are feasible over 1000 kW and gasification plants are competitive with other technologies under 1000 kW installed plant capacity. Although the IRR of the projects reaches around 12 % in the steam turbine and ORC case and 7% in gasification case, sensitivity analysis revealed that there are several important factors which have a great impact on the feasibility of the projects such as fuel cost and capacity factor of the plant.
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# Appendix

## Matlab code

```matlab
clear all
close all

for k=1:3
    if k==1
        Cap_installed = [250 500 750 1000 1250 1500 1750 2000]; %Installed capacity [kW]
    end

    if k==2
        Cap_installed = [250 500 750 1000 1250 1500 1750 2000 ]; %Installed capacity [kW]
    end

    if k==3
        Cap_installed = [180 360 540 720 900 1080 1260 1440 1620 1800 1980]; %Installed capacity [kW]
    end

for m=1:length(Cap_installed)
    ip = 0.1; %ratio of electricity which is consumed for the station service power
    ElRevenue(1,m)=el_generation(Cap_installed(1,m))*(1-ip)*40; %Electricity unit price for unused wood under 2MW: 40 [JPY/kwh]
    ElRevenue_unit(1,m)=40; %Electricity unit price for unused wood under 2MW: 40 [JPY/kwh]
    ThermalRevenue(1,m)=th_generation(Cap_installed(1,m),k)*5.1; %Heat unit price: [JPY/kwh]
    ThermalRevenue_unit(1,m)=5.1/(el_generation(Cap_installed(1,m))*(1-ip)); %Heat unit price: [JPY/kwh]

    Fuelconsumption_tot(1,m)=Fuel_consumption(Cap_installed(1,m),k);
    Fuelconsumption_unit(1,m)=Fuel_consumption(Cap_installed(1,m),k)/el_generation(Cap_installed(1,m));

    FuelCost_tot(1,m)=C_fuel(Cap_installed(1,m),k);
    FuelCost_unit(1,m)=C_fuel(Cap_installed(1,m),k)/el_generation(Cap_installed(1,m));

    LaborCost_tot(1,m)=C_labor(Cap_installed(1,m),k);
    LaborCost_unit(1,m)=C_labor(Cap_installed(1,m),k)/el_generation(Cap_installed(1,m));

    Depreciation_tot(1,m)=C_capital_tot(Cap_installed(1,m),k)/20;
    Depreciation_unit(1,m)=C_capital_tot(Cap_installed(1,m),k)/(20*el_generation(Cap_installed(1,m),k));

    OtherCost_tot(1,m)=C_other(Cap_installed(1,m),k);
```

42
\[
\text{OtherCost}_{\text{unit}}(1,m) = \frac{C_{\text{other}}(\text{Cap}_\text{installed}(1,m),k)}{\text{el generation}(\text{Cap}_\text{installed}(1,m))};
\]

\[
\text{AshCost}_{\text{tot}}(1,m) = C_{\text{ash}}(\text{Cap}_\text{installed}(1,m),k);
\]

\[
\text{AshCost}_{\text{unit}}(1,m) = \frac{C_{\text{ash}}(\text{Cap}_\text{installed}(1,m),k)}{\text{el generation}(\text{Cap}_\text{installed}(1,m))};
\]

\[
\text{MaintainanceCost}_{\text{tot}}(1,m) = C_{\text{maintainance}}(\text{Cap}_\text{installed}(1,m),k);
\]

\[
\text{MaintainanceCost}_{\text{unit}}(1,m) = \frac{C_{\text{maintainance}}(\text{Cap}_\text{installed}(1,m),k)}{\text{el generation}(\text{Cap}_\text{installed}(1,m))};
\]

\[
\text{UtilityCost}_{\text{tot}}(1,m) = C_{\text{utility}}(\text{Cap}_\text{installed}(1,m),k);
\]

\[
\text{UtilityCost}_{\text{unit}}(1,m) = \frac{C_{\text{utility}}(\text{Cap}_\text{installed}(1,m),k)}{\text{el generation}(\text{Cap}_\text{installed}(1,m))};
\]

\[
\text{TaxCost}_{\text{tot}}(1,m) = C_{\text{tax dues}}(\text{Cap}_\text{installed}(1,m),k);
\]

\[
\text{TaxCost}_{\text{unit}}(1,m) = \frac{C_{\text{tax dues}}(\text{Cap}_\text{installed}(1,m),k)}{\text{el generation}(\text{Cap}_\text{installed}(1,m))};
\]

\[
\text{TotalCost}_{\text{tot}}(1,m) = \text{FuelCost}_{\text{tot}}(1,m) + \text{LaborCost}_{\text{tot}}(1,m) + \text{Depreciation}_{\text{tot}}(1,m) + \text{AshCost}_{\text{tot}}(1,m) + \text{MaintainanceCost}_{\text{tot}}(1,m) + \text{UtilityCost}_{\text{tot}}(1,m) + \text{TaxCost}_{\text{tot}}(1,m);
\]

\[
\text{TotalCost}_{\text{unit}}(1,m) = \frac{\text{FuelCost}_{\text{unit}}(1,m) + \text{LaborCost}_{\text{unit}}(1,m) + \text{Depreciation}_{\text{unit}}(1,m) + \text{AshCost}_{\text{unit}}(1,m) + \text{MaintainanceCost}_{\text{unit}}(1,m) + \text{UtilityCost}_{\text{unit}}(1,m) + \text{TaxCost}_{\text{unit}}(1,m)}{\text{el generation}(\text{Cap}_\text{installed}(1,m))}.
\]

\[\%\text{NPV}\]
\[
d = 0.05; \quad \%\text{Discount rate}
\]

\[
\text{for} \quad y = 1:20
\]

\[
\text{PV}_{y}(1,m) = \frac{((\text{ElRevenue}(1,m) - \text{TotalCost}_{\text{tot}}(1,m))*(1-0.35) + \text{Depreciation}_{\text{tot}}(1,m))}{((1+d)^{y})}; \quad \%\text{El only case}
\]

\[
\text{PV}_{y}(1,m) = \frac{((\text{ElRevenue}(1,m) + \text{ThermalRevenue}(1,m) - \text{TotalCost}_{\text{tot}}(1,m))*(1-0.35) + \text{Depreciation}_{\text{tot}}(1,m))}{((1+d)^{y})}; \quad \%\text{El + Thermal case}
\]

\[
\begin{align*}
\text{if} \quad y &= 1; \\
\text{PV}(1,m) &= \text{PV}_{y}(1,m); \\
\text{else} \\
\text{PV}(1,m) &= \text{PV}(1,m) + \text{PV}_{y}(1,m); \\
\end{align*}
\]

\[\text{NPV}(1,m) = \text{PV}(1,m) - C_{\text{capital tot}}(\text{Cap}_\text{installed}(1,m),k);\]

\[\%\text{IRR}\]

\[
\text{CF} = \text{zeros}(1,21); \quad \%\text{Generate vector of IRR}
\]

\[
\text{for} \quad j = 1:21
\]

\[
\text{if} \quad j = 1
\]

\[
\text{CF}(1,j) = (C_{\text{capital tot}}(\text{Cap}_\text{installed}(1,m),k)) * (-1);
\]

\[
\text{else}
\]

\[
\begin{align*}
\text{CF}(1,j) &= ((\text{ElRevenue}(1,m) - \text{TotalCost}_{\text{tot}}(1,m))*(1-0.35) + \text{Depreciation}_{\text{tot}}(1,m)) : \%\text{Cash flow of year j-1. El only case. Corporation tax is 35%} \\
\text{CF}(1,j) &= ((\text{ElRevenue}(1,m) + \text{ThermalRevenue}(1,m) - \text{TotalCost}_{\text{tot}}(1,m))*(1-0.35) + \text{Depreciation}_{\text{tot}}(1,m)) : \%\text{Cash flow of year j-1. El + Thermal case. Corporation tax is 35%}
\end{align*}
\]

\[\text{end}\]

\[\text{end}\]

\[
\text{IRR}(1,m) = \text{irr} (\text{CF}); \quad \%\text{Generate vector of IRR}
\]
End

if k==1
    IRR_1=IRR %Generate IRR vector of steam turbine
    NPV_1=NPV %Generate NPV vector of steam turbine
else if k==2
    IRR_2=IRR %Generate IRR vector of ORC
    NPV_2=NPV %Generate NPV vector of ORC
else
    IRR_3=IRR %Generate IRR vector of gasification
    NPV_3=NPV %Generate NPV vector of gasification
end

%Plot a figure of cost share per kWh
-------------------------------------
C=vertcat(Depreciation_unit,FuelCost_unit,LaborCost_unit,AshCost_unit,MaintainanceCost_unit,UtilityCost_unit,TaxCost_unit);
if k==1
    figure('Name','Steam cost');
    bar(Cap_installed, C.', 'stacked');
    title('Steam cost share per kWh');
else if k==2
    figure('Name','ORC cost');
    bar(Cap_installed, C.', 'stacked');
    title('ORC cost share per kWh');
else if k==3
    figure('Name','Gas cost');
    bar(Cap_installed, C.', 'stacked');
    title('Gas cost share per kWh');
end

xlabel('Installed Capacity (kW)');
ylabel('JPY/kWh');
legend('Depreciation','FuelCost','LaborCost','Ash Cost','MaintenanceCost','UtilityCost','Tax');

%--------------------------------------

%Plot a figure of Revenue and Cost comparison
----------------
C=vertcat(ElRevenue,ThermalRevenue,TotalCost_tot);%
if k==1
    figure('Name','Revenue Vs Cost Steam');
    bar(Cap_installed, C.);%
    title('Revenue Vs Cost Steam');
else if k==2
    figure('Name','Revenue Vs Cost ORC');
    bar(Cap_installed, C.);%
    title('Revenue Vs Cost ORC');
else if k==3
    figure('Name','Revenue Vs Cost Gas');
    bar(Cap_installed, C.');
    title('Revenue Vs Cost Gas');
end
end
xlabel('Installed Capacity(kW)');
ylabel('Revenue Vs Cost (JPY)');
legend('ElRevenue','ThermalRevenue','Total Cost');

figure('Name','IRR comparison')
Cap_installed = [250 500 750 1000 1250 1500 1750 2000]; %Installed capacity [kW]
plot(Cap_installed, IRR_1.*100, 'o-')
hold on
Cap_installed = [250 500 750 1000 1250 1500 1750 2000 ]; %Installed capacity [kW]
plot(Cap_installed, IRR_2.*100, 'o-')
hold on
Cap_installed = [180 360 540 720 900 1080 1260 1440 1620 1800 1980]; %Installed capacity [kW]
plot(Cap_installed, IRR_3.*100, 'o-')
title('IRR comparison');
xlabel('Installed Capacity (kW)');
ylabel('IRR(%)');
legend('steam','ORC','Gasification');

figure('Name','NPV comparison')
Cap_installed = [250 500 750 1000 1250 1500 1750 2000]; %Installed capacity [kW]
plot(Cap_installed, NPV_1*0.000001, 'o-')
hold on
Cap_installed = [250 500 750 1000 1250 1500 1750 2000 ]; %Installed capacity [kW]
plot(Cap_installed, NPV_2*0.000001, 'o-')
hold on
Cap_installed = [180 360 540 720 900 1080 1260 1440 1620 1800 1980]; %Installed capacity [kW]
plot(Cap_installed, NPV_3*0.000001, 'o-')
title('NPV comparison');
xlabel('Installed Capacity (kW)');
ylabel('NPV(million JPY)');
legend('steam','ORC','Gasification');

%--------------------------------------------------------Sensitivit analysis--------------------------------------------------------

for k=1:3
%Steam turbine or ORC (Case 1 or 2)
if k==1|2
    Cap_installed(1,1) = 2000;
end

%gasification (Case 3)
if k==3
    Cap_installed(1,1) = 360; % Installed capacity [kW]
end

for o=1:8
for n=1:5;
m=1;
ip = 0.1: % ratio of electricity which is consumed for the station service power

ElRevenue_s(1,n)=el_generation(Cap_installed(1,m))*(1-ip)*40; % Electricity unit price for unused wood under 2MW: 40 [JPY/kwh]
ThermalRevenue_s(1,n)=th_generation(Cap_installed(1,m),k)*5.1; % Heat unit price: [JPY/kwh]

FuelConsumption_tot_s(1,n)=Fuel_consumption(Cap_installed(1,m),k);
FuelCost_tot_s(1,n)=C_fuel(Cap_installed(1,m),k);
LaborCost_tot_s(1,n)=C_labor(Cap_installed(1,m),k);
Depreciation_tot_s(1,n)=C_capital_tot(Cap_installed(1,m),k)/20;
MaintenaceCost_tot_s(1,n)=C_maintainance(Cap_installed(1,m),k);
UtilityCost_tot_s(1,n)=C_utility(Cap_installed(1,m),k);
TaxCost_tot_s(1,n)=C_tax_dues(Cap_installed(1,m),k);
AshCost_tot_s(1,n)=C_ash(Cap_installed(1,m),k);

if o==1
    FuelCost_tot_s(1,n)=C_fuel(Cap_installed(1,m),k)*(0.7+0.1*n);
end
if o==2
    Depreciation_tot_s(1,n)=C_capital_tot(Cap_installed(1,m),k)*(0.7+0.1*n)/20;
end
if o==3
    ThermalRevenue_s(1,n)=th_generation(Cap_installed(1,m),k)*5.1*(0.7+0.1*n);
end
if o==4
    ElRevenue_s(1,n)=el_generation(Cap_installed(1,m))*(1-ip)*40*(0.7+0.1*n);
if \( o == 5 \)
\[
\text{AshCost}_{\text{tot}}(1,n) = C_{\text{ash}}(\text{Cap}_{\text{installed}}(1,m),k) \times (0.7 + 0.1 \times n);
\]
end

if \( o == 6 \)
\[
\text{LaborCost}_{\text{tot}}(1,n) = C_{\text{labor}}(\text{Cap}_{\text{installed}}(1,m),k) \times (0.7 + 0.1 \times n);
\]
end

if \( o == 7 \)
\[
\text{MaintainanceCost}_{\text{tot}}(1,n) = C_{\text{maintainance}}(\text{Cap}_{\text{installed}}(1,m),k) \times (0.7 + 0.1 \times n);
\]
end

if \( o == 8 \)
\[
\text{UtilityCost}_{\text{tot}}(1,n) = C_{\text{utility}}(\text{Cap}_{\text{installed}}(1,m),k) \times (0.7 + 0.1 \times n);
\]
end

\[
\text{TotalCost}_{\text{tot}}(1,n) = \text{FuelCost}_{\text{tot}}(1,n) + \text{LaborCost}_{\text{tot}}(1,n) + \text{Depreciation}_{\text{tot}}(1,n) + \text{AshC}
\]
\[
\text{ost}_{\text{tot}}(1,n) + \text{MaintainanceCost}_{\text{tot}}(1,n) + \text{UtilityCost}_{\text{tot}}(1,n) + \text{TaxCost}_{\text{tot}}(1,n);
\]

\%NPV and IRR
\[
\text{CF}_s = \text{zeros}(1,21);
\]
for \( j = 1:21 \)
if \( j == 1 \)
\[
\text{CF}_s(1,j) = (\text{Depreciation}_{\text{tot}}(1,n) \times 20) \times (-1);
\]
else
\[
\text{CF}_s(1,j) = (\text{ElRevenue}_s(1,n) + \text{ThermalRevenue}_s(1,n) - \text{TotalCost}_{\text{tot}}(1,n)) \times (1 - 0.35) + \text{Depreciation}_{\text{tot}}(1,n);  \%\text{Cash flow of year j-1. El + Thermal case. Corporation tax is 35%}
\]
end
end
\[
\text{NPV}_s(1,n) = \text{pvvar} (\text{CF}_s,0.05);  \%\text{Generate a vector of NPV}
\]
\[
\text{IRR}_s(1,n) = \text{irr} (\text{CF}_s);  \%\text{Generate a vector of IRR}
\]
end

\[
\text{IRR}_s\_\text{change} = \text{IRR}_s - \text{IRR}_s(1,3);
\]
if \( o == 1 \)
\[
\text{IRR}_s\_\text{change}_1 = \text{IRR}_s\_\text{change};
\]
end

if \( o == 2 \)
\[
\text{IRR}_s\_\text{change}_2 = \text{IRR}_s\_\text{change};
\]
end

if \( o == 3 \)
\[
\text{IRR}_s\_\text{change}_3 = \text{IRR}_s\_\text{change};
\]
end

if \( o == 4 \)
\[
\text{IRR}_s\_\text{change}_4 = \text{IRR}_s\_\text{change};
\]
end

if \( o == 5 \)
\[
\text{IRR}_s\_\text{change}_5 = \text{IRR}_s\_\text{change};
\]
end

if \( o == 6 \)
\[
\text{IRR}_s\_\text{change}_6 = \text{IRR}_s\_\text{change};
\]
end
if o==7
    IRR_s_change_7=IRR_s_change;
end
if o==8
    IRR_s_change_8=IRR_s_change;
end
end

parameter = [0.8 0.9 1 1.1 1.2]
figure('Name','IRR sensitivity analysis')
plot(parameter, IRR_s_change_1.*100,'o-');
hold on
plot(parameter, IRR_s_change_2.*100,'o-');
hold on
plot(parameter, IRR_s_change_3.*100,'o-');
hold on
plot(parameter, IRR_s_change_4.*100,'o-');
hold on
plot(parameter, IRR_s_change_5.*100,'o-');
hold on
plot(parameter, IRR_s_change_6.*100,'o-');
hold on
plot(parameter, IRR_s_change_7.*100,'o-');
hold on
plot(parameter, IRR_s_change_8.*100,'o-');
hold on

title('IRR sensitivity analysis');
xlabel('Change rate');
ylabel('IRR difference(%)');
legend('Fuel cost','Capital cost','Thermal Revenue','Capacity factor','Ash cost','Labor cost','Maintainance cost','Utility cost');

end

function [ out ] = Fuel_consumption( Cap_installed, type )
    
%Steam turbine(Case 1)
    if(type==1)
        LHV_f=2833; % [kWh/ton] (Wood Chip, Wt=40%)
        el_eff=(5.762*log(Cap_installed)-26.65)*0.01; %electrical efficiency of El only case
        el_eff=(5.762*log(Cap_installed)-26.65)*0.01*0.5; %electrical efficiency of El+Thermal case
    end

%ORC(Case 2)
    if(type==2)
        LHV_f=2833; % [kWh/ton] (Wood Chip, Wt=40%)
        el_eff=0.17; % Electrical efficiency for ORC
    end
%gasification(Case 3)
if (type==3)
    LHV_f=4556: % [kWh/ton] (Wood Pellet, Wt=10%)
    el_eff=0.3: % Electrical efficiency for Gasification
end

out=el_generation(Cap_installed)./(LHV_f.*el_eff); %Fuel consumption [ton]

function [ out ] = C_capital_tot( Cap_installed, type )

%Steam turbine(Case 1)
if (type==1)
    out=Cap_installed*(8.35*(Cap_installed^(0.673)))/Cap_installed*1000000;
end

%ORC(Case 2)
if (type==2)
    out=Cap_installed*(-0.89*log(Cap_installed)+7.77)*1000000;
end

%gasification(Case 3)
if (type==3)
    out=Cap_installed*920000; %[920,000 JPY/kWh]
end

end

function [ out ] = C_fuel(Cap_installed, type )

%Steam turbine(Case 1)
if (type==1)
    out=Fuel_consumption(Cap_installed, type )*12000; %12,000[JPY/ton] (Wood chip, Wt=40%)
end

%ORC(Case 2)
if (type==2)
    out=Fuel_consumption(Cap_installed, type )*12000; %12,000[JPY/ton] (Wood chip, Wt=40%)
end

%gasification(Case 3)
if (type==3)
    out=Fuel_consumption(Cap_installed, type )*35000; %35,000[JPY/ton] (Wood pellet, Wt=10%)
end

end
function [ out ] = C_labor( Cap_installed, type )

%Steam turbine (Case 1)
if (type==1)
    if (Cap_installed<=1000)
        n_labor=0.005*Cap_installed;
    else
        n_labor=0.000778*Cap_installed+4.222;
    end
end

%ORC (Case 2)
if (type==2)
    if (Cap_installed<=1000)
        n_labor=0.005*Cap_installed;
    else
        n_labor=0.000778*Cap_installed+4.222;
    end
end

%gasification (Case 3)
if (type==3)
    n_labor=0.5;
end

wage=5000000: % 6,000,000 [JPY/Person.Year]
out=n_labor*wage:
end

function [ out ] = C_tax_dues( Cap_installed, type )

out=C_capital_tot( Cap_installed, type )*0.5*0.014: % Cost of tax and dues (simplified that 1.4 % of average of capital cost )
end

function [ out ] = el_generation( Cap_installed)

CapacityFactor=0.85;
out=Cap_installed.*CapacityFactor.*8760:
end
function [ out ] = th_generation( Cap_installed, type )

%Steam turbine(Case 1)
if(type==1)
    LHV_f=2889; % [kWh/ton] (Wood Chip, Wt=40%)
    out = Fuel_consumption( Cap_installed, type )*LHV_f*(0.7-(5.762*log(Cap_installed)-26.65)*0.01*0.5); % Thermal efficiency = 70% - El efficiency
end

%ORC(Case 2)
if(type==2)
    LHV_f=2889; % [kWh/ton] (Wood Chip, Wt=40%)
    out = Fuel_consumption( Cap_installed, type )*LHV_f*0.68; % Thermal efficiency = 68%
end

%gasification(Case 3)
if(type==3)
    LHV_f=4556; % [kWh/ton] (Wood Pellet, Wt=10%)
    out = Fuel_consumption( Cap_installed, type )*LHV_f*0.45; % Thermal efficiency = 45%
end
end

function [ out ] = C_ash( Cap_installed, type )
out = Fuel_consumption(Cap_installed, type)*0.01*20000; % Ash content is 1 % of fuel, Disposal cost = 20,000 JPY/ton
end

function [ out ] = C_maintainance( Cap_installed, type )

%Steam turbine(Case 1)
if(type==1)
    out=C_capital_tot( Cap_installed, type )*0.03; % Cost of maintainacet(3% of Capital cost)
end

%ORC(Case 2)
if(type==2)
    out=C_capital_tot( Cap_installed, type )*0.015; % Cost of maintainace cost(1.5% of Capital cost)
end

%gasification(Case 3)
if(type==3)
    out=C_capital_tot( Cap_installed, type )*0.015; % Cost of maintainace cost(1.5% of Capital cost)
function [ out ] = C_utility( Cap_installed, type )

%Steam turbine(Case 1)
if (type==1)
    out=C_capital_tot( Cap_installed, type )*0.005; % Cost of utilities (0.5% of Capital cost)
end

%ORC(Case 2)
if (type==2)
    out=C_capital_tot( Cap_installed, type )*0.0025; % Cost of utilities (0.25% of Capital cost)
end

%gasification(Case 3)
if (type==3)
    out=C_capital_tot( Cap_installed, type )*0.0025; % Cost of utilities (0.25% of Capital cost)
end