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Energy Supply Alternatives for CCS at Tata Steel IJmuiden

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Research report of Tarun Rohra

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ABSTRACT

Tata Steel IJmuiden is an integrated steel mill which produces and supplies more than 7 million tonnes of high quality and coated steel to various sectors. The production of such substantial amount of steel comes with huge carbon dioxide emissions, to put it into perspective Tata Steel alone is responsible for 7% of the Dutch CO_2 emissions. Nonetheless, the company has been heavily investing and researching methods to decrease its CO_2 emissions in its attempt to become a carbon-neutral steelmaker by 2050. The first intermediate goal to reach this target are the 2030 climate goals for heavy industry and to attain these Tata Steel is deploying a CCS project to securely capture and store CO_2 in the North Sea. Carbon Capture and Storage is already proven to be feasible and is a mature technology. However, deploying CCS demands enormous volumes of heat and electricity. The estimated heat demand for the solvent regeneration phase is between 2.5 – 4.0 GJ/tonne of CO_2 dependent on the process design, type of solvent and quality of CO_2 source (Ali et al. 2018). Once the CO_2 is separated from the solvent it is essential to compress it, which requires electricity, for transport and storage. Due to these factors, it is essential that the thermal and electrical energy are provided for, while incurring the minimum energy penalty. Currently, the plan for providing steam to the CCS plant is assumed to be a gas-fired Boiler. In this research, three different scenarios are analysed and modelled as an alternative to the boiler to optimise the heat and energy infrastructure of Tata Steel IJmuiden, while taking into consideration decarbonisation goals and investment costs, after the implementation of carbon capture and storage.

LIST OF ABBREVIATIONS

BFG – Blast Furnace Gas
BOS – Basic Oxygen Steelmaking
CBA – Cost-Benefit Analysis
CCS – Carbon Capture and Storage
CCUS – Carbon Capture Utilization and Storage
CHP – Combined Heat and Power
CO2 – Carbon Dioxide
COG – Coke Oven Gas
FY – Fiscal Year
GT – Gas Turbine
HBS – Hot Blast Stove
HP – High Pressure
HRSG – Heat Recovery Steam Generator
IP – Intermediate Pressure
KPI – Key Performance Indicators
LP – Low Pressure
RES – Renewable Energy System
ST – Steam Turbine
STEG – Stoom- en gascentrale
TRL – Technology Readiness Level
TSIJ – Tata Steel IJmuiden
ULCOS – Ultra Low Carbon Dioxide Steelmaking
VN – Velsen Noord
BF – Blast Furnace
WAG – Work Arising Gas
WHR – Waste Heat Recovery

1. INTRODUCTION

Tata Steel IJmuiden is an integrated steel mill located in the vicinities of Beverwijk, Velsen Noord and Wijk aan Zee which produces and supplies more than 7 million tonnes of high-quality and coated steel to various sectors such as the automotive industry, construction, and packaging industries every year (Tata Steel 2020). According to *Ritchie and Roser 2017* industrial sources accounts for 20% of CO_2 emissions on an annual basis. Within industrial sources, the steel industry is a substantial source of anthropogenic CO_2 emissions. Tata Steel IJmuiden is currently responsible for around 7% of all Dutch carbon dioxide emissions (Tata Steel 2020).

The climate goals for 2030 demand a decrease in emissions by 43% compared to 2005 levels (European Commission 2014) and an increase in energy efficiency by 32.5% (European Commission 2018). The national targets for the Netherlands are also clearly defined and it demands 14.3 million tonnes of CO_2 reduction in the industrial sector by 2030 (Klimaatakkord 2019). The accomplishment of these goals require huge investments in research, development and deployment of new assets and technologies. Each company has a responsibility to achieve these goals and decrease their emissions, however, there are several constraints for this accomplishment, the primary being no compromise on competitive position.

1.1 Sustainability at Tata Steel

Steel is the most commonly used metal in the world. With modernisation and gentrification, the demand for steel is expected to keep on rising because of its benefits compared to other materials. However, steel can easily be integrated into the circular economy as steel is never consumed and is infinitely recylable without and loss on quality (Tata Steel 2020). TSIJ already utilizes 20% steel scrap in their integrated steelmaking process, for instance, when an asset/plant at TSIJ reaches the end of its lifetime, the beams, pipes and other components of the plant are recycled to produce more high-quality steel. Thus, it is fair to say that steel maximizes the value of resources.

Tata Steel is a member of the ULCOS (Ultra-Low CO_2 Steelmaking), which is a partnership between European organizations with a goal to decrease the carbon dioxide emissions of steelmaking by 50% by the year 2050 (Tata Steel 2020). As TSIJ still uses the blast-furnace route to produce steel there is a limit to the possibility of decarbonization and achieving the goal of becoming a carbon-neutral steelmaker. They are investigating and researching in different routes as an alternative to the blast-furnace route, however, in the near future this route is still going to be the primary method to produce steel and there have to be technologies which complement it instead of completely replacing it.

Tata Steel has improved its energy efficiency by 30% over the past 30 years and is constantly investing and researching methods to decrease it's CO_2 emissions for its target to become a carbon-neutral steelmaker by 2050, in line with the European targets (Tata Steel Sustainability Report 2018). TSIJ utilizes methods at its disposal and further invests in emerging technologies such as carbon capture and storage/utilization: converting process gases from steel production into feedstock for the chemical industry and securely storing CO_2 in empty gas fields, hydrogen from renewable energy, recycling and using scrap and, it's breakthrough technology HISarna to pace into a circular economy. This makes it one of the world's most CO_2 efficient steel companies.

1.2 Carbon Capture Storage and Utilization at Tata Steel

The CCUS initiative of TSIJ is one of the most ambitous Dutch CCS projects as it aims to decrease direct/scope 1 CO_2 emissions by 4 to 5 million tonnes every year by the storage of CO_2 in an empty gas field in the North Sea and utilization of CO_2 as a feedstock for the chemical industry. This initiative is called Project Everest and stands for "**E**nhancing **V**alues by **E**missions **R**e-use and **E**missions **St**orage."

This initiative would complement the Athos Consortium [Tata Steel, GasUnie, EBN and Port of Amsterdam] which aims to create a network for the safe transportation and storage of CO_2 from different industries based in the North Sea canal to empty gas fields in the North Sea. The consortium has already carried out feasibility studies and shown that there are no technical barriers or new technologies needed to be developed for the implementation of this project (Athos 2018).

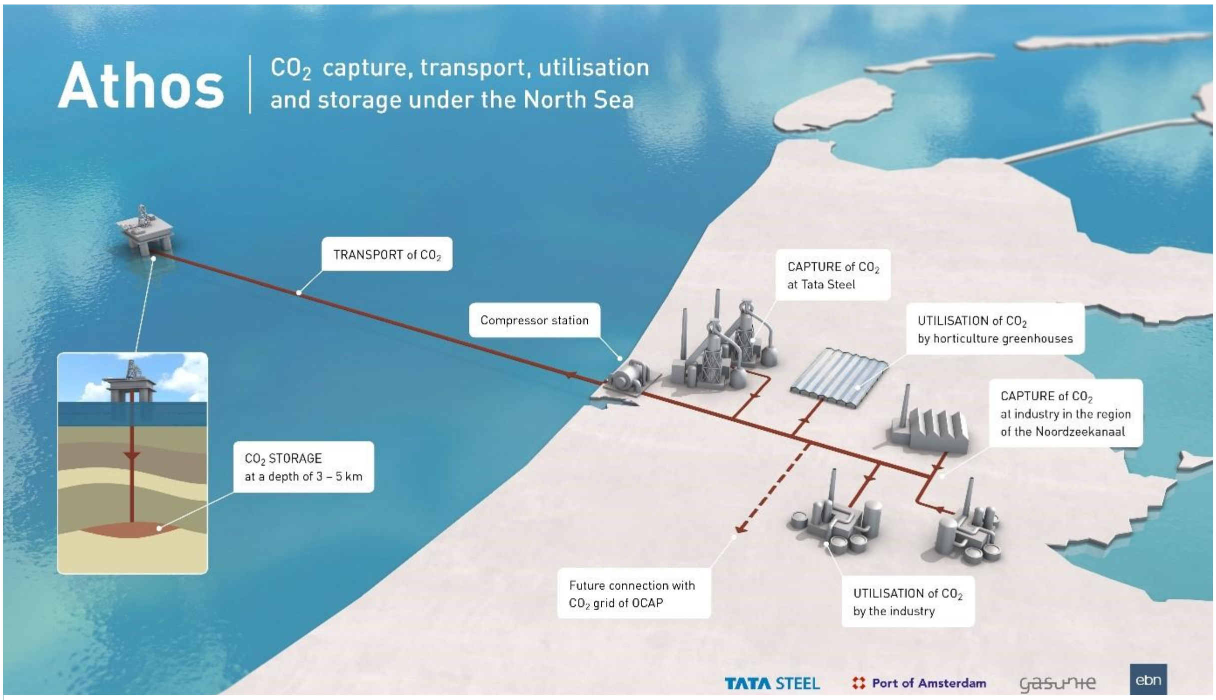


Figure 1: Athos Overview [Figure reproduced in full from Port of Amsterdam website]

1.3 Energy Demand of CCS

Carbon Capture and Storage is going to be a vital part for the energy transition and meeting the goals put forward by the Climate Agreement. However, while talking about CCS is often overlooked that it demands huge volumes of heat and electricity. New technologies are currently being researched on to make these demands smaller, however, with the current technology it is inevitable that CCS would incur an energy penalty to any industry.

As described in the section above the feed stream has to go through several steps to finally be stored securely in a reservoir. Each step has a different amount and different type of energy required, however, the largest energy requirements are allocated to the so-called stripping section and compression of the product CO_2. Carbon separation through absorption (post-combustion) is one of the most mature CO_2 capture technologies, however, for the amine regeneration and the absorbed carbon dioxide separation phase, substantial volumes of heat are required, which is the major energy penalty of the whole process (Wang et al 2011). The estimated heat demand is between 2.5 – 4.0 MJ/kg CO_2 depending on the process design, type of solvent and quality of CO_2 source (Ali et al 2018).

For the compression of the CO_2 to be further transported for storage, electricity is required, and this adds to the demand of CCS as well. For Project Everest, these demands are already quantified and described further in the methodology section.

2. RESEARCH BACKGROUND

2.1 Existing System

As Tata Steel is an integrated mill and uses the blast-furnace route for the steelmaking process, it emits several **W**ork **A**rising **G**ases (WAGs) namely Blast Furnace gas (BFG), Basic Oxygen Steelmaking gas (BOSG) and Coke Oven Plant gas (COG). Due to the high volumes of steel production, the amount of these gases emitted by TSIJ are also immense. However, as these gases are not completely combusted and contain non-combusted elements (such as CO and H_2) they can be combusted further to be utilized as a heat or power source within the site. Currently, TSIJ utilizes these gases to satisfy its own heat and electricity demand using different boilers and powerplants on site. Although these gases contain the energy required in order to satisfy the demand of the site, a minimal amount of natural gas is also imported for two reasons, balancing supply and demand and increasing the heating value of WAGs in order to improve the efficiency at which they are combusted and converted into electricity and heat.

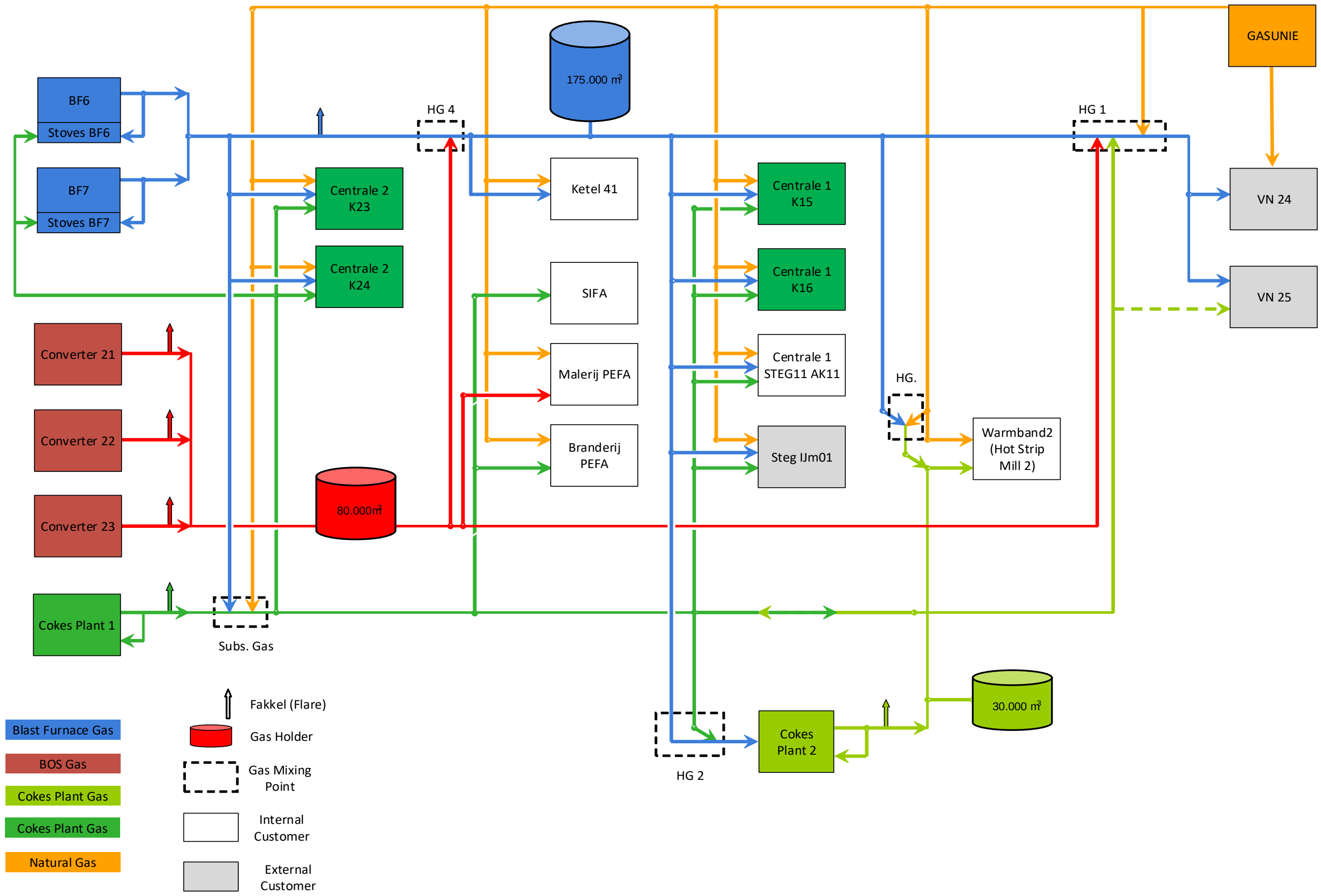


Figure 2: Existing System at TSIJ [Produced in full from Tata Steel Internal Documentation]

From the above figure, the different streams of WAGs can be seen according to the legend. The WAGs are utilized for different internal consumers and external consumers as a heat source. After the utilization of the WAGs by the internal consumers, the excess is sent to Steg IJm01, VN24 and VN25 [marked in grey]. These three consumers are the power plants at TSIJ and provide for the electricity of the whole site (owned by Vattenfall).

The WAGs differ from each other and based on their properties (composition, LHV, etc) they are utilized by different steps of the steelmaking process and the excess is sent for power production. Even though TSIJ is such an enormous site with different plants and consumers, that require these

WAGs, the amount of excess gas that is sent for power production is quite significant. On an average 700,000 Nm^3/hr is sent to Vattenfall, and at a maximum 780,000 Nm^3/hr.

2.2 Implementation of Project Everest

Project Everest is divided into two phases, carbon capture and storage being the phase 1 and carbon capture and utilisation being phase 2. The first phase aims to achieve a reduction of 3 Mton/year. The whole process consists of 8 different steps and is realized in two phases:

Phase 1: Carbon Capture and Storage

1. Gas Cleaning: removal of contaminants
2. LP(Low Pressure) CO_2 Absorption: removal of CO_2 by amine solvent absorption
3. Amine Stripper: regeneration of CO_2 rich amine solvent and liberaton of CO_2
4. CO_2 Compression: compression of CO_2 for Athos

Phase 2: Carbon Utilization and Storage

5. Water-Gas Shift Reaction: catalytic reaction of process gases with water, to adjust the H_2:CO ratio for syngas conversion
6. HP(High Pressure) CO_2 Absorption: removal of CO_2 [produced due to step 5] by amine solvent absorption
7. Syngas Conversion: production of hydrocarbons from syngas
8. Product Recovery: seperation of hydrocarbons

However, for this research project only Phase 1 was considered as finalizations for Phase 2 are still underway at TSIJ.

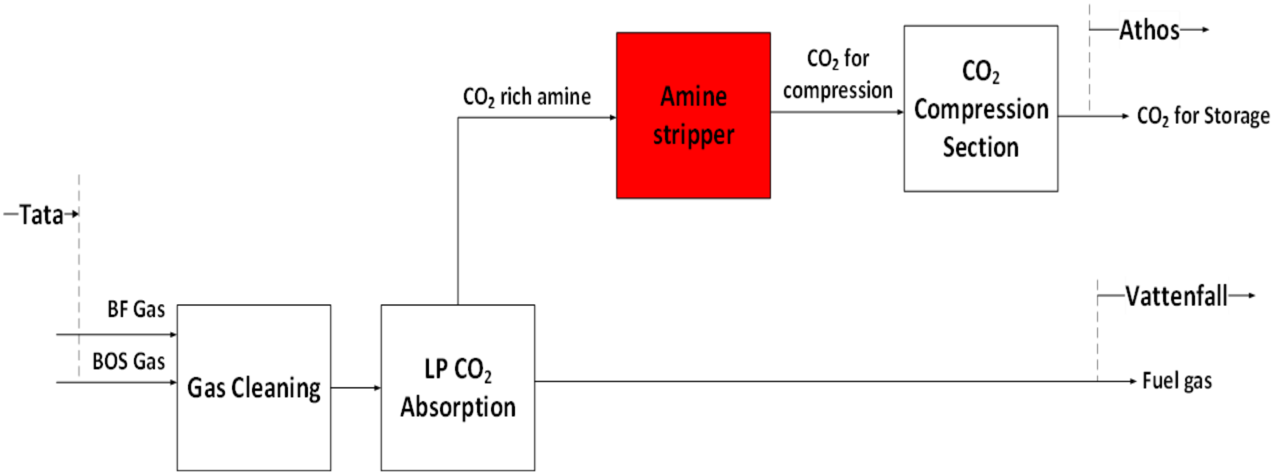


Figure 3: Phase 1 of Project Everest [Reproduced in full from TSIJ Everest Project Description]

After removing contaminants from the stream of WAGs entering Everest, its sent to the LP CO_2 absorption section where the main goal is to capture most of the CO_2 from the WAGs. Currently, the solvent is assumed to be methyl diethanolamine (MDEA) and the anticipated absorption efficiency is 88% for this study, the actual target for CO_2 recovery is >95%. Now, the stream of WAGs is divided into two streams, one being the CO_2 rich amine and the other being the fuel gas (or Everest Gas) which is sent for power production.

The CO_2 rich amine is sent to an amine stripper, where it is subjected to high volumes of heat to liberate the CO_2 and regenerate the amine solvent. The amine solvent is recycled and used again in the LP CO_2 absorption stage whereas the CO_2 stream is sent to the compressor where it's compressed to the required pressure of the Athos network and subsequently transported for storage in the North Sea.

2.3 Energy and Heat Demand of Tata Steel IJmuiden

2.3.1 Tata Steel IJmuiden

According to the Project Everest poster, the amount of WAGs required for the heat and energy demand [Appendix Table I, FY 15/16]:

(i) Heat Demand TSIJ: **29.8 PJ**
(ii) Power Requirements TSIJ: **25.2 PJ**

The total amount of WAGs required for power production was 25.2 PJ in three different powerplants namely IJm01, VN24 and VN25. Thus:

a. For IJm01

A total of 8.3 PJ [7.7 PJ of BF gas, 0.6 PJ of BOSG] was sent to IJm01 in 15/16 for power production. Assuming an efficiency of 42% [actual efficiency depends on amount of gas provided and differs dynamically] the total power capacity was: **110.54 MW**

b. <u>For VN24 and VN25</u>

A total of 16.8 PJ [12.2 PJ of BFG, 1.6 PJ of COG, 3 PJ of BOS] was sent to VN24/25 in 15/16 for power production. Assuming an efficiency of 38% the total power capacity was: **202.43 MW**

Hence, the total power demand of TSIJ for FY15/16 was **313 MW**

2.3.2 Tata Steel IJmuiden with Project Everest

The heat and energy demand changes after the implementation of Project Everest, however, the original heat flows are assumed to be the same, thus:

(i) Heat Demand TSIJ: **29.8 PJ**
(ii) Power Requirements TSIJ: **313 MW**
(iii) Heat Demand Everest: The stripper duty is anticipated to be 2.7 GJ/ton of CO_2 and an estimated 3 million tons of CO_2 is to be captured in phase 1. Therefore, making the total stripper demand**: 8.1 PJ** [this is an assumption, actual calculation is done in the model at an hourly basis]
(iv) Compressor Demand: **40 MW**

2.3.3 Changes in Existing System

As shown in figure 3, the WAGs which are fed to Project Everest are BFG and BOSG. The amount of BFG and BOSG sent to Project Everest is the same as the amount sent to Vattenfall (700,000 Nm^3/hr on an average). Once CO_2 is absorbed from the feed-stream, the CO_2-lean gas (Fuel Gas or Everest Gas) is utilized using the same priorities as before, first, it is sent to the internal consumers and then the excess is sent for power production.

However, as Project Everest requires heat energy for the stripper demand a new asset must be built to provide for the demand of the stripper. Thus, for most of the new assets it is anticipated that the Everest Gas will be combusted to provide for the stripper demand. Hence, the total amount of Everest Gas going for power production decreases as some of it is displaced to provide for the stripper demand. It is essential to find out which asset utilizes the Everest Gas in the most optimal way.

3. PROBLEM DEFINITION AND RESEARCH AIM

3.1 Problem Definition

As described above, TSIJ utilizes its WAGs for power and heat production, and this satisfies the demand of the entire steel mill. However, after the implementation of carbon capture storage and utilization the energy flows within the steelworks would be altered. Also, as there are additional assets which are added to the whole system the energy requirements of the steelworks would increase, which is counterintuitive to the decarbonisation goal as more energy utilization correlates to higher greenhouse gas emissions.

Considering the high volumes of CO_2 TSIJ aims to store the energy requirements are substantial and an extra import of electricity is inevitable. Hence, a strategy must be developed to optimize the energy flows and keep the import of energy minimal with technologies or a combination of technologies.

3.2 Research Question

The aim of this research internship is to design a model and analyse the different pathways or scenarios which could potentially optimise the energy infrastructure of TSIJ. Comparing a combination of best available technologies and emerging technologies to realise a concise and optimal solution for keeping energy import and CO_2 emissions at a minimum, taking into consideration added costs which would be required to deploy these pathways. A significant aspect of the project would be to compare these pathways on key performance indicators such as CO_2 emissions, operational costs, import of electricity, etc.

The main research question is as follows:

“What technology or a combination of technologies has the highest potential to optimise the energy infrastructure of Tata Steel IJmuiden, taking into consideration the decarbonisation goals and investment & operating costs of deploying the same, after the implementation of carbon capture and storage/utilization?”

For answering the overarching question, there are various sub-questions formulated but not limited to the following:

(i) How can TSIJ keep powering the site while reducing emissions in the most energy efficient way?

(ii) What is the most cost-effective combination in terms of construction and operations of power and heat production against the import of electricity from the grid?

What assets will become obsolete and which would have to be further developed?

4. SYSTEM AND MODEL EXPLANATION

As this is partly a modelling assignment, the first step was to perform an internal and external literature study to understand and program the current infrastructure and energy flows within Tata Steel IJmuiden. The whole model was built separating different systems and defining inputs and outputs of that block. There were various documents within TSIJ and also similar studies, research performed by other companies around the world which helped in determining the best viable pathways and also provide a first look on how feasible and potentially interesting several pathways were in the real world. Although internal documentation provided a good overall picture of the flows and infrastructure, there were also some expert interviews with people from different departments within TSIJ for the potential implementation of a certain pathway/technologies and how it would perform as an addition to the current infrastructure.

4.1 GoldSim

The model was built using the GoldSim Academic Environment, as this software provided the possibility of doing a scenario analysis and allowed inclusion of complex and detailed flows. The major advantage of this software was that it allowed for stochastic inputs when enough data was not available to determine and quantify some variables. There were several pathways reviewed in the beginning of the project and as the project progressed more were added. The model was built for the base-case and then cloned several times to perform a CBA and calculate the key performance indicators.

4.2 Input Basis of the Model

Energy Flows were modelled into the GoldSim Environment using the Project Everest poster as the main reference, the first attempt was to use all the energy flows provided by TSIJ [Tata Steel Internal Documentation, FY15/16] and then input the additional EVEREST parameters into the model. However, for optimization and simplicity the internal consumers were combined thus eliminating the need of excess blocks in the model. These internal consumers were defined as the overall needs of TSIJ.

4.2.1 Feed Flow to Everest

The WAGs which are used on site, excluding the WAGs for the hot blast stoves was the feed flow input to Everest. As mentioned below, the amount of WAGs sent to Vattenfall on an average is 700,000 Nm^3/hr and maximum is 780,000 Nm^3/hr. However, due to fluctuations in gas flows and production the feed flow can be different. Thus, the feed flow was determined using real-time process data, however, the maximum amount of stream that could go to Everest was capped at 780,000 Nm^3/hr. The feed stream was calculated using the parameters below:

(i) **Blast Furnace Gas Input**: From real-time process data 2015 – 2019. The hourly feed to Everest from BFG is determined by deducting the Hot Blast Stove consumption, and the excess is sent to Everest.

(ii) **Hot Blast Stove Consumption Input**: From real-time process data 2015 – 2019.

(iii) **Basic Oxygen Steelmaking Gas Input**: From real-time process data 2015 – 2019. The BOSG is sent to Everest only if there is not enough BFG available for the 780,000 Nm^3/hr feed. Thus, BOSG is used as a buffer to maximise the CO_2 captured by Everest.

Therefore,

When, BFG - HBS >= 780,000 Nm^3/hr
Feed Flow Rate = 780,000 Nm^3/hr

When, BFG - HBS < 780,000 Nm^3/hr and BOSG > 0 Nm^3/hr [after providing for internal consumers]

Feed Flow Rate = [BFG – HBS] + BOSG

4.2.2 Energy Flow and Energy Content of WAGs [LHVs]

The feed flow was determined using the methodology described in section 4.2.2. However, this only gives the amount of gas being fed to Everest and to translate it into the amount of energy is essential for the balances. The LHV of a gas is estimated using the composition of the gas and is known for the WAGs at Tata Steel. However, once the CO_2 has been captured from the WAGs the LHV of the gas increases due to removal of a non-combustible component. The complete composition of both the gases are in Appendix Table II.

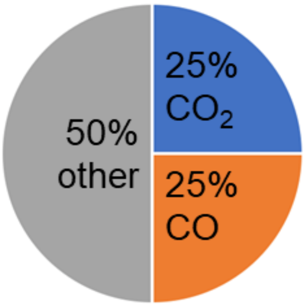


Figure 4: Composition of BFG

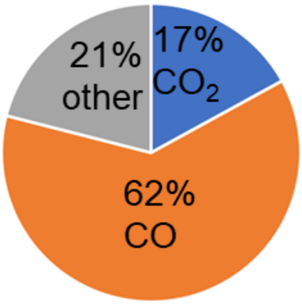


Figure 5: Composition of BOSG

LHV of BFG: ***4022 kJ/m^3***

LHV of BOSG: ***8000 kJ/m$^{3'}$***

The CO_2 absorption rate is 88%, thus the processed WAGs provide more energy per m^3 of gas, this was calculated using the separate LHV values of components and adding them up:

LHV of CO_2-lean BFG: **4900 kJ/m^3**

LHV of CO_2-lean BOSG: **9400 kJ/m^3**

Thus, using the above LHVs and Feed Flow Rate determined using methodology from section 4.2.2, the energy flow of the WAGs is determined for every hourly iteration, using respective LHVs:

Energy Flow WAGs [Hourly Iteration] = (Feed Flow Rate [BFG] * LHV of CO_2-lean BFG) + (Feed Flow Rate [BOSG] * LHV of CO_2-lean BOSG)

4.2.3 CO_2 Captured by Everest

The CO_2 captured by absorption is dependent primarily on the feed flow and the composition of the gas. This parameter is also calculated on an hourly basis as we have all the data required at our disposal. The CO_2 captured is calculated using the parameters below:

(i) **Feed Flow Rate:** Determined using above methodology in section 4.2.1.

(ii) **Absorption Rate:** The absorption rate is anticipated to be 88% by the Everest team, however, this is kept dynamic and can be changed in the future.

(iii) **CO_2 Composition:** From real-time process data 2015 – 2019, for BFG from BF6, BF7 and BOS plant. The CO_2 composition of BFG and BOSG also changes on an hourly basis, and this is also input into the model.

Therefore, CO_2 Captured = Feed Flow Rate * Absorption Rate * CO_2 Composition

4.2.4 Amine Stripper and Compressor Demand

The Amine Stripper is the major consumer of energy for the CCS process. TSIJ has anticipated the solvent to be MDEA and thus this governs the amount of energy required for the regeneration of amine and liberation of carbon dioxide.

The process steam required to satisfy the requirements of the solvent is estimated to be superheated steam of **3.5 bar at 160 °C**. Thus, this helped in defining the energy and mass flow required for the heat demand of the stripper.

Latent Heat of Superheated Steam [3.5 bar, 160 °C]: **2130 kJ/kg**
Estimated Total Stripper Demand: **8.1 PJ/year**

Assuming total amount of working hours as **8400 hours**:-

Energy flow: **964 GJ/hour**
And, the amount of mass flow: **452 tonnes/hour**

After the amine is stripped and CO_2 is liberated, the CO_2 stream is sent for further compression to a pressure required by Athos. Currently, the anticipated pressure at which Athos would transport CO_2 is **20 bara** and its anticipated by TSIJ that the power required to operate Everest and compress the CO_2 to this pressure is **40 MW.**

4.2.5 Electricity Production

Tata Steel IJmuiden has three power plants on site to provide for its electricity demands. For this modelling assignment it was assumed that all the excess gas, after internal users and Everest have been provided with the required fuel gas, would go to VN25 for electricity production. The reason for this assumption is that closure of one of the power plants is foreseen. The volume of fuel gas after subtraction of the heat requirements of Everest, exceeds the capacity of IJm01 thus VN25 is assumed to be operated. Thus, once the CO_2 is absorbed from the feed stream of Everest it is sent to internal consumers and the excess remaining Everest Gas is sent for electricity production to VN25.

The efficiency assumed for power production at VN25: **38%**

4.3 Waste Heat Recovery

As Tata Steel has so many assets and plants, there is a lot of potential for Waste Heat Recovery. There have already been various studies to see which sources of waste heat can be applicable to Project Everest. Thus, this was used as a toggle switch to see how much difference it makes in terms of the KPIs for each scenario. The data for the Waste Hate Recovery was according to the following table:

Table 1: Waste Heat Recovery Potential (Tata Steel Internal Documentation 2020)

Source	Technology	Waste Heat Potential [PJ/yr]	TRL	Investment (MMEuro)	Max Allowable Investment (MMEuro)
HSM2 Oven	Flue Gas Boiler	0.4	9	4 - 20	12
Cokes Plant 1	CDQ	1.5	9	30 - 80	44
Cokes Plant 2	CDQ	1.2	9	30 - 80	35
SiFA hot air	Flue Gas Boiler	0.75 – 2.2	9	6.3	15
CON23 flue gas	Flue Gas Boiler	0.5	9	30	15
HDG 3	Flue Gas Boiler	0.1	9	4.3	3

Looking at table 1, a total potential of 6.9 PJ can be harvested, however, for the purpose of this project only the sources with flue gas boilers are taken into consideration as its speculated that only these sources would have enough exhaust heat to produce LP steam. The amount of waste heat is variable depending on how much potential is realized, for simplicity, this was used as a stochastic input in the model to see how much difference it makes in terms of KPIs.
Stochastic Input of Waste Heat: **0.4 – 3.2 PJ/year**

4.4 Net Reduction Potential

Tata Steel aims to decrease 3 million tonnes of CO_2 in the first phase, however, it inevitably imports electricity from the grid thus, also importing some emissions because of it. Thus, the actual reduction potential of the whole project changes because of these imported emissions. Further emissions caused by the processing of CO_2 by Athos, for further compression, transport, and storage, are yet undefined and also left out of scope. Both the volume and the cost of those emissions is equal in all scenarios (the amount of captured CO_2 does not differ), so margin improvements in both cost and net reduction potential are not influenced by these emissions.

Net Reduction Potential = 3 Mton – CO_2 Emissions Imported Because of Electricity

For the study, it was assumed that the electricity imported is from the Dutch grid and thus,
CO_2 Emissions Imported = **414 g/KWh** [EnTrance 2019]

4.5 Financial Analysis

Based on current forecasts Tata Steel expects that it must pay the following price for electricity from the Dutch grid by the time Everest becomes operational: **51 EUR/MWh**

4.5.1 Maximum Allowable Investment

A financial analysis was performed to compare the different scenarios and how viable they are in terms of investment costs. However, as it is highly complicated to have a proper quantification of CAPEX for such complex assets, the analysis was done using a Maximum Allowable Investment method. Thus, assuming a payback period of 5 years and the OPEX being comparable on all aspects such as personnel, utilities, and maintenance apart from energy related OPEX. It should also be realised once more that the direct emissions resulting from the combustion of CO_2 lean WAGs will be equal in all scenarios, as all the WAGs will be combusted somewhere in each scenario. This makes the electricity imported from the grid the only parameter to be minimised, both from a cost and a net emission reduction perspective, and that parameter was compared to the base-case scenario.

Thus, Maximum Allowable Investment = **Electricity Savings for 5 Years**

However, it is important to note that the Maximum Allowable Investment would be the investment allowed over the CAPEX of the boiler, which was also deliberately left out of scope.

4.5.2 Volatility of Electricity Markets

As the Net Reduction Potential and OPEX for the scenarios mainly depends on electricity imported from the grid. A sensitivity analysis was performed using different electricity costs to see how much difference it makes in the financial analysis for the different scenarios.

The trend of the electricity prices is input into the model using the research done by CE Delft, combining two scenarios [2030 electricity forecasted and 2030 high RES electricity forecast]. It is probable that NL moves to a high RES source but for the sake of simplicity, the range is used from 2030 low prices all the way to 2030 high RES prices and compared on the basis of a minimum and maximum basis. So, two different values are analysed to see how it affects the different scenarios:

Thus, the baseload electricity prices which are input [Source: CE Delft, 2016]:

Table 2: Electricity Prices for 2030 [CE Delft, 2017]

	Low Prices	High Prices
2030 [€/MWh]	41.8	69.8
2030 high RES [€/MWh]	31.4	53

The main difference in these two scenarios are that if the Netherlands transits towards high RES there would be considerably lower CO2 emissions imported and the electricity prices would be also lower. This is beneficial for Tata Steel as it increases the net reduction potential of the whole project.

5. SCENARIO MODELLING

5.1 Boiler Scenario [Base-case]

For the base-case scenario a boiler fired by the Everest gas would provide for the stripper demand, inevitably decreasing the electricity produced on site by Tata Steel. Thus, the Everest Gas priorities would be as follows: *(i) Internal Consumers at TSIJ, (ii) Everest Boiler and the remaining excess would go to (iii) Velsen Noord 25 (VN25 – Vattenfall Power Plant).*

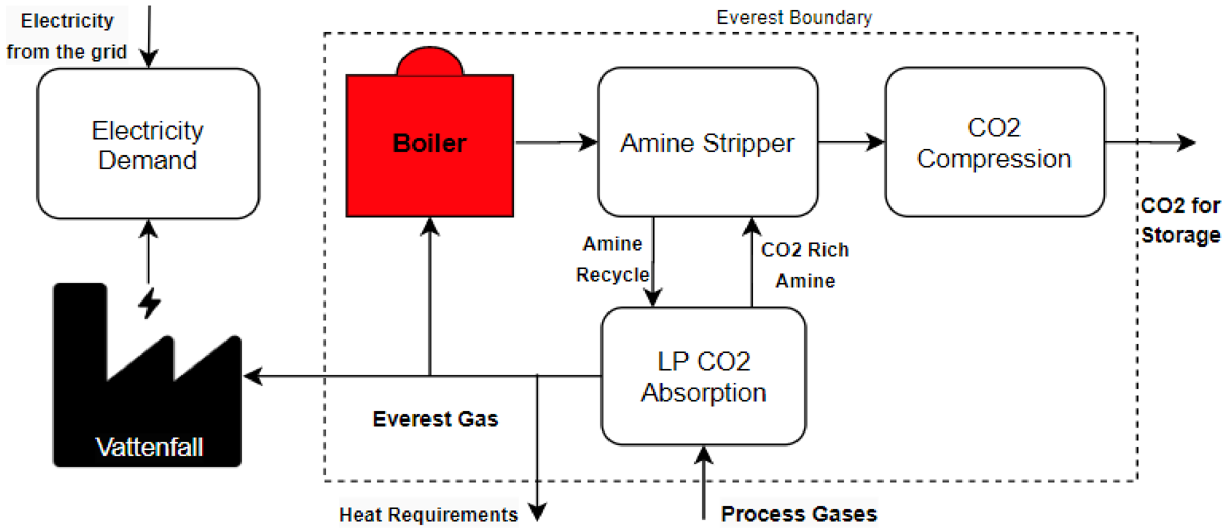


Figure 6: Block Flow Diagram of Everest [Base-Case Scenario]

This configuration inevitably decreases the amount of Everest Gas going to the power plant and subsequently also the electricity produced on site. Thus, the remaining electricity demand which is not met by the electricity production on site would be imported from the grid.

Efficiency of Steam Production in the Boiler: **85%**

5.2 High Temperature Heat Pump Scenario [Heat Pump]

In this scenario, a high temperature heat pump powered by electricity would provide for the heat requirements of the stripper. So all the Everest Gas would go for power production to Vattenfall at 38%, however, as the overall electricity demand of the site has increased (Compressor demand + also heat pump demand) electricity would have to be imported from the grid as well. Currently, there are various companies which provide for high temperature steam pumps at a commercial level, however, for steam generation there are only a handful of companies which provide for the same. For this model, the data has been taken from one of the publicly available brochures of one of these companies (Durr thermea 2019)

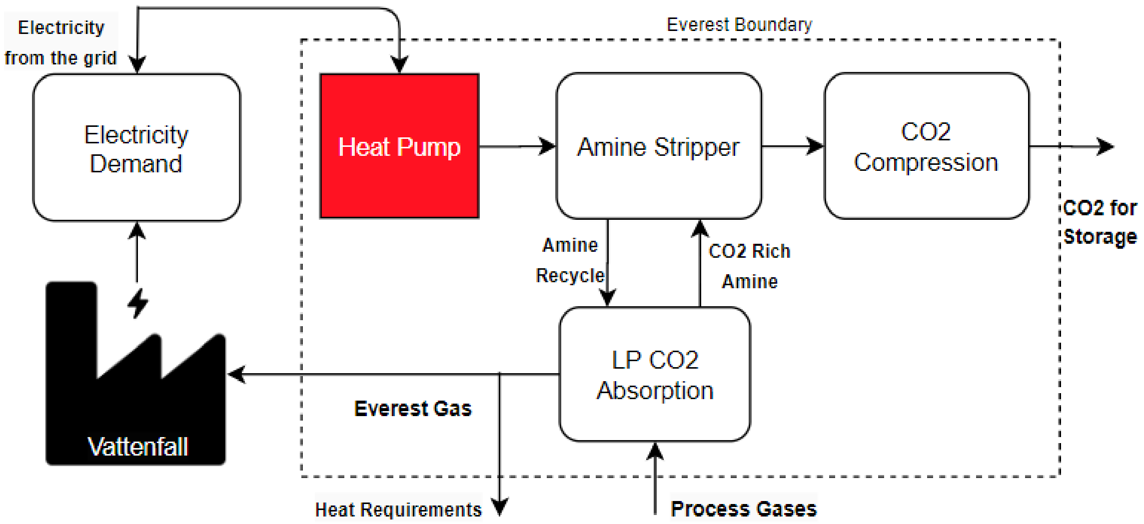


Figure 7: Block Flow Diagram for Everest [Heat Pump Scenario]

The primary requirement of a steam generation heat pumps is that there should be ample waste heat at a reasonable temperature continuously available. These heat pumps which provide steam at temperatures above 110 °C have an average temperature lift of 130K to 25K with an COP ranging from 1.6 to 5.8, respectively (Arpagus et al. 2018). There are also various research and development projects of heat pumps around the world which are in high TRL stages right now.

Durr thermea claims that it can make a temperature lift of 100 K, using multiple steps with a COP of 2.8, and hence the data from them was chosen as the basis of this heat pump scenario. This heat pump prepares high temperature water (<100 °C) in the first step and then using a vapour steam compressor vaporises the water to low pressure steam (around 70 °C, 0.32 bar), the next step is an adiabatic compression which prepares steam of 130 °C at 1.5 bar. The assumption here is that this steam satisfies the stripper requirements.

(i) *C.O.P is inversely proportional to the temperature lift, the smaller the temperature lift higher is the C.O.P:* ***2.8 for 80 K temperature lift (inversely proportional)***

(ii) *Stochastic input for Waste Heat Stream and assumption that it is continuously available:* ***50 ± 20 °C***

<u>Monte Carlo Simulations:</u>

There were Monte Carlo simulations performed for the heat pump scenario due to the uncertainty of available waste heat and variable C.O.P. The results for the same are in Appendix Table III. The Monte Carlo simulations provided with a range of possible outcomes, however, for the simplicity of comparison between scenarios, the mean values were used (thus, the values obtained for a C.O.P of 2.8, for a 80K temperature lift and available waste heat at 50 °C).

5.3 Combined Heat and Power Plant Scenario

Three variants of CHPs were decided for a preliminary analysis as the research progressed, they were modelled into GoldSim, to get the following results. The scenario with a newly built boiler and back-pressure turbine as described in section 5.3.2 uses steam properties and state-of-the art boiler & backpressure turbine properties to yield the results, whereas, the scenario with a gasturbine and heat recovery steam generator as described in section 5.3.1 directly uses assumed efficiencies [Tata Steel Internal Documentation, 2020] for HRSG and Gas Turbine to yield the results and the scenario with the combination of the gas turbine, heat recovery steam generator and back-pressure turbine as described in section 5.3.3 is a combination of the two above and uses a efficiencies of gas turbine, HRSG and a backpressure steam turbine.

The heat to power ratios of the combinations are as follows [Johansson et al. 2012]:

Gas Turbine + HRSG: **2:1**
HP Boiler + BP Turbine: **3:1**
Gas Turbine + HRSG + BP Turbine: **3:2**

5.3.1 Gas Turbine and Heat Recovery Steam Generator [HRSG + Gas Turbine]

In this type of Combined Heat and Power Plant, the fuel gas is directly combusted and expanded through a gas turbine to produce electricity. The output stream of this turbine still has substantial heat energy and is recovered using a Heat Recovery Steam Generator to provide for the stripper demand. It was assumed that the steam recovered from the HRSG would be at the appropriate pressure and temperature for the stripper demand. Everest Gas Priorities: *(i) Internal Consumers at TSIJ, (ii) Gas Turbine + HRSG and the remaining excess would go to (iii) Velsen Noord 25 (VN25 – Vattenfall Power Plant).*

Efficiency of Gas Turbine: ***40%***
Efficiency of Heat Recovery Steam Generator: ***85%***

The whole system was sized using the process steam requirements as defined in section 4.2.4.

Heat Recovery Steam Generator:

Energy Flow of Process Steam: ***964 GJ/hr***
Efficiency of HRSG: **85%**
Input Stream for Heat Recovery Steam Generator: **964 GJ/hr / 0.85 = 1134 GJ/hr**

The amount of heat which comes to the HRSG is the exhaust of the gas turbine, which was not used. Thus, if the assumed efficiency of the gas turbine is 40%, the remaining exhaust is 60% and the heat received by the HRSG is 60% of the total WAGs energy supplied to the combination.

Gas Turbine:

Output Stream of Gas Turbine: **1134 GJ/hr**
Efficiency of Gas Turbine: **40%**
Input Stream for Gas Turbine: 1134 GJ/hr / (1 – 0.4) = 1890 GJ/hr

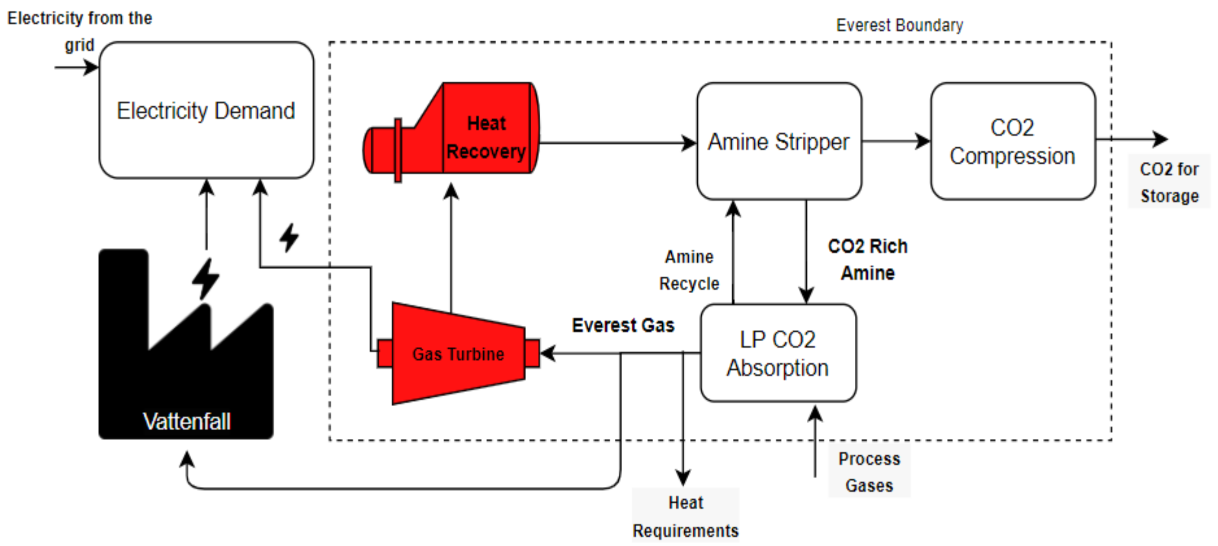


Figure 8: Block Flow Diagram for Everest [HRSG + Gas Turbine Scenario]

Thus, for this combination the feed stream of Everest Gas is 1890 GJ/hr, and the excess remaining Everest Gas is sent to Vattenfall for electricity production. The remaining electricity demand is imported from the grid.

5.3.2 Boiler + Back-pressure Steam Turbine [Boiler + BP Turbine]

In this pathway, a combination of a HP Boiler and back-pressure turbine would provide for the stripper demand and electricity as a by-product. The Everest Gas would be combusted to generate HP steam in a boiler and this HP steam would subsequently be expanded through a back-pressure turbine to give the output as the desired process steam for the stripper.

Efficiency of HP Boiler: **85%**

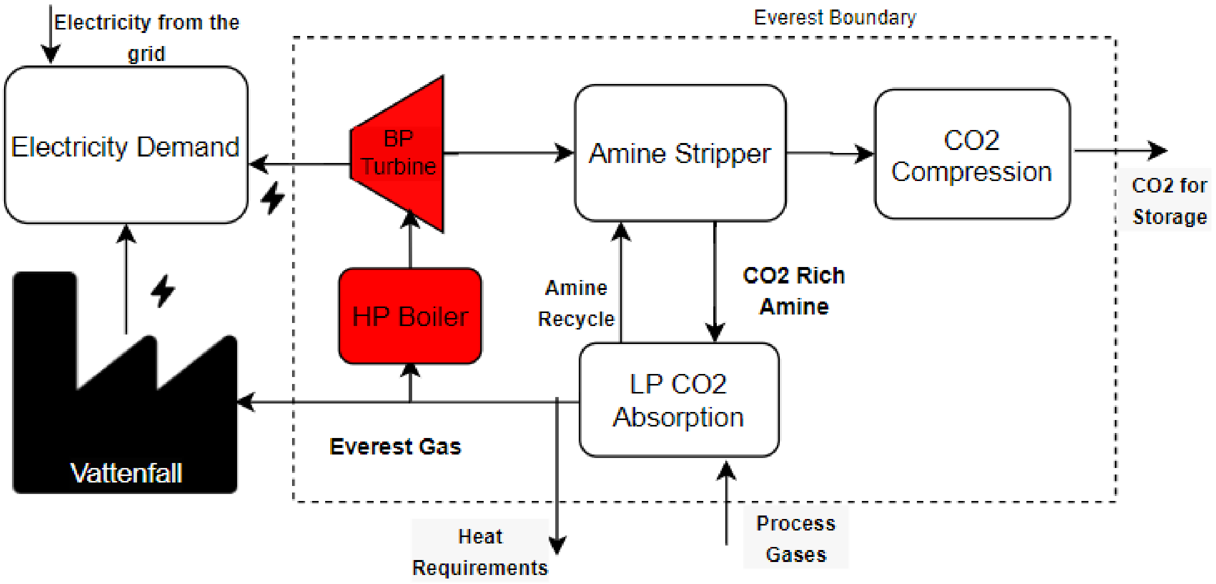


Figure 9: Block Flow Diagram for Everest [Boiler + BP Turbine Scenario]

Steam Turbine Calculations:

For the inlet conditions, a generic HP input was used thus 150 bar and the outlet steam conditions were the process steam requirements, thus, 3.5 bar at 160 °C.
Now, for a steam turbine:

Assuming inlet entropy = outlet entropy and the isentropic efficiency as 75%, the temperature of the inlet steam was interpolated to be 600 °C. (Steam System Modeler Tool, US department of Energy)

Inlet Steam Conditions: ***150 bar, 600 °C***
Outlet Steam Conditions: ***3.5 bar, 160 °C***
Mass Flow: ***452 tonnes/hour***

Power Out = Mass Flow (Inlet Enthalpy – Outlet Enthalpy)
= ***452 tonnes/hour (3542 kJ/kg – 2771.24 kJ/kg) = 97.5 MW***

Everest Gas Input:
*As the steam conditions, mass flow and boiler efficiency are known, the energy flow required to the boiler can be calculated = (Mass Flow * Inlet Enthalpy) / HP Boiler Efficiency*
*= (**452 tonnes/hour * 3542 kJ/kg) / 0.85***
= 1882 GJ/hour

Thus, for this combination the feed stream of Everest Gas is 1882 GJ/hr, and the excess remaining Everest Gas is sent to Vattenfall for electricity production. The remaining electricity demand is imported from the grid.

5.3.3 Gas Turbine, Heat Recovery Steam Generator and Steam Turbine [GT + HRSG + ST]

In this scenario, first the Everest Gas would be expanded through a gas turbine and subsequently the exhaust will be used to produce steam (high pressure in this case), similar to scenario 5.3.1, however, once the HP steam is produced it will be expanded through a steam turbine for increased electrical efficiency taking into consideration the final output process steam conditions i.e. 3.5 bar, 160 degree-Celsius.

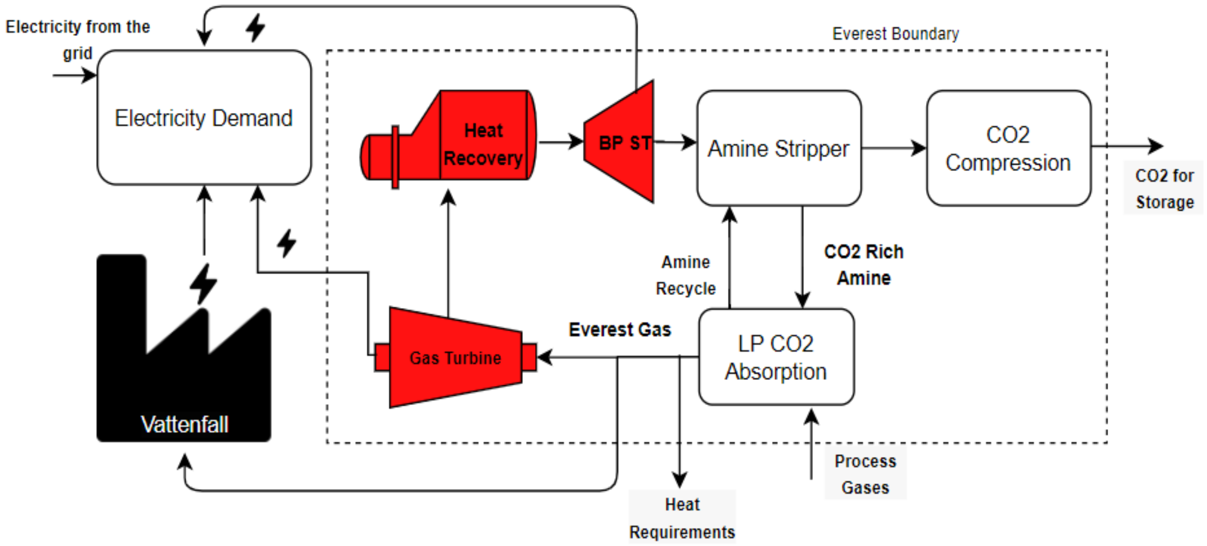


Figure 10: Block Flow Diagram for Everest [GT + HRSG + ST Scenario]

The assumption is all the Everest Gas is sent to this plant, which is **19.9 PJ/year,** thus **2270 GJ/hour.** This is done because there should be enough amount of steam to yield electricity from the back-pressure steam turbine as well.

Efficiency of Gas Turbine: **40%**
Efficiency of HRSG: **85%**
Efficiency of Back-pressure steam turbine: **21%**
[This is done, as, according to steam calculations (in Appendix IV) the maximum possible conditions of steam generation is lower than required, thus, for the sake of simplicity and in the future if more gas was available, thus increasing the overall yield, the efficiency of the turbine was calculated using scenario 5.3.2.

The remaining electricity demand was met by importing electricity from the grid.

5.4 Extraction of Steam

In this scenario, VN25 will be converted into a CHP, using extraction of steam. The extraction of steam is possible only between the IP turbine and the LP turbine because of pressure and flow constraints for the LP turbine. This would result in a higher power loss when compared to extracting steam from the LP turbine at the given conditions, as more heat is wasted for the extraction of steam.

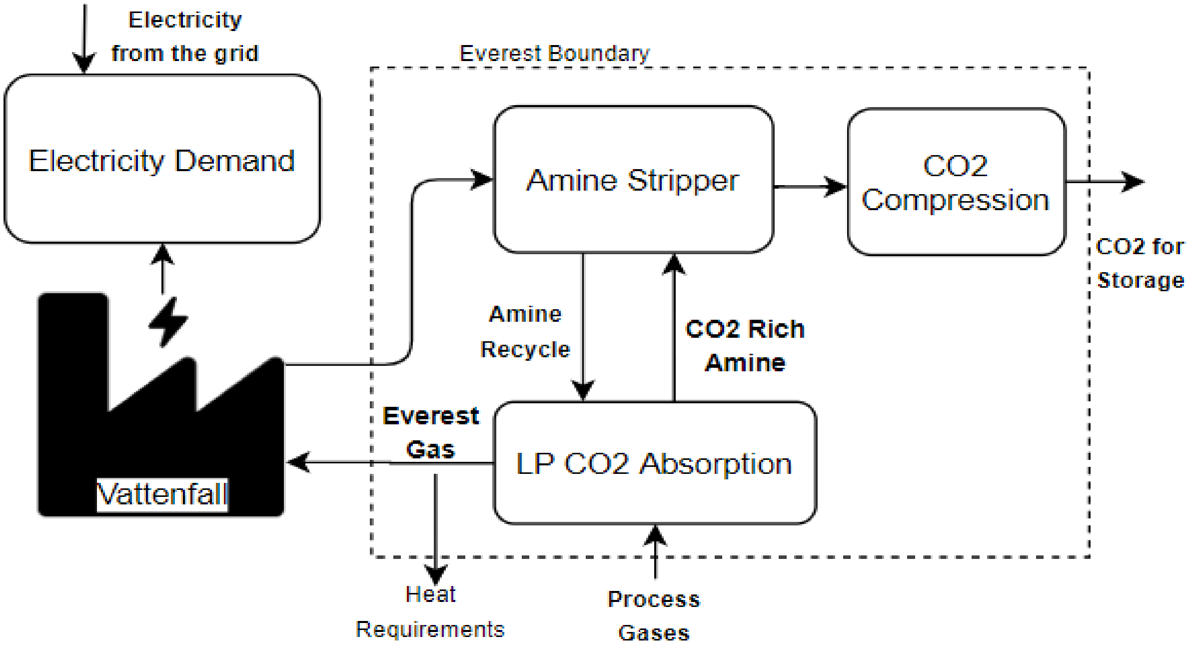


Figure 11: Block Flow Diagram Everest [Extraction of Steam Scenario]

5.4.1 Using Steam Properties

Assumption: *Steam extracted at pressure between IP and LP is satisfiable for the stripper demand*

<u>Velsen 25 Specifications</u>:

Steam Turbine with Single Reheat

Efficiency: ***38%***
Steam Conditions HP Turbine: ***180 bar, 540 °C***
Generator Capacity: ***360 MWe***
Input Energy Flow for VN25: **2670 GJ/hour** [including BFG, BOS and CGP]

We know the conditions for exhaust steam, which are the requirements of the stripper [**3.5 bar, 160 °C, 2711.24 kJ/kg**]. However, due to the mechanics of the turbine steam cannot be extracted in the LP turbine and hence would have to be extracted between the IP and LP turbine through an extraction port. The steam required at the extraction port is **452 tonnes/hour** to satisfy the demand of the stripper.

Inlet Enthalpy: **3390 kJ/kg**
Energy Flow: 2540 GJ/hour
Mass Flow of Steam Turbine in VN25: **730 tonnes/hour**

Using this data, and the input conditions which are known we can interpolate the output enthalpy (for simplicity purposes, usually the efficiency is more because of feedwater heating and condensing turbine).

Using 38% efficiency for an energy flow of **2670 GJ/hour** [including BFG, BOS, COG, NG], the power output is **276 MW.**

Steam Turbine Calculations:
*Inlet Enthalpy of Steam: **3390 kJ/kg***
*Outlet Enthalpy of Steam: **2777 kJ/kg***

Power Out = Mass Flow (Inlet Enthalpy – Outlet Enthalpy), Thus **276 MW = 730000 (3390 – x)**
Therefore, outlet enthalpy is circa ***2000 kJ/kg***

Thus, now calculating power loss equating the amount of steam extracted,

Total Power = Mass Flow (Inlet Enthalpy – Enthalpy Steam Extraction) + (Mass Flow – Mass Steam Extracted) (Enthalpy Steam Extraction – Outlet Enthalpy)

5.4.2 Using Extraction of Steam v/s Power Loss

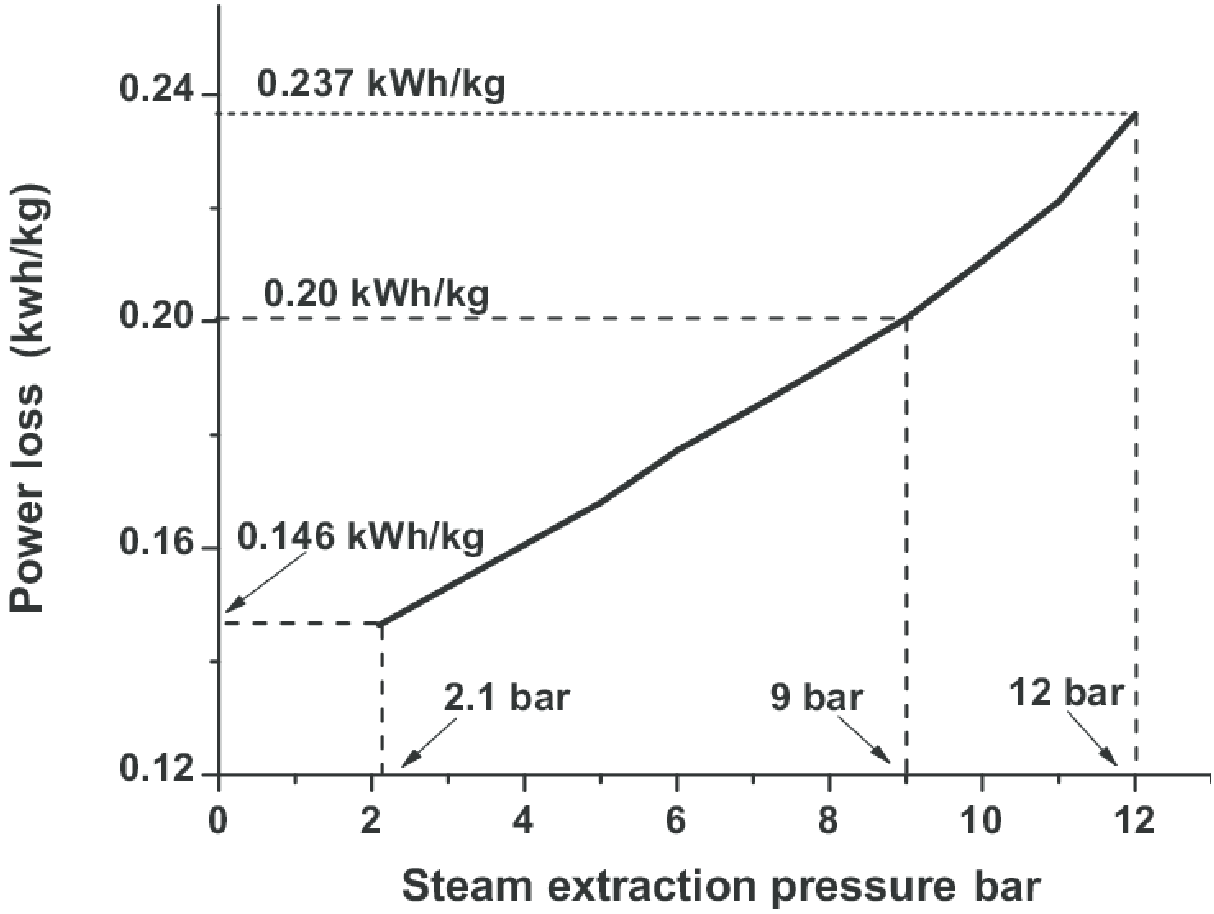


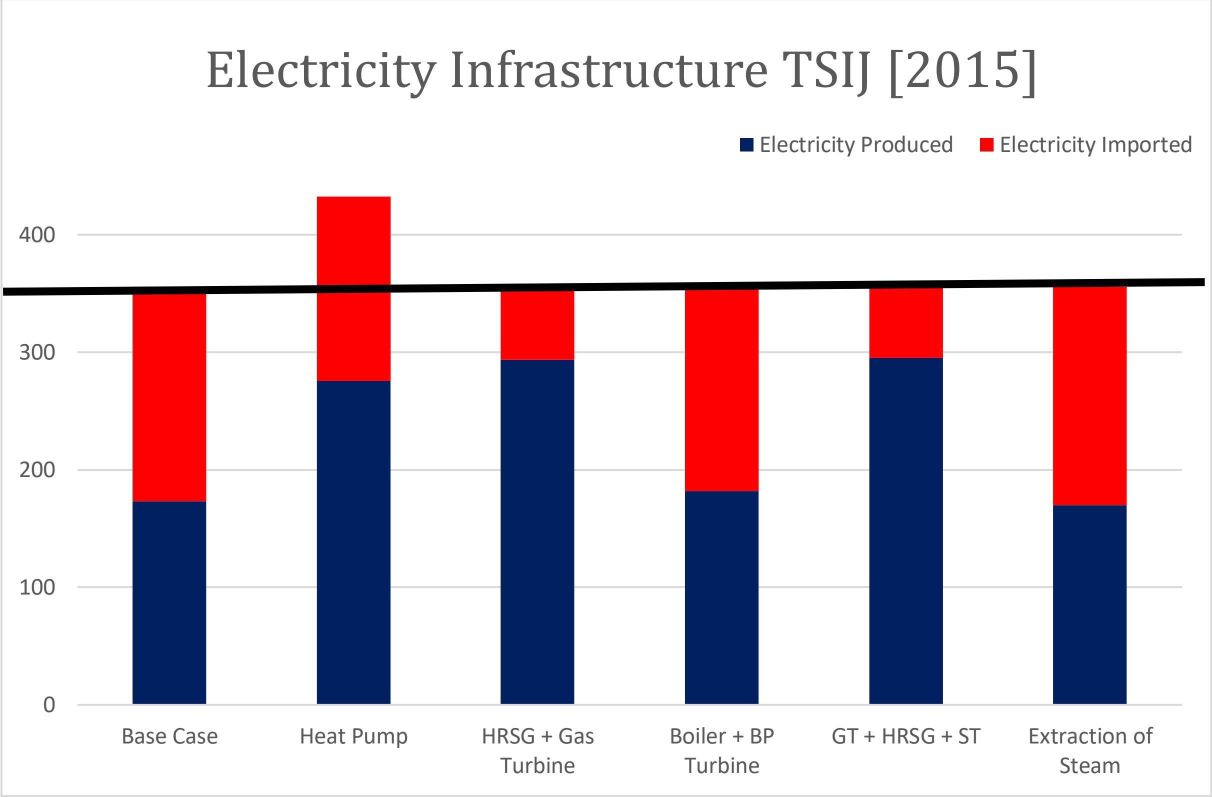
Figure 12: Steam Extraction vs Power Loss [Reproduced in full from Li et al 2019]

(i) *If steam could be extracted at required conditions i.e. 3.5 bar, 160 °C, then power loss = 0.16 kWh * 450,000 kg =* ***72 MW***

(ii) *Constraint: Extraction between IP and LP, the pressure between IP and LP is usually 8 - 12 bar, thus the loss of power would be between* ***85 MW*** *to* ***107 MW*** *from the diagram.*

6. RESULTS

6.1 Electricity Infrastructure

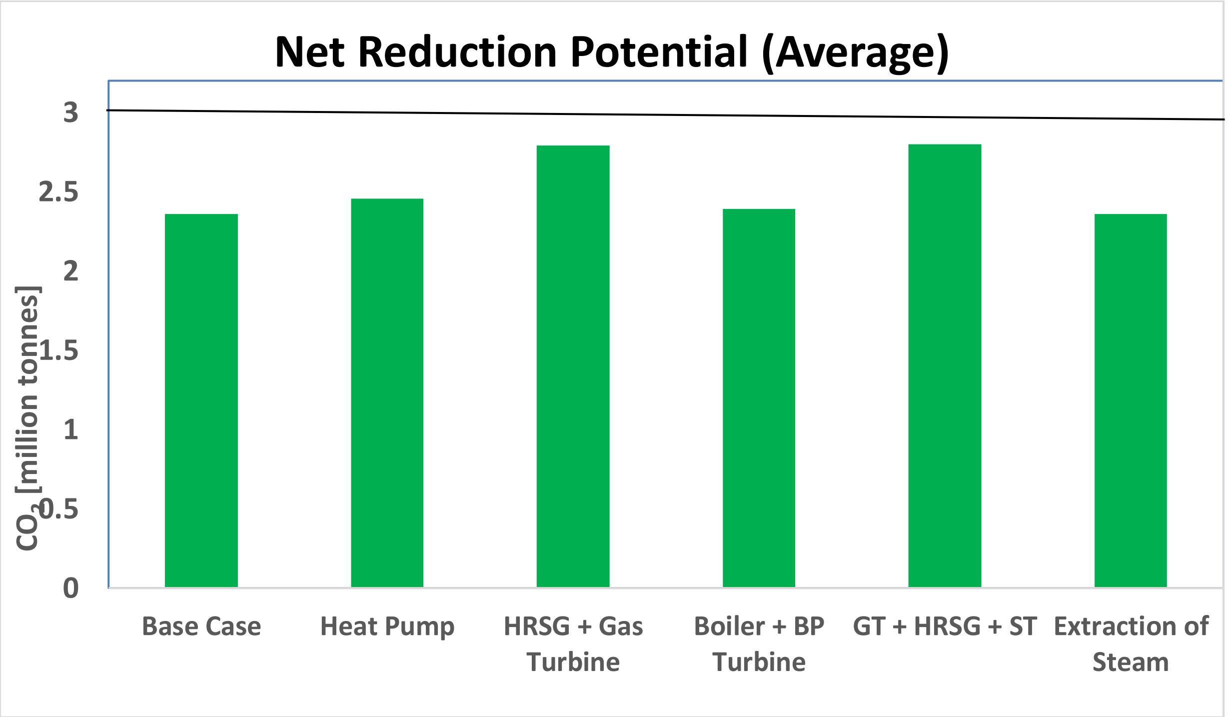


Graph 1: Electricity Infrastructure 2015 at TSIJ

Graph 1 shows the difference in electricity produced and electricity imported between different scenarios. The black line signifies the electricity demand of TSIJ + Everest. It is clearly seen that the maximum benefit in terms of the electricity infrastructure would be in deploying the CHPs which include GT + HRSG combination. The heat pump scenario is also optimistic, however, the amount of electricity imported is twice the amount required for the combinations of CHPs. The extraction of steam, backpressure turbine and base-case yield the least amount of benefits in terms of electricity infrastructure, however, the CAPEX for these pathways would probably be lower than that of the CHPs.

Graph 1 above, only shows the comparison for 2015, the remaining results for 2016 - 2019 are tabulated in the Appendix Table V.

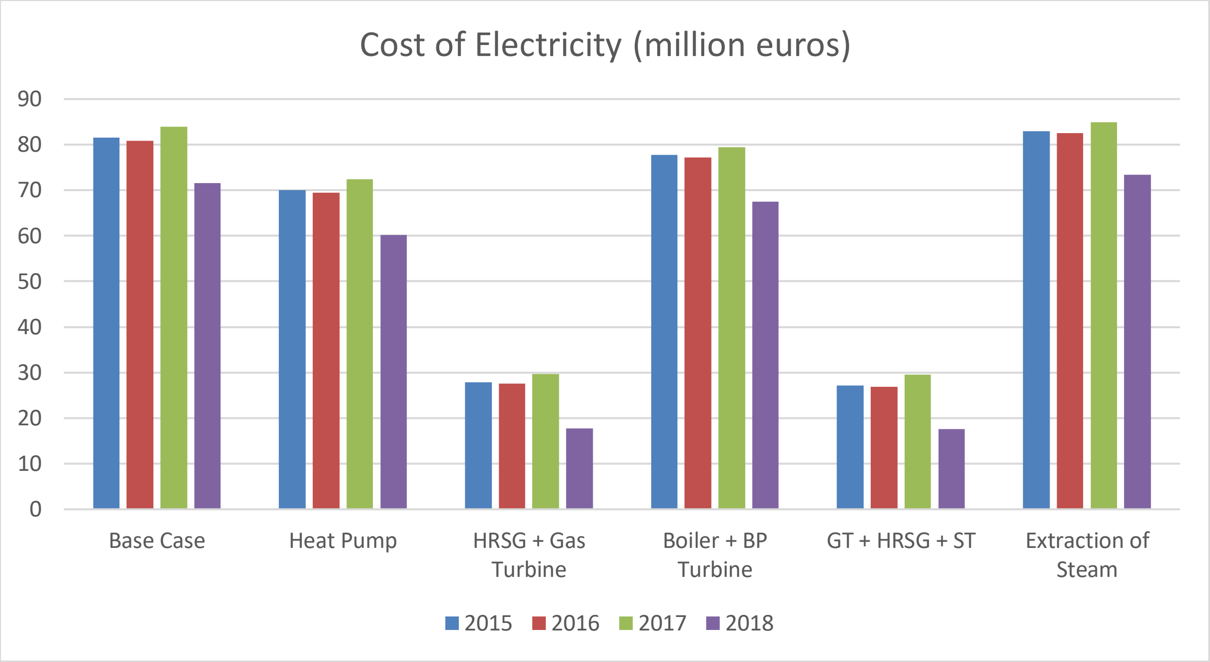
6.2 Net Reduction Potential



Graph 2: Net Reduction Potential of Scenarios

The net reduction potential of a certain technology signifies the actual amount of CO_2 reduced. In this case, this includes only the emissions added due to the import of electricity from the Dutch grid. This is due to the fact that the emissions from the process gases are assumed to be equal in each scenario as TSIJ would emit that amount of CO_2 regardless, as it would combust the process gases for heat or electricity anyway. Graph 3 shows the average (for 4 years) difference between the net reduction potential for the scenarios. As this is directly proportional to the amount of electricity imported, the CHPs with the GT + HRSG yield the maximum benefits as well. The actual results are in the Appendix Table VI.

6.3 Financial Analysis



Graph 3: Electricity Costs of Different Scenarios

Table 3: Maximum Allowable Investment of Different Scenarios

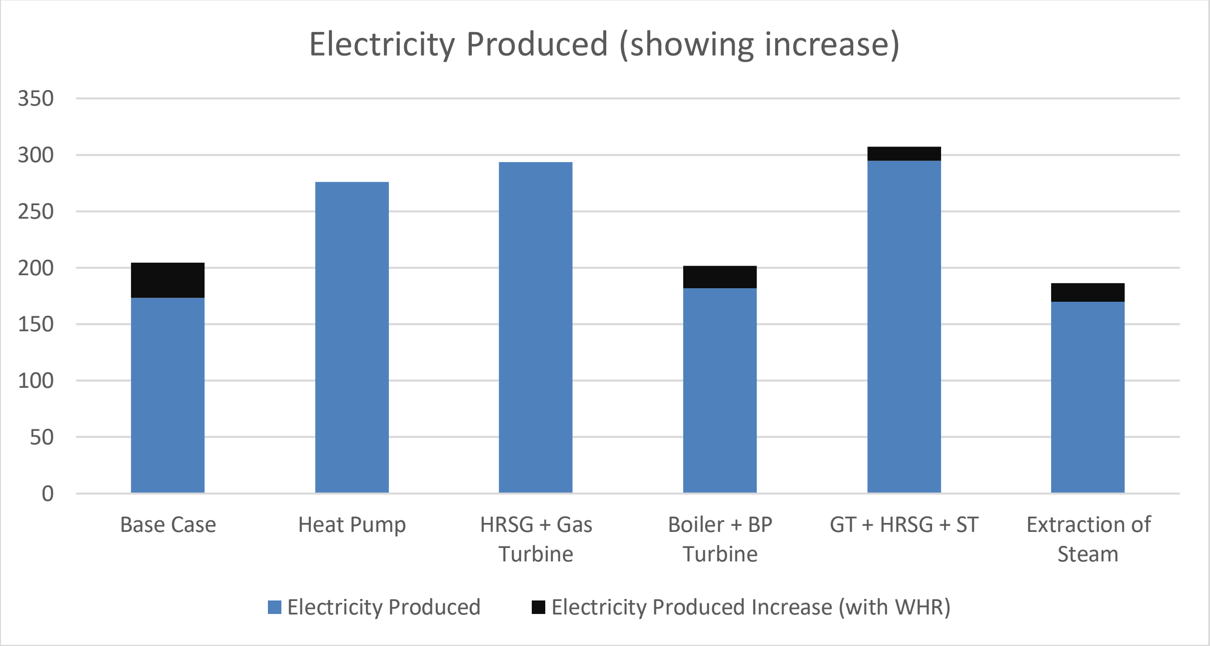
	Allowable Investment
Heat Pump	**+57 MEUR**
HRSG + GT	**+268 MEUR**
BP	**+20 MEUR**
HRSG + GT + BP	**+271 MEUR**
Extraction	**-7.5 MEUR**

The above table shows the maximum allowable investment for a payback period of 5 years. Here, it is seen the maximum benefit is in the CHPs with the GT + HRSG combination. However, it is also seen that the benefit of having a HRSG + GT + BP over a HRSG + GT is not large.

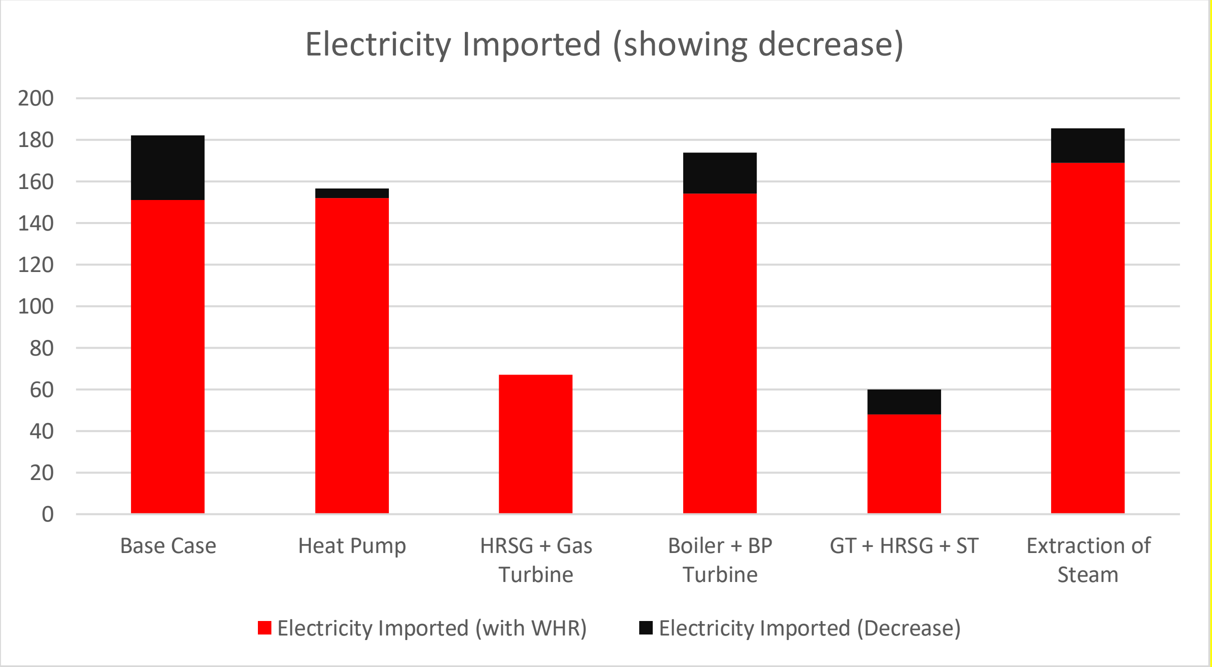
For the extraction of steam scenario, the maximum allowable investment is negative, however, it is anticipated that the CAPEX to retrofit an existing plant would probably be lower than building a new plant. These calculated results should be compared with the CAPEX once it has been determined to know which scenario yields the maximum benefit. The results are in a tabulated form in Appendix Table VIII.

6.4 Waste Heat Recovery

As WHR allows for more Everest Gas to be sent for electricity production, the electricity infrastructure changes, and more electricity is produced on site and less electricity is imported. Graph 4 and Graph 5 below show the difference in electricity produced and electricity imported for the year 2015 for all the scenarios.



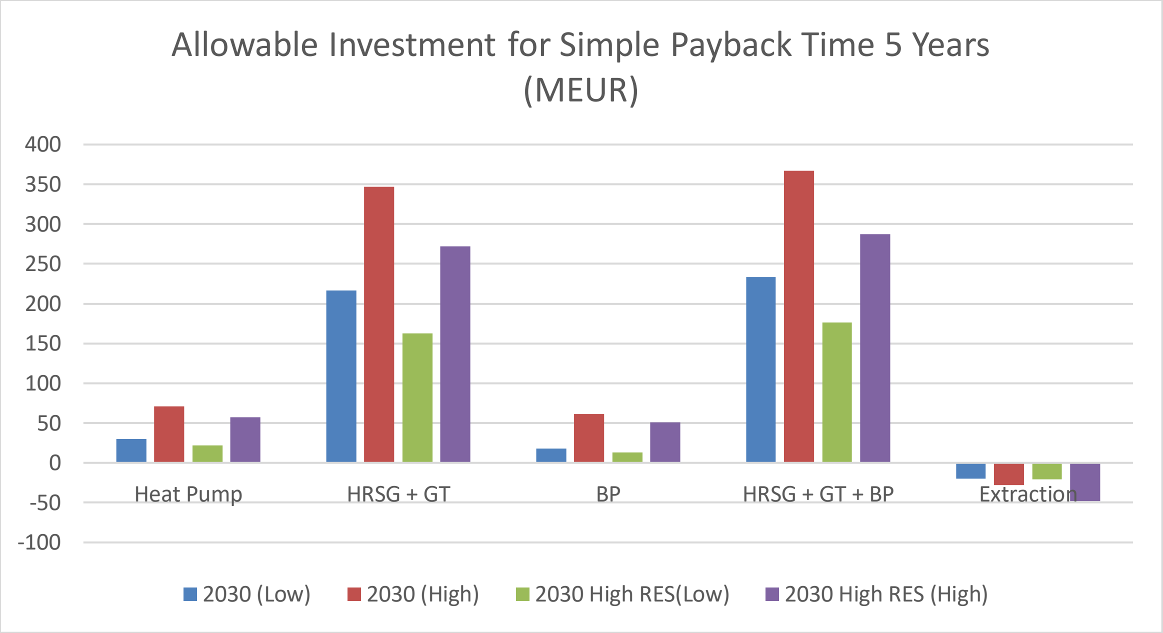
Graph 4: Increase in Electricity Production due to WHR



Graph 5: Decrease in Electricity Import due to WHR

However, graph 4 and graph 5 show a tainted picture, because in the other scenarios apart from the base case scenario each asset is modelled in such a way that it satisfied the demand of steam requirements of Everest, because there is some process steam displaced due to Waste Heat Recovery, the amount of Everest Gas which goes to these assets is decreased, and goes to VN instead, thus decreasing the efficiency of the overall production of steam and electricity and increasing the amount of electricity imported from the grid. Thus, an optimisation model is necessary for other scenarios to identify the benefits of Waste Heat Recovery in these scenarios and do a proper financial analysis for them. However, the financial analysis with the tables and graphs are in the Appendix Table VII.

6.5 Volatility of Electricity Markets



Graph 6: Maximum Allowable Investment for Volatility of Electricity Markets

Graph 6 shows how the electricity prices changes the maximum allowable investment for the different assets. It uses the electricity prices from the CE Delft report and interpolates the 4 years average calculated to 5 years. Here it is seen that the CHP combinations with GT + HRSG still have the maximum benefit even if the prices go low and virtually CO_2 free there is still circa 100 MMEuro benefit in these scenarios when compared to the others.

7. DISCUSSION AND CONCLUSION

Carbon Capture and Storage is essential for Tata Steel IJmuiden to realistically achieve the 2030 climate goals for heavy industry and there are various options to provide for the energy demands of CCS. This research was aimed to compare different alternatives to the current anticipated method of providing this energy, which was a LP Boiler. As the research progressed, it was observed that there are other alternatives which could also provide for the same and thus added to the scope of the project. All of the alternative scenarios were compared using key performance indicators which were the electricity imported from the grid, net reduction potential and operating costs.

To answer the research question as described in section 3.2; a scenario modelling approach was used and there were assumptions and simplifications to make the model as realistic and accurate as possible. However, where assumptions and simplifications were not able to provide a clear picture, numbers were quantified stochastically, thus, making it a range of results instead. As described in this report, most of the assumptions are based on extensive research, internal documentation, and literature, therefore, making the data and results reliable.

From the above results, it can be concluded that:

(i) The CHP variants which deploy GT + HRSG combination provide the maximum amount of benefits with regards to all the KPIs: Net Reduction Potential, Optimization of Energy Infrastructure, Finances.
(ii) As most of the scenarios are modelled in such a way that they are sized according to the process steam requirements, the results show a tainted picture for the application of Waste Heat Recovery.
(iii) The volatility of electricity markets i.e. if electricity becomes cheap and CO_2 free it still does not overpower the benefits from a CHP.

Also, as the research progressed, there were more points which could increase the accuracy and details of the report. Thus, the following recommendations can be used for the future:

(i) Comparison of scenarios after the determination of CAPEX.
(ii) Optimization of assets to see how the system would behave if they were sized in an optimal manner.
(iii) WHR after optimization of assets.
(iv) Comparison of electricity costs and net reduction potential in the likelihood of import of electricity from green sources.

The steelmaking sector and heavy industry in general must make huge investments and compromises in their aim to achieve their climate goals. Carbon Capture Utilization and Storage is going to be an essential part of this pathway towards these goals. For industries, which have high amounts of process gases due to manufacturing processes such as cement and steel, a combined heat and power plant would yield maximum net reduction potential and maximum efficiency. However, for other CO_2 industrial sources, further research would be required to establish which is the optimum solution.

8. REFERENCES

"2030 climate & energy framework." *Climate strategies & targets.* European Commission, 2014. Retrieved from: https://ec.europa.eu/clima/policies/strategies/2030_en

"2050 long term strategy." *Climate strategies & targets.* European Commission, 2018. Retrieved from: https://ec.europa.eu/clima/policies/strategies/2050_en

"Het project Athos." Athos, 2018. Retrieved from: https://athosccus.nl/project/

"Tata Steel in IJmuiden." *Tata Steel Nederland.* Tata Steel Europe Limited, 2020. Retrieved from: https://www.tatasteel.nl/nl/over/organisatie/in%E2%80%93ijmuiden

Arpagus, C., Bless, F., Uhlmann, M., Schiffman, J., Bertsch, S. High temperature heat pumps: Market overview, state of the art, research status, refrigerants, and application potentials, 2018. *Energy 152,* 985 – 1010.

Energy and electricity price scenarios 2020 – 2023 – 2030. CE Delft, 2017.

Johansson, D., Sjoblom, J., Berntsson, T. Heat supply alternatives for CO_2 capture in the process industry, 2012. *International Journal of Greenhouse Gas Control 8,* 217 – 232.

Klimaatakkoord, 2019. Retrieved from: https://www.klimaatakkoord.nl/klimaatakkoord/documenten/publicaties/2019/06/28/klimaatakkoord

Lucquiaud, M., Liang, X., Errey, O., Chalmers, H., Gibbins, J. Addressing technology uncertainties in power plants with post-combustion capture, 2013. *Energy Procedia* 37, 2359–2368.

Steam System Modeler Tool, Energy Efficiency and Renewable Energy US Department of Energy. Used from:
https://www4.eere.energy.gov/manufacturing/tech_deployment/amo_steam_tool/equipTurbine

Van Zutphen, H. Project Everest, 2018. CATO Meets the Projects. Retrieved from: https://www.co2-cato.org/publications/library1/20181204-project-everest

Visser, M. Renewable Energy in the Netherlands, 2019, EnTranCe.

Xu, G., Yang, Y., Ding, J., Li, S., Kai Zhang, W.L. Analysis and optimization of CO_2 capture in an existing coal fired power plant in China, 2013. *Energy 58,* 117 – 127.

Tata Steel Internal Documentation:

"Project Everest Project Description." *Project Everest, Tata Steel Nederland.* Tata Steel Europe Limited, 2020.
"Process Narrative for Naphtha Case." *Project Everest*, *Tata Steel Nederland.* Tata Steel Europe Limited, 2020.
"Project Everest Poster." *Tata Steel Nederland.* Tata Steel Europe Limited, 2020.
"Sustainability Report 15/16." *Tata Steel Nederland.* Tata Steel Europe Limited, 2020.
"Sustainability Report 19/20." *Tata Steel Nederland.* Tata Steel Europe Limited, 2020.
"Rich Purge Gas Recycle." *Project Everest, Tata Steel Nederland.* Tata Steel Europe Limited, 2020.
"Rationale voor warmtekracht." *Tata Steel Nederland.* Tata Steel Europe Limited, 2020.

“VN25 technical specifications.” *Tata Steel Nederland.* Tata Steel Europe Limited, 2020.
“Real-time process data 2015 – 2019.” *Tata Steel Nederland.* Tata Steel Europe Limited, 2020.

APPENDIX

Table I

Distributiuon of the WAGs for the FY15/16

Plant	BF Gas		CGP gas		BOS gas		NG		CO_2 Emissions
	PJ/a	kmol/h	PJ/a	kmol/h	PJ/a	kmol/h	PJ/a	kmol/h	Mt CO_2/a
Stove BF6	3.0	4230.9	0.6	178.6	0.0	0.0	0.1	7.6	0.8
Stove BF7	4.1	5774.4	1.0	302.0	0.0	0.0	0.1	10.5	1.1
K 15	1.0	1395.8	0.2	54.8	0.1	54.0	0.1	12.6	0.3
K 16	0.3	407.2	0.1	45.7	0.0	15.8	0.0	1.3	0.1
K 23	1.4	1937.9	0.1	33.2	0.0	0.0	0.1	12.9	0.4
K 24	0.6	860.2	0.3	81.7	0.0	0.0	0.0	3.5	0.2
K 41	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
# 3	0.0	0.0	0.0	0.0	0.0	0.0	0.3	36.6	0.0
# 4	0.8	1156.5	0.0	0.0	0.1	44.7	0.0	2.5	0.2
KGF1	1.9	2725.6	2.2	688.1	0.2	105.4	0.0	0.0	0.6
KGF2	0.0	0.0	3.7	1147.1	0.0	0.0	0.0	0.0	0.2
PeFa	0.0	0.0	1.4	429.8	0.8	560.8	0.2	25.5	0.2
SiFa	0.0	0.0	0.6	174.4	0.0	0.0	0.0	0.8	0.0
HSM2	0.0	27.9	4.6	1438.4	0.0	0.9	3.1	452.7	0.4
AK 11	0.7	983.4	0.0	0.0	0.1	38.0	1.0	149.3	0.3
IJm01	7.7	10875.0	0.0	0.0	0.6	420.8	0.0	0.0	2.1
VN 24/25	12.2	17155.6	1.6	506.3	3.0	1967.0	0.0	4.8	3.8
Rest	-	-	0.3	79.4	0.3	173.2	4.5	646.4	-
Σ Total	33.8	47530.2	16.5	5159.5	5.P1	3380.7	9.5	1366.9	10.6
Σ Total Nm3/h	1065327		115643		75773		25670,1		

Table II

Gas Amounts (vol. %)

Component	BF Gas	BOS gas	CGP Gas
Ar	0.0%	0.5%	0.4%
N_2	38.9%	14.0%	4.8%
O_2	0.0%	0.0%	0.0%
H_2O	5.1%	5.1%	5.1%
CO_2	25.1%	16.4%	0.7%
CO	25.5%	61.8%	5.8%
H_2	5.4%	2.0%	57.1%

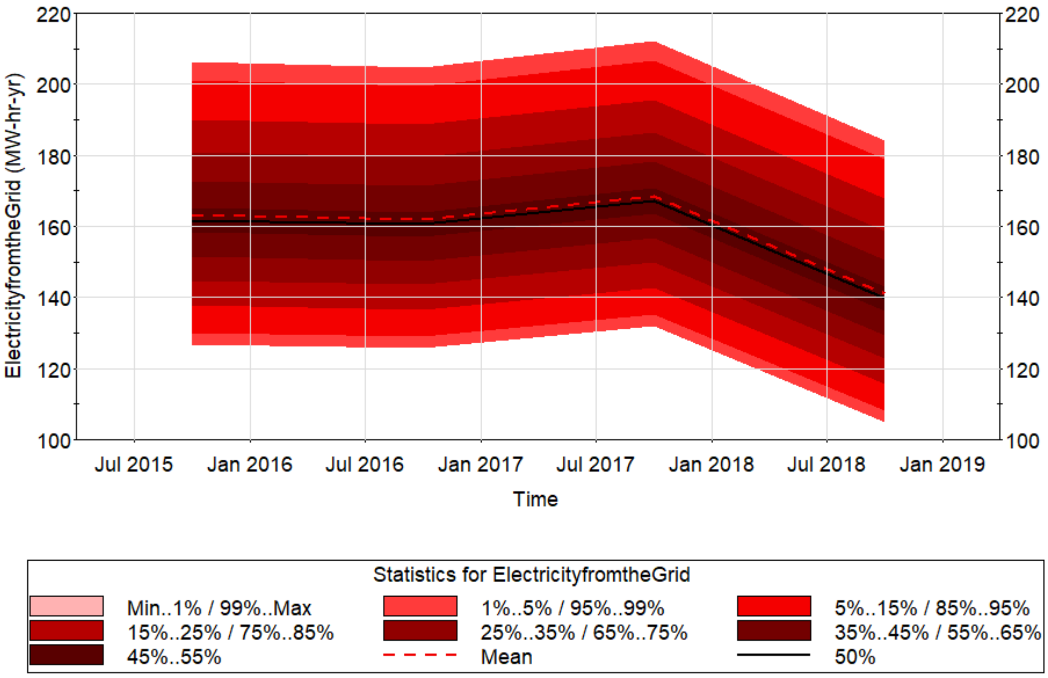
CH_4	0.0%	0.0%	23.4%
C_2H_6	0.0%	0.0%	0.6%
C_3H_8	0.0%	0.0%	0.0%
C_4H_{10}	0.0%	0.0%	0.0%
C_5H_{12}	0.0%	0.0%	0.0%
C_6H_{14}	0.0%	0.0%	0.0%
C_2H_4	0.0%	0.0%	1.8%
C_3H_6	0.0%	0.0%	0.3%
C_4H_8	0.0%	0.0%	0.0%
C_6H_6	0.0%	0.0%	0.0%

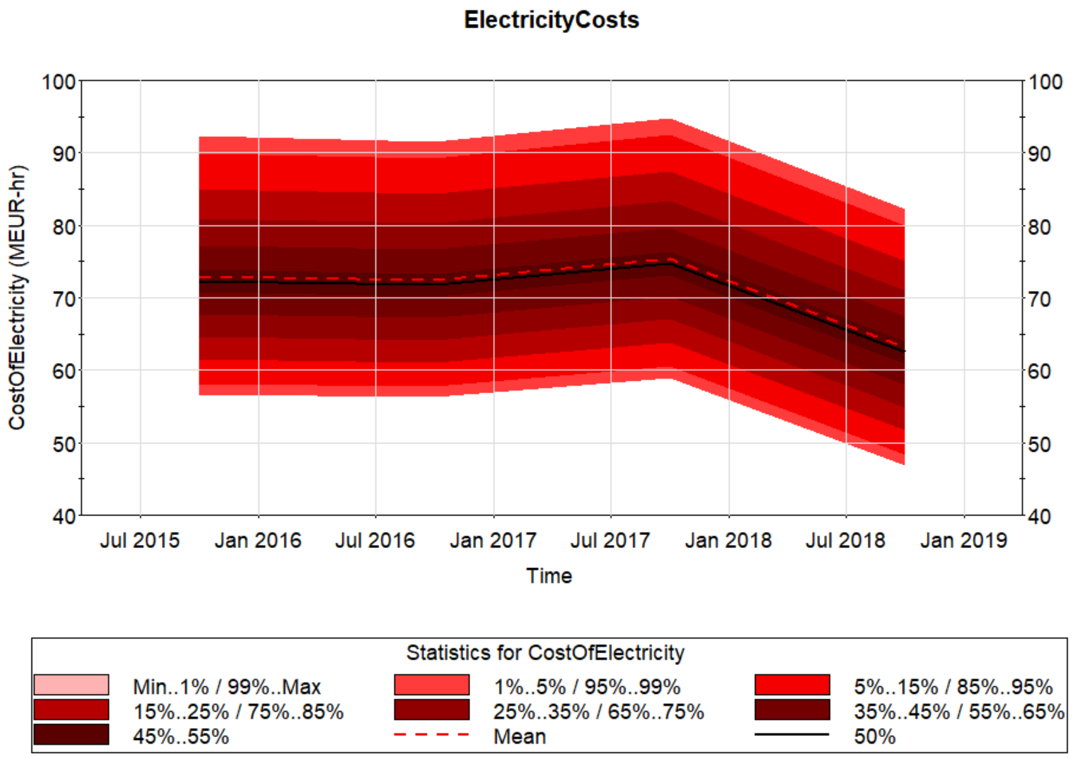
III

Monte Carlo Simulations:

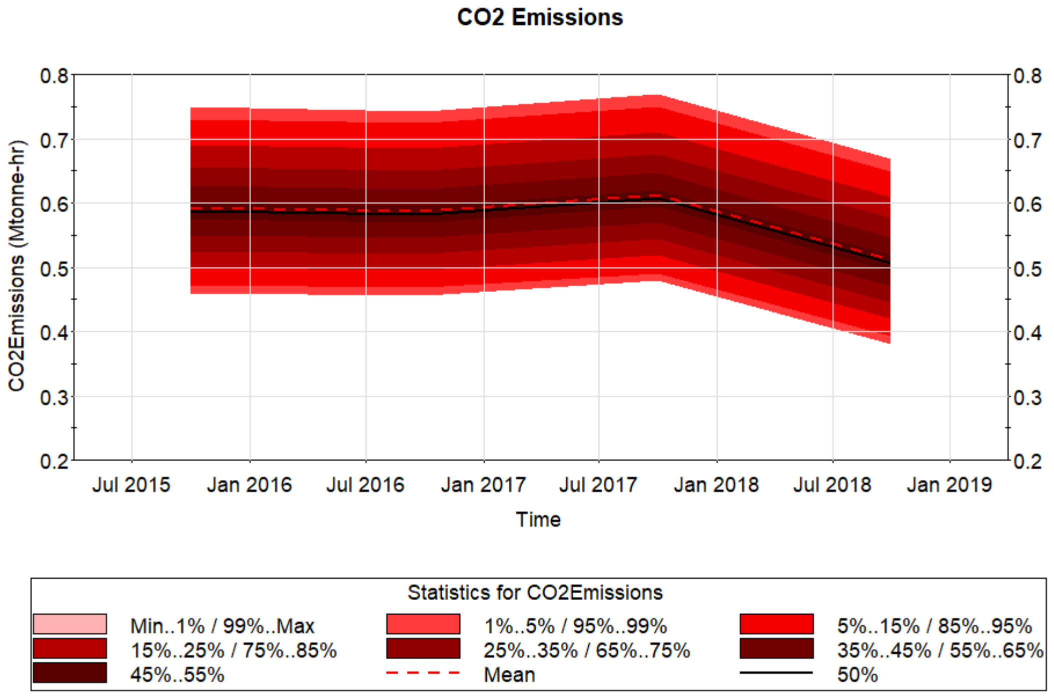
Number of Realizations: 50, Confidence intervals: in graph

III (a): Electricity Imported from the grid.





III (b) [picture above]: Electricity Costs
III (c) [picture below]: CO_2 emissions



IV

The assumption is all the Everest Gas is sent to this plant, which is **19.9 PJ/yr,** thus **2370 GJ/hr** ***(8400 hours assumption)***.

(i) **Gas Turbine**

Electricity Produced = 2370 GJ/hr * 0.4 = **265 MW**

(ii) **HRSG**

Heat recovered = 2370 GJ/hr * 0.6 * 0.85 = **1210 GJ/hr**

(iii) **Back-pressure Turbine**

Now, we know the mass flow required is 452 ton/hr, thus the enthalpy of input steam should be *1210 GJ/hr / 452000 kg/hr = 2676 kJ/kg.* [**As this is lower than the enthalpy of steam required at output conditions this option is not viable to deploy]**
However, for the sake of simplicity and future references, if there was more gas available or a substitute was used:

Taking into consideration efficiency similar to Scenario V (a) i.e. circa 21%, the maximum power that can be gained from the output stream of HRSG and output stream of BP turbine would be: ***1210 GJ/hr – 964 GJ/hr * 0.21*** **= 14.45 MW**

Table V

Table V (a): Electricity Produced within Tata Steel

	Electricity Produced [Base Case Scenario]	Electricity Produced [Heat Pump Scenario]	Electricity Produced [HRSG + Gas Turbine]	Electricity Produced [Boiler + BP Turbine]	Electricity Produced [HRSG + GT + BPST]	Electricity Produced [Extraction Scenario]
2015	173.4 MW	275.8 MW	293.5 MW	181.8 MW	295 MW	170.1 MW
2016	173.8 MW	275.5 MW	293.1 MW	182 MW	294.5 MW	170 MW
2017	167 MW	270 MW	288.3 MW	177.1 MW	288.8 MW	164.7 MW
2018	194.6 MW	296.5 MW	315 MW	203.8 MW	315.5 MW	190.4 MW

Table V (b): Electricity Imported from the Grid

	Electricity Imported [Base Case Scenario]	Electricity Imported [Heat Pump Scenario]	Electricity Imported [HRSG + Gas Turbine]	Electricity Imported [Boiler + BP Turbine]	Electricity Imported [HRSG + GT + BPST]	Electricity Imported [Extraction Scenario]
2015	182.3 MW	156.6 MW	62.26 MW	173.9 MW	60.72 MW	185.7 MW
2016	180.9 MW	155.3 MW	61.65 MW	172.8 MW	60.27 MW	184.7 MW
2017	187.8 MW	161.9 MW	66.42 MW	177.6 MW	65.96 MW	190 MW
2018	160.1 MW	134.5 MW	39.68 MW	150.9 MW	39.2 MW	164.3 MW

Table VI

Table VI (a): CO$_2$ Emissions Imported from Grid

	CO2 Emissions Imported [Base Case Scenario]	CO2 Emissions Imported [Heat Pump Scenario]	CO2 Emissions Imported [HRSG + Gas Turbine]	CO2 Emissions Imported [Boiler + BP Turbine]	CO2 Emissions Imported [HRSG + GT + BP]	CO2 Emissions Imported [Extraction Scenario]
2015	0.66 Mtonne	0.56 Mtonne	0.23 Mtonne	0.63 Mtonne	0.22 Mtonne	0.63 Mtonne
2016	0.65 Mtonne	0.56 Mtonne	0.22 Mtonne	0.62 Mtonne	0.21 Mtonne	0.67 Mtonne
2017	0.68 Mtonne	0.58 Mtonne	0.24 Mtonne	0.64 Mtonne	0.23 Mtonne	0.68 Mtonne

2018	0.58 Mtonne	0.48 Mtonne	0.14 Mtonne	0.54 Mtonne	0.14 Mtonne	0.59 Mtonne

Table VII

<u>Table VII (a): Base Case Scenario [With Waste Heat Recovery Scenario]</u>

	Electricity Produced [MW]		Electricity Imported [MW]		Electricity Costs [MEUR}	
2015	185.7	219.6	136.2	170.1	60.87	76.03
2016	185.5	219.4	135.4	169.3	60.52	75.68
2017	180.5	214.3	140.5	174.2	62.8	77.89
2018	207	240.6	114.1	147.7	51.02	66.05

<u>Table VII (b): Heat Pump Scenario [With Waste Heat Recovery Scenario]</u>

	Electricity Produced [MW]		Electricity Imported [MW]		Electricity Costs [MEUR}	
2015	275.8	275.8	120	177.9	53.67	79.53
2016	275.8	275.8	119.3	177	53.33	79.12
2017	270	270	124.7	182.4	55.75	81.55
2018	296.5	296.5	98.21	155.9	43.9	69.7

<u>Table VII (c): HRSG + Gas Turbine Scenario [With Waste Heat Recovery Scenario]</u>

	Electricity Produced [MW]		Electricity Imported [MW]		Electricity Costs [MEUR}	
2015	285.5	291.6	64.14	70.2	28.68	31.38
2016	285	291	63.75	69.79	28.5	31.2
2017	280.1	286.3	68.51	74.67	30.63	33.38
2018	306.7	312.9	41.77	48.04	18.68	21.48

<u>Table VII (d): BP Turbine Scenario [With Waste Heat Recovery Scenario]</u>

	Electricity Produced [MW]		Electricity Imported [MW]		Electricity Costs [MEUR}	
2015	190.7	214.5	141.2	165	63.12	73.78
2016	190.4	214.2	140.6	164.3	62.85	73.47
2017	185.7	209.3	145.5	169.1	65.04	75.59
2018	212.4	235.9	118.8	142.3	53.12	63.64

Table VI(e): HRSG + Gas Turbine + BP Scenario [With Waste Heat Recovery Scenario]

	Electricity Produced [MW]		Electricity Imported [MW]		Electricity Costs [MEUR}	
2015	301.7	313.1	42.58	53.99	19.04	24.14
2016	301.2	312.6	42.18	53.56	18.86	23.94
2017	295.5	306.9	47.87	59.25	21.4	26.49
2018	322.2	333.6	21.11	32.49	9.44	14.53

Table VII (f): Extraction from Velsen [With Waste Heat Recovery Scenario]

	Electricity Produced [MW]		Electricity Imported [MW]		Electricity Costs [MEUR}	
2015	178.6	195.5	160.3	177.1	71.65	79.18
2016	178.6	195.3	159.4	176.2	71.27	78.77
2017	173.3	190.1	164.7	181.5	73.62	81.13
2018	199	215.8	138.9	155.7	62.12	69.62

Mean Values [With Waste Heat Recovery Potential]

Table VII (g): Electricity Produced On Site

	Electricity Produced [Base Case Scenario]	**Electricity Produced [Heat Pump Scenario]**	**Electricity Produced [HRSG + Gas Turbine]**	**Electricity Produced [Boiler + BP Turbine]**	**Electricity Produced [HRSG + GT + BPST]**	**Electricity Produced [Extraction Scenario]**
2015	204.7	275.8	288.4	201.8	307.4	186.6
2016	204.5	275.8	287.7	201.4	306.8	186.5
2017	199.5	270	282.9	196.6	301.1	181.2
2018	225.9	296.5	309.6	223.3	327.8	206.9

Table VII (h): Electricity Imported from the Grid

	Electricity Imported [Base Case Scenario]	**Electricity Imported [Heat Pump Scenario]**	**Electricity Imported [HRSG + Gas Turbine]**	**Electricity Imported [Boiler + BP Turbine]**	**Electricity Imported [HRSG + GT + BPST]**	**Electricity Imported [Extraction Scenario]**
2015	151	153.3	67.37	154	48.36	169.2
2016	150.2	152.5	67.02	153.4	47.94	168.3
2017	155.2	157.9	71.85	158.2	53.63	173.5
2018	128.9	131.4	45.14	131.5	26.87	147.8

Table VII(i): CO_2 Emissions Imported from Grid

	CO2 Emissions Imported [Base Case Scenario]	CO2 Emissions Imported [Heat Pump Scenario]	CO2 Emissions Imported [HRSG + Gas Turbine]	CO2 Emissions Imported [Boiler + BP Turbine]	CO2 Emissions Imported [HRSG + GT + BP]	CO2 Emissions Imported [Extraction Scenario]
2015	0.54	0.55	0.24	0.55	0.17	0.61
2016	0.54	0.54	0.24	0.55	0.17	0.61
2017	0.56	0.57	0.26	0.57	0.19	0.62
2018	0.46	0.47	0.16	0.47	0.09	0.53

Table VIII

Table VIII (a): Mean Electricity Costs

	Electricity Costs [Base Case Scenario]	Electricity Costs [Heat Pump Scenario]	Electricity Costs [HRSG + Gas Turbine]	Electricity Costs [Boiler + BP Turbine]	Electricity Costs [HRSG + GT + BP]	Electricity Costs [Extraction Scenario]
2015	81.51 MEUR	69.99 MEUR	27.83 MEUR	77.75 MEUR	27.15 MEUR	83.01 MEUR
2016	80.88 MEUR	69.45 MEUR	27.56 MEUR	77.25 MEUR	26.94 MEUR	82.59 MEUR
2017	83.96 MEUR	72.37 MEUR	29.69 MEUR	79.40 MEUR	29.49 MEUR	84.95 MEUR
2018	71.59 MEUR	60.12 MEUR	17.74 MEUR	67.45 MEUR	17.53 MEUR	73.44 MEUR

Table VIII (b): Allowable Investment (Mean Values)

	Electricity Costs [Base Case Scenario]	Electricity Costs [Heat Pump Scenario]	Electricity Costs [HRSG + Gas Turbine]	Electricity Costs [Boiler + BP Turbine]	Electricity Costs [HRSG + GT + BP]	Electricity Costs [Extraction Scenario]
2015	81.51	11.52	53.68	3.76	54.36	-1.5
2016	80.88	11.43	53.32	3.63	53.94	-1.71
2017	83.96	11.59	54.27	4.56	54.47	-0.99
2018	71.59	11.47	53.85	4.14	54.06	-1.85
Total (2015-2018)		46.01	215.12	16.09	216.83	-6.05
5 Years		57	268	20	271	-7.5

TABLE IX

Table IX (a): Electricity Prices (according to 2016 trend) [all in MEUR]

	2015		2016		2017		2018	
Base Case	70.46	109.2	69.92	108.4	72.58	112.5	61.89	95.95
Heat Pump	64.5	94.85	64	94.11	66.64	97.99	55.69	81.89
HRSG + GT	27.1	39.48	26.86	39.13	28.98	42.21	18.71	27.26
BP	67.02	97.13	66.59	96.51	68.45	99.2	58.14	84.26

HRSG + GT + BP	23.72	35.48	23.54	35.21	25.76	38.54	15.31	22.91
Extraction	71.99	113.5	71.63	112.9	73.67	116.1	63.69	100.4

<u>Table IX (b): High RES Electricity Prices (Min vs Max)</u>

		2015		2016		2017		2018
Base Case	53.22	85.39	52.81	84.73	54.82	87.96	46.75	75
Heat Pump	48.81	73.86	48.43	73.28	50.43	76.3	42.14	63.77
HRSG + GT	20.48	30.59	20.29	30.31	21.89	32.7	14.13	21.12
BP	50.61	75.15	50.29	74.67	51.69	76.75	43.91	65.2
HRSG + GT + BP	17.93	27.61	17.79	27.41	19.47	29.99	11.57	17.84
Extraction	53.6	86.97	53.34	86.54	54.86	89	47.43	76.95

Now, the economic evaluation is done using a simple payback time of 5 years, as the above data provides data for 2015 – 2019, it is interpolated from 4 to 5 years and the maximum additional CAPEX is determined for each different scenario.

<u>Table IX (c) : Allowable Investment for Each Scenario</u>

	2030 (Low)	2030 (High)	2030 High RES(Low)	2030 High RES (High)	Mean Values [Current Prices]
Heat Pump	+30 MEUR	+71 MEUR	+22 MEUR	+57 MEUR	+57 MEUR
HRSG + GT	+216.5 MEUR	+347 MEUR	+163 MEUR	+272 MEUR	+268 MEUR
BP	+18.31 MEUR	+61 MEUR	+13 MEUR	+51 MEUR	+20 MEUR
HRSG + GT + BP	+233.1 MEUR	+367 MEUR	+176 MEUR	+287 MEUR	+271 MEUR
Extraction	-7 MEUR	-21 MEUR	-2 MEUR	-8 MEUR	-7.5 MEUR