ENTERING AN INTEGRATED CLUSTER

A model-based approach to support a utility provider in its investment decision-making to enter an industrial cluster

Martje Bijloo

Master Systems Engineering, Policy Analysis & Management
Faculty of Technology, Policy and Management
Delft University of Technology

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by

Martje Bijloo

September 2014

TU Delft

Student

Martje Bijloo – 1515977
Delft University of Technology (DUT)
Technology, Policy and Management (TPM)
master Systems Engineering, Policy Analysis and Management

Graduation Committee

Prof. dr. ir. W.A.H. Thissen (chairman)
section Policy Analysis

Dr. P.W.G. Bots (first supervisor)
section Policy Analysis

Dr. ir. Z. Lukszo (second supervisor)
section Energy & Industry

Company

The company for which this thesis was conducted will not be mentioned for confidentiality reasons.

Preface

This document represents my final work as a student at Delft University of Technology. My bachelor and master Systems Engineering, Policy Analysis and Management allowed me to learn scientific as well as social skills. Besides my studies, I also got the chance to be actively involved in sports teams, gain managerial experience in student societies, study in Japan and do a research internship. To conclude this enriching period, I got the opportunity to do a graduation internship at an inspiring company.

That is why I firstly want to thank WB of the company I conducted this research for. Due to your ability to always see opportunities, you provided me with a research project that fits a SEPAM student perfectly. I appreciated your openness and the fact that you were always available for questions and stimulated me to ask them. In addition, I want to thank RE. Besides your help due to your extensive knowledge of the project, your open and supportive character motivated me to keep going. The way you involved me in the project team was heartwarming and it felt like my research mattered.

Next I would like to thank my supervisors at TPM. First, Pieter Bots for always taking the time for me and providing me with sharp insights. Your positive feedback and genuine personal interest were just what I needed to bring this research to a good end. Secondly, I want to thank Zofia Lukszo. When I asked you to be my second supervisor, you actually did not have enough time, but you were too enthusiastic to turn it down. I am grateful for that, because you still taught me much during my research. I enjoyed these final lessons very much. Lastly, I would like to thank Wil Thissen for chairing my graduation committee. The thought of working still scares me, but when I look at you, this fear disappears. The passion you have for your work is enviable. It was a pleasure to have the three of you as my graduation committee.

Finally I want to thank my family and friends for supporting me during my master thesis and making this a fun period, even though I struggled sometimes. In particular I want to thank my parents. It is the unlimited faith you have in me that gives me self-confidence to pursue whatever dreams I have. And last, but certainly not least, I want to thank Robbin Kwa for executing the entire lay-out of this thesis report to my wishes. And even more so for your company, support and patience.

Concluding I can honestly say that I am sad, but also very proud and happy that by writing down these words an inspiring period has come to an end.

Martje Bijloo

Delft
September 10, 2014

Summary

Over the last few decades, a wealth of articles on the design and optimization of utility systems in industrial clusters has been published. Most of these articles seem to disregard non-technical factors, whereas these appear to play a significant role when optimizing an integrated utility system. In particular, long-term development plans that companies within a cluster make for future development of their own plants limit efficiency gains that could potentially be achieved with integration. This thesis presents a model-based approach to support a utility provider in its investment decision-making to enter an industrial cluster. To test the applicability and to illustrate the proposed approach a case study has been done.

Since 2013 Energy Company A (ECA) operates a biomass plant that solely produces electricity. The name of this biomass plant that is biomass plant of company A (BPA). This plant is located in an industrial cluster, which is called site Y. In the 1960s the first plant on this site was established by production company X (PCX). Afterwards PCX built more plants in the same area, many of which it later sold to other companies. It is due to this history that the cluster that emerged became closely integrated in terms of product and utility flows.

A very important utility for production processes of companies in site Y is steam. Current steam production in site Y exists from a combined heat and power plant (CHP) on natural gas and from a waste incinerator. The CHP is owned by PCX and will therefore be called combined heat and power plant of company X (CHPX). Besides production, there is one utility company in site Y which is the main supplier of steam to all steam consuming companies in the cluster. This utility company is also owned by PCX and it will be called PCX Utility Company (PCX UC). Because the steam supply in this cluster is controlled by one company, it is expected that this company aims to purchase steam at the lowest cost in order to get the highest margin over the steam sold to its customers. Reason for this is that no internal steam market exists, which means that steam prices are fixed in contracts between PCX UC and its customers.

Recently two trends in site Y have given rise to a seemingly opportunity for ECA. Firstly steam production with a CHP became more expensive due to a rise in the natural gas price and a drop in the electricity price. Therefore PCX UC is eagerly looking for cheaper sources to purchase steam. Secondly, since the area of site Y showed economic contraction and a high unemployment rate, there is large political emphasis on improving the utility system in site Y. The idea behind this is that good utility facilities will improve the economic performance of existing firms in the site Y area, which will improve economic performance of the area. Also good utility facilities might attract new investors. To provide cheaper steam and hence improve the utility system of site Y, large scale steam production with BPA might be a solution. If this solution benefits site Y, it can count on political support. This is expressed by the adjustment of a subsidy scheme to provide subsidy for the co-production of steam with a biomass plant.

ECA will only invest in the adjustment of its biomass plant for the production of steam if large scale steam supply with BPA is an improvement to BPA's current business case in which it solely produces electricity. Besides, the expectation is stakeholders will only support or buy steam from ECA if it benefits them compared to other options they have. Therefore the main research question is:

What are the benefits for stakeholders if biomass plant A will supply steam in site Y?

The research question includes multiple aspects, because entrance of BPA to the steam production system of site Y can induce various benefits for stakeholders. These aspects include economic, social and environmental aspects. However PCX UC is expected to make a sourcing decision based on unit cost. Therefore it is most important to find out whether BPA would provide PCX UC with lower unit costs than other options it has. To this end, a model-based approach is proposed. A systematic overview of this approach is presented in figure i.

The only realistic development plans of stakeholders that were identified are the construction of a new bio or gas boiler by PCX. Therefore these two options have been included in the modelling effort besides current steam production units and alternatives of BPA. The three alternatives of BPA consist of solely producing electricity, which

is the current business case. It could also be adjusted with a back pressure steam turbine (BPST), with which it is able to produce steam and still a significant amount of electricity. Or it could be adjusted with a pressure reducing de-superheater (PRDS) with which it can produce a large amount of steam and very little electricity.

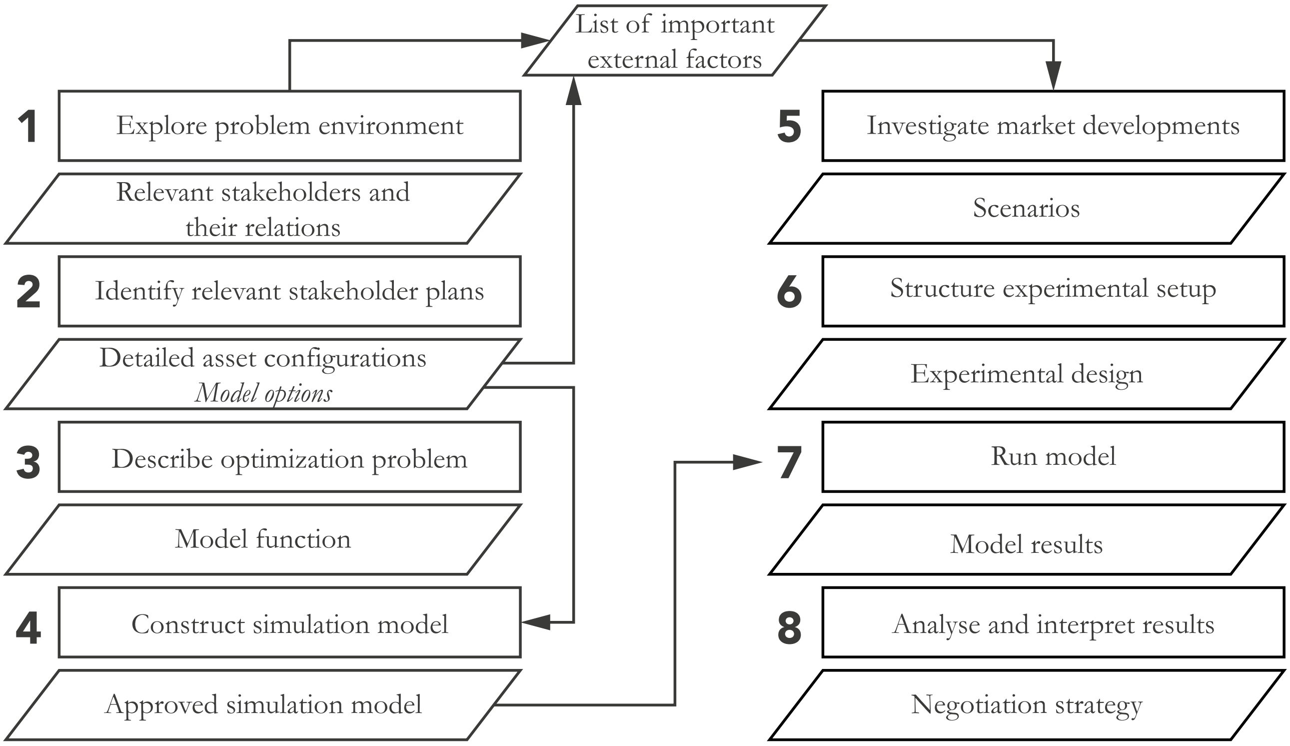

Figure i: Research approach to support a utility provider in its investment decision-making to enter an industrial cluster

Steam production units that produce steam at the lowest cost at a certain moment, will be operated to produce steam at that moment. Due to fluctuations in resource and electricity prices, this sourcing decision can change in time. To see how various configurations of steam production units would perform under various circumstances, a simulation model has been constructed that simulates the sourcing decision in site Y. A sourcing decision is supported by optimization behaviour. Therefore optimization runs were carried out with the simulation model.

From the model results it is derived that steam production alternatives of BPA on average score better than the solo electricity alternative for BPA on the total system profits to meet the total steam demand in site Y. This means that the system would be better off if BPA would produce steam. However for some steam production units, investment costs and subsidies play a large role. After taking operational expenditures and subsidy into account the earlier stated conclusion still holds. This means that independent of its future plans to build new facilities, it would benefit PCX UC in terms of unit costs to make an arrangement with ECA for the supply of steam.

For other stakeholders in site Y, a reduction in the purchase price of steam by PCX UC could result in a reduction in the selling price of steam by PCX UC to its steam customers. However whether it does result in a reduction in the steam price depends on whether PCX UC and ECA are prepared to provide transparency in the steam system. Therefore an improvement to the steam production system by a steam production alternative of BPA does not necessarily have to benefit other stakeholders in site Y.
For ECA the benefit of producing steam can be found in the economic aspect. If ECA will be able to get a good price for the steam it sells, its profits will increase compared to its current operation of BPA. Furthermore whether steam production with BPA benefits ECA depends on the selling conditions it establishes in negotiations with PCX. For PCX other advantages besides the economic aspect should also be taken into account when BPA will be supplying steam.

Advantages of steam supply by BPA to PCX are the following:

- Keeping the over allocation of CO2 rights, result: being able to keep over a million euro per year
- Less pressure on CHPX 1 to meet strict new emission rules posed onto CHPX 1 in 2016
- Opportunity for gradual decrease production CHPX 1 to avoid large maintenance due to reaching end of economic lifespan CHP
- Lower operational costs due to shutting down of one extra gas turbine (minimum operation)
- Improving sustainable image, which also applies to the other stakeholders

Besides the benefits that steam production by BPA has for PCX and possibly other stakeholders, it does have one downside. The BPA runs on biomass. Problems of using biomass in boilers are fouling, deposits, slagging and corrosion issues (Saidur, Abdelaziz, Demirbas, Hossain, & Mekhilef, 2011). This causes more (un)planned stops, which results in a lower number of operational hours per year and a lower reliability of steam supply from BPA. Therefore back-up capacity has to be available at all times. Keeping back-up capacity available induces costs. Since PCX UC is the responsible company for steam supply in site Y, these costs will have to be incurred by PCX UC. Therefore compensation would be needed.

Based on the model results and the other identified benefits for stakeholders it is advised to ECA to take the following steps:

- Negotiate with a collaborative style. This means that ECA should:
  - Not act in purely self-serving manner;
  - Accurately disclose relevant information when requested;
  - Not change supply specifications without consultation;
  - Generally act in an ethical manner (Smeltzer, 1997).
- Aim for good selling conditions, which are:
  - A steam price higher than the threshold price of ECA;
  - A steam price connected to the average steam price (incl. CO2 costs) of the previous year;
  - No possibility for large claims in case of plant failure BPA;
  - No possibility for breaching contract by PCX;
  - Base load steam supply by BPA.
- Wait with signing a contract until a final version of the new subsidy scheme is available, because
  - Subsidy should be granted to ECA;
  - Subsidy amount should be high enough.
- If good selling conditions are established and subsidy is sufficient, ECA should invest in the PRDS alternative.

Abbreviations

This is a public report. The names of the involved companies will not be mentioned, since this project was done confidentially. Therefore the companies involved will be referred to as described below. In the text, they will only be referred to with these abbreviations.

<u>Company names</u>

ECA	-	Energy Company A
BPA	-	Biomass plant A
PCX	-	Production Company X
PCX UC	-	Production Company X Utility Company
CHPX	-	Combined Heat and Power plant of Production Company X
YAC	-	site Y Authority Company
PCB	-	Production Company B
RIA	-	Research Institute A

<u>Others</u>

NSS	-	New subsidy scheme
OSS	-	Old subsidy scheme
LP	-	Low pressure
MP	-	Medium pressure
HP	-	High pressure
GT	-	Gas turbine
ST	-	Steam turbine
HRSG	-	Heat Recovery Steam Generator
CFB	-	Circulating Fluidized Bed
PRDS	-	Pressure Reducing De-Superheater
BPST	-	Back Pressure Steam Turbine

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INTRODUCTION

1. Introduction

An industrial cluster is a geographically bounded collection of similar and/or related firms that together create competitive advantages for member firms and the host economy (Barkley & Henry, 1997). The theory of economic development based on industrial clusters hypothesizes that the colocation of firms or industries that complement each other or share utilities leads to increasing returns to scale (Hill & Brennan, 2000). Recently rising fuel prices, increasing costs associated with CO2 emissions and the threat of global warming make efficient use of energy increasingly important. Industrial clusters have the potential to significantly increase energy and hence cost efficiency by utility collaboration (Hackl, Andersson, & Harvey, 2011). Cooperation between companies within industrial clusters can strengthen the competitive position of individual companies in those clusters. The importance of localization of production within industrial districts is that, by providing opportunities for the industrial district as a whole to secure internal economies of scale and external benefits denied to isolated firms, it improves the competitive position of individual firms (Newlands, 2003).

Utility systems are an important part of most processing sites (Varbanov, Doyle, & Smith, 2004). Over the last few decades, a wealth of articles on the design and optimization of utility systems in industrial clusters has been published. Most of these articles seem to disregard non-technical factors, whereas these appear to play a significant role when optimizing an integrated utility system. In particular, long-term development plans that companies within a cluster make for future development of their own plants limit efficiency gains that could potentially be achieved with integration. This thesis presents a model-based approach to support a utility provider in its investment decision-making to enter an industrial cluster. To test the applicability and to illustrate the proposed approach a case study has been done.

1.1 Case study

Energy Company A (ECA) is one of the largest energy suppliers in Country A. This company aims to maximize its profits to be able to sustain its business in the long term. Exploiting its current installed capacity in the most profitable way is one of the activities that ECA can undertake to reach this goal. It can do this by improving the efficiency of the current plants and by investigating whether a different use of a particular plant can increase the profitability of that plant. The goal tree of ECA, which supports the analysis above, can be found in Appendix A.

ECA is the owner of biomass plant A (BPA), which is located in an industrial cluster called 'site Y'. The biomass plant is currently solely configured to produce electricity. Since mid-2008 electricity prices in Europe have dropped and experts foresee no significant increase in electricity prices in the future. Since EU heads of state have agreed to set a binding target for renewable energy use at 20 percent of the EU's total energy needs by 2020 (Johnstone, Hašcic, & Popp, 2010) installed renewable capacity in Europe increased. According to Würzburg, Labandeira, and Linares (2013) an increased renewable production of electricity crowds out other high(er) marginal-cost technologies and results in lower electricity prices. If no significant rise in electricity price occurs, BPA will become unprofitable at the end of its current subsidy scheme. Therefore the BPA does not meet the expectations of ECA in terms of profitability.

1.1.1 Opportunity

<u>Steam production in site Y becomes more expensive</u>

CHPX 1 is one of the main steam producing units for site Y. This is a joint venture between production company X (PCX) and Energy Company B, because PCX is one of the main steam consumers in site Y. CHPX is a combined heat- and power (CHP) plant that runs on natural gas and produces electricity and steam at the same time.

Spark spreads are cross-commodity options paying out the difference between the price of electricity sold by generators and the price of the fuels used to generate it (Deng & Oren, 2006). A low electricity price and a high natural gas price cause steam production with a CHP to be expensive (Gerdes, Marbus, & Boelhouwer, 2013). Until recently the electricity price used to be higher than the gas natural price. Therefore CHPX could provide steam that was cheaper than the fuel price. However since the electricity price dropped and the natural gas price increased, the spark spread was pressured. This means that it became more expensive to produce steam with a CHP. Due to these drastic changes in the energy market, CHPX already decided to not fully operate its capacity (no reference attached due to confidentiality reasons). However CHPX continues to incur losses (business manager production site Y, personal communication, May 16, 2014). Therefore PCX is looking for new ways to obtain cheaper steam in order to operate CHPX as little as possible under current circumstances.

Since BPA is a production facility that runs on biomass, the production costs of steam produced by the BPA are not dependent on the gas price. The natural gas price is highly volatile. Not only is the gas price related to changes in weather and storage (Mu, 2007), it is also closely related to micro- and macroeconomic developments (Correljé & van der Linde, 2006). However the price of biomass is not as volatile, because biomass can easily be stored on site and therefore this fuel can be bought on the market whenever it is cheap. Therefore steam production with BPA could be one of the options to provide cheaper steam in site Y.

Governmental emphasis on improvement site Y

Secondly in the early beginning of 2014, a large plant in site Y went bankrupt and had to close due to the inability to compete with plants in countries with lower electricity prices. The closure of this plant was a large loss for the province in which site Y is located. The loss of this large production plant, economic contraction and a high unemployment rate in the province in which site Y is located made the government decide to do something about it (business manager production site Y, personal communication, May 16, 2014). Therefore an action committee has been formed to construct a plan to strengthen the industrial cluster of the site Y area to boost the economy of the area and to create more jobs.

One of the key focus points of this plan is to organize and strengthen joint utilities in the area. The idea behind a good utility system is that the availability of joint, reliable and affordable utilities and mutual connections will provide cost reduction, flexibility and lower environmental taxes (no reference included due to confidentiality reasons). These advantages should strengthen the area and make the area more attractive for new investors. The plan of the action committee has put more emphasis on steam provision of BPA in site Y. Therefore involved governmental parties and the site Y authority company (YAC) are very well-willing to support BPA in production and supply of steam in site Y. At this moment ECA gets subsidy for the electricity produced by the BPA. This subsidy accounts for a large part of the income from the biomass plant. There is no subsidy on bio steam yet. However the government supports the plan of the action committee and is therefore prepared to adjust the current subsidy arrangements into a subsidy that also reimburses an amount for bio steam.

ECA has spotted an opportunity to increase the profitability of BPA by producing steam for steam consumers in site Y. This opportunity arose by the coincidence of two events. The current production of steam in site Y became very expensive, which created a sense of urgency PCX to change its situation. Secondly a large political emphasis on improving the utility system in site Y arose. Therefore ECA wants to investigate whether producing steam or a combination of steam and electricity with BPA is more profitable than solely producing electricity as it does now.

1.1.2 Cluster complexity

In the late 1950's, PCX built a plant in the area of site Y for industrial production. This plant formed the basis of site Y. After PCX built its first plant in site Y, it extended its business in the area with many other plants. Some of which it has ceded in a later stage. Therefore most companies that are established in the area now were formerly owned and operated by PCX. Because of the historical background of site Y and the fact that PCX is still the owner of the land on which the other companies have their plants (business manager production site Y, personal communication, May 16, 2014), PCX has a dominant position in the cluster. Furthermore PCX Utility Company (PCX UC) distributes cooling water, steam, electricity, air, process water, demineralized water, natural gas and drinking water for many companies in site Y (no reference included due to confidentiality reasons). Therefore most companies in site Y are dependent on PCX UC.

Because of this dependency, PCX UC gains the power to set the rules under which it delivers utilities. The conditions under which PCX UC delivers steam to consumers in site Y are favouring PCX business units. As result of the above mentioned, the steam consumers in site Y are dissatisfied with the contractual conditions under which they receive steam at the moment and are therefore looking for new ways to obtain cheaper steam or get better contractual conditions. However since they are still dependent on PCX for the supply of utilities plus the land on which they operate, a cautious approach is needed. Since the beginning of this cluster, it has been highly integrated. Therefore most companies are mutually dependent on each other.

Below is a representation of steam cluster site Y. In this representation BPA is shown as new entrant as steam producer in the site Y. However at this moment BPA does not have the ability to produce steam yet. Alternative steam production and demand will be taken into account in this system which is shown in figure 1.

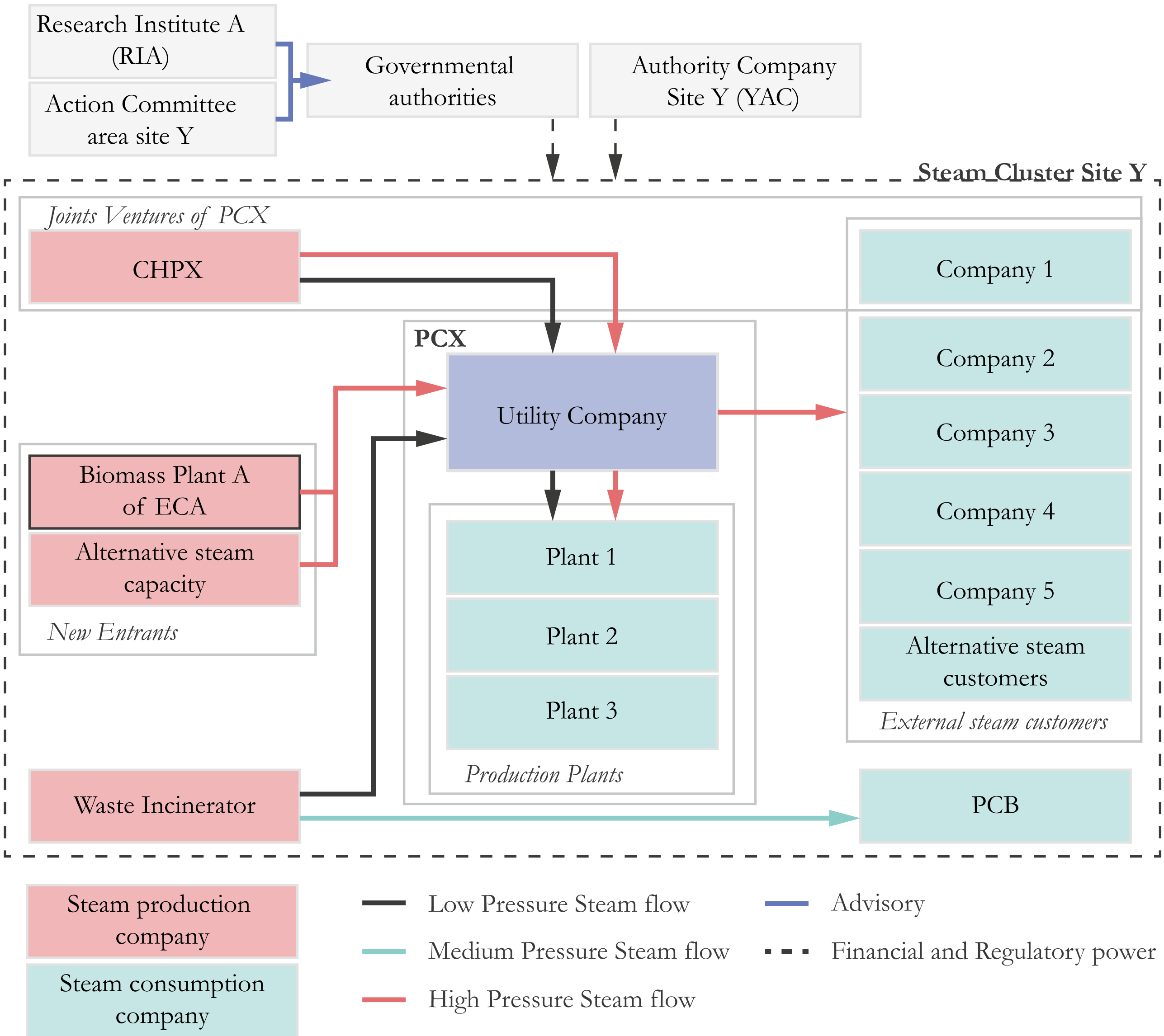


Figure 1: Stakeholder diagram site Y

1.2 Research objectives

ECA's goal is to maximize profits and to do so it wants to operate its existing facilities in the most profitable way. Recently it seems like an opportunity has arisen for ECA to operate BPA in a more profitable way than it currently does. Therefore ECA wants to further investigate this opportunity.

The main objective of this research is to support ECA in making an investment decision on whether or not it should invest in steam production with BPA. If it turns out that ECA should invest in adjusting BPA, a choice should be made about what steam production alternative would be best for ECA and its customers. Furthermore a lowest price point per ton of steam supplied by ECA should be established to define the negotiation space. Finally an advice will be given on how to proceed negotiations with steam consumers. The research objectives will be briefly summed up below:

- Support the investment decision of ECA in adjusting BPA for steam production
- Support the choice for a steam production alternative for BPA
- Define negotiation space in terms of steam price
- Give advice on how to proceed negotiations with stakeholders about steam supply by BPA

1.3 Research questions

The main goal of this research is to find out whether ECA should invest in adjusting BPA to produce steam. If BPA will produce steam, it will be supplying steam in site Y. To understand the situation, transaction cost theory will be used. Furthermore in transaction cost theory, the underlying behavioural assumptions are bounded rationality and opportunism (Frauendorf, 2006). Applying the theory to the situation of ECA provides the expectation that steam consumers in site Y will only want to buy steam from ECA if they think that buying steam from BPA is more advantageous to them than other options they have. Besides ECA will only be prepared to adjust BPA to produce steam if selling steam is more advantageous than BPA's current operation. Therefore the main question that ECA has is:

What are the benefits for stakeholders if biomass plant A will supply steam in site Y?

This research question does not only include unit cost of steam, but it also takes into account other economic, as well as social and environmental dimensions. On the basis of the insight gained from the answer on the main research question, a negotiation strategy will be designed.

To answer the main question firstly an analysis will be done about what steam production plants will be included in the analysis. This is followed up by the collection of detailed production specifications of the identified production plants. Cluster mapping will be complemented with information about steam consuming companies in site Y, that together make up the steam demand. To finish off the analysis of possible future developments in the steam production system in site Y, external factors that influence the steam system will be discussed. If all stakeholders and external factors influencing the steam market in site Y are clear, an analysis will be done on what steam production units benefit stakeholders under which conditions.

1.4 Research approach

To gain insight in how the steam system behaves under various configurations of assets and various market circumstances, a simulation model will be constructed. Future plans of relevant stakeholders are investigated, and subsequently included in a simulation model that mimics plant operations aiming for maximum efficiency at cluster level. This model is run according to an experimental design that explores a set of possible combinations of assets and uncertain market conditions. Model behaviour and results are interpreted to determine the negotiation position of ECA, which then serves as a starting point for the design of a negotiation strategy.

1.5 Relevance

In recent years, much research has been done on the topic of the design and synthesis of utility systems in industrial clusters. Mixed Integer Linear Programming (MILP) is a commonly used approach for performing structural and parameter optimization in the synthesis of utility systems. However according to Baas (2008) it is increasingly being found that there has been too much emphasis upon the technological and mechanical dimensions of change and far too little emphasis upon understanding and working with non-technical dimensions. Therefore, better success is being achieved by integration of the economic, environmental and social dimensions into industrial collaboration activities.

During research of Hackl and Harvey (2013) factors which are important for collaboration across company borders besides the technical feasibility were identified. One of the challenges is to investigate long term development plans for such clusters. Each company within a cluster has plans for future development of its own plant and such plans should be included in an effort towards cluster collaboration. According to Hackl and Harvey (2013) further research work should include these factors and develop strategies to overcome non-technical obstacles in industrial cluster collaborations.

In this research the aim is to include non-technical factors into the optimization effort of a utility system. As Hackl and Harvey (2013) mentioned data is uncertain about potential future plant developments. Therefore in this study firstly possible plans for future plant developments will be identified, which will then be accounted for in an optimization effort by means of an experimental design. Furthermore a scenario analysis will be done, in which various market developments will be posed onto the system to test robustness of various plant developments.

1.6 Report structure

This research report will be divided into four parts, following the IMRAD method. Each section will be clearly marked by a different colour in order to provide the reader with a guideline.

Firstly in chapter 1, the research problem is introduced and the research objectives and questions are identified. Secondly chapters 2 until 6 cover the method. Chapter 2 describes the theoretical framework that is developed which forms the basis for this research. Chapter 3 reviews the cluster complexity in the steam utility system of site Y. Besides important development plans of stakeholders in the cluster will be identified. Next in chapter 4 technical specifications of current and identified future steam production units will be described. Subsequently, chapter 5 discusses the model specification. The simulation model will be constructed to simulate the steam production system in site Y. Lastly, the method description will be wrapped up in chapter 6 with a verification and validation of the simulation model. Thirdly, model results will be discussed. Chapter 7 discusses the results of the model, which will be used to define the negotiation space. Chapter 8 provides how the model can be used to enter negotiations with important stakeholders. Finally, chapter 9 describes the conclusions and recommendations. This chapter also comprises a reflection on the research and suggestions for future research.

METHOD

2. Theoretical framework

In this chapter an explanation will be given about the theoretical framework that will be used to structure research to support a utility provider wishing to enter an integrated cluster in its investment decision-making. In section 1 the problem environment of an industrial cluster, which is highly integrated, will be discussed. Subsequent the implications of decision making under uncertainty will be discussed in section 2, because a large part of the uncertainty is caused by interdependencies within an industrial cluster. Furthermore in section 3 the make-or-buy decision will be given attention, because this decision underlies the sourcing decision of the utility systems in industrial clusters. To finish off in section 4 the method of optimization will be introduced with respect to similar topics. On the basis of the theoretical background introduced in sections 1 until 4, in section 5 a flow chart will be presented, which gives a systematic overview of the approach that will be used to support ECA in making an investment decision about entering site Y as a steam provider.

2.1 Industrial ecology

In chapter 1 a short introduction has been given about the industrial cluster that biomass plant A is located in. Broadly defined, an industrial cluster is a geographically bounded collection of similar and/or related firms that together create competitive advantages for member firms and the host economy (Barkley & Henry, 1997). The theory of economic development based on industrial clusters hypothesizes that the colocation of firms or industries that complement each other, compete against each other, or share utilities leads to increasing returns to scale. The increasing returns can take the form of lower unit operating costs due to the concentration of specialized suppliers or the existence of pipeline economies (Hill & Brennan, 2000). Integration in an industrial cluster, in which the consumption of energy and materials is optimized and the effluents of one process serve as the raw material(s) or energy for another process is called industrial ecology (Frosch & Gallopoulos, 1989). According to Chertow (2000) the keys to industrial ecology are collaboration and the synergistic possibilities offered by geographic proximity.

Industrial clusters often consist of several plants with different plant owners. Plant operators usually have no detailed knowledge about the energy and material flows in their neighbouring plants. During the research of R. Hackl and Harvey (2013) factors which are important for collaboration across company borders besides the technical feasibility were identified. One of the challenges is to investigate long term development plans for such clusters. Each company within a cluster has more or less far-reaching plans for future development of its own plant and such plans should be included in an effort towards cluster collaboration. However, data collection is a complicated process, especially if data is uncertain and about potential future plant developments. Other factors include inter alia, ownership structure of the companies and policy instruments supporting the implementation of energy efficiency measures and renewable materials. According to R. Hackl and Harvey (2013) further research work should include these factors and develop strategies to overcome non-technical obstacles in industrial cluster collaborations. Furthermore Baas (2008) stated that it is increasingly being found that there has been too much emphasis upon the technological and mechanical dimensions of change in cluster collaborations and far too little emphasis upon understanding and working with the non-technical dimensions. Therefore, better success is being achieved by integration of the economic, environmental and social dimensions into industrial collaboration activities.

Among many studies, in the research of Roman Hackl et al. (2011) was shown that large improvements in utility systems in industrial clusters are possible. However for the purpose of synthesis of utility systems collaboration is needed. Due to the competitive character of most stakeholders in a cluster, this collaboration is difficult to achieve. Therefore an approach is needed, in which social dimensions are taken into account.

2.1.1 Establishing stakeholder relationships in an industrial cluster

Industrial clusters are central to improved economic performance and regional development in a variety of ways (Jaegersberg & Ure, 2011). Many case studies have been executed to explore advantages to companies that developed long-term highly interdependent relationships with a small group of suppliers. Researchers found that it wasn't just the existence of the relationship that was important, but the quality of the relationship also mattered. Trust was an essential ingredient for successful, profitable supply-chain relations. A relationship with an external stakeholder – the customer – is a very important determinant of long-term corporate profitability (Svendsen, 1998). Therefore in the case of large companies such as ECA and PCX, the relationship is very important, since the two companies might meet in other areas as well. This can be confirmed by past collaborations between the two companies.

Even though many business leaders acknowledge the power of long-term, positive stakeholder relationships, still in most companies competitive pressures keep all eyes focused on the short term. This makes it extremely difficult to bring long-term issues to the forefront. Traditional accounting systems based on financial measures of performance make it difficult to assess the impact of intangibles like relationships or reputation. And collaboration means letting go of control, which is always difficult when active in a competitive environment (Svendsen, 1998). Furthermore communication issues and poorly aligned incentives are major barriers for stakeholder collaboration in clusters and therefore hamper economic benefits for a regional cluster (Jaegersberg & Ure, 2011). These barriers should be taken into account when considering strategies to establish a relationship. Reason for this is that despite these barriers, stakeholder relationships do offer enormous potential and can be a source of competitive advantage (Svendsen, 1998).

2.1.2 Negotiation styles for industrial buyers' behaviour

When providing an utility in an industrial cluster, agreements have to be reached to set the conditions under which an utility is being provided. For this purpose negotiations are very important. Not only are negotiations important for reaching short-term agreements on conditions, but also can these negotiations form the basis for a long-term relationship. Therefore choosing the right negotiation strategy is key for long-term success. For this purpose Perdue, Day, and Michaels (1986) presented two negotiation styles that appear to be relevant for describing industrial buyers' behaviour in the context of buyer-seller negotiation. Those styles are the collaborative and competitive styles, which will be briefly presented below:

- Collaborative: the buyer attempts to fully satisfy both his/her own concerns and the concerns of the seller. This is an integrative, "problem-solving" style in which the buyer's main objective is the maximization of the joint gain of both parties.
- Competitive: the buyer attempts to fully satisfy his/her own concerns at the expense of the seller's concerns. This is a "win-lose" style in which the buyer attempts to enhance his/her own position relative to the seller.

Perceptions of effectiveness are an important measure of what actually occurs in a negotiation. These perceptions create the tone and atmosphere of a particular negotiation and can also affect a company's reputation in the future. Schneider (2002) studied what skills make more effective negotiators. The analysis of a problem-solving group of negotiators confirms that the skills used by problem-solving negotiators make these negotiators more effective than hard bargainers. However what negotiation style is appropriate depends on the situation. Hence insight in stakes, interests and negotiation strategy of the opponent is of large importance.

2.2 Decision making under uncertainty

If ECA decides to adjust its biomass plant for large scale steam production, it has to invest a large amount of money. Economics defines investment as the act of incurring an immediate cost in the expectation of future rewards (Dixit, 1994). The investments that ECA has to make are risky, because those future rewards depend on many uncertain factors. The success of this project is not only dependent on developments on the energy market and governmental policy, but also on the behaviour of the other (future) stakeholders in the industrial cluster it operates in. If ECA invests in steam production with BPA, it has to be able to sell enough steam- and/or electricity at a good price to earn back the investment made.

Most investment decisions have three characteristics in common. First, the investment is partially or completely irreversible. Second, there is uncertainty over the future rewards from the investment. Third, there is some leeway about the timing of the investment. Those three characteristics interact to determine the optimal investment decisions (Dixit, 1994). Most decisions, almost by definition, involve some consideration of unknown factors. Often, the decision making process takes the form of "what if' reasoning, in which the outcomes of different decisions are evaluated in the light of various possible end values of the unknown factors (Greengard & Ruszczynski, 2002). Evaluation of an investment decision in providing an utility in an industrial cluster considers economic uncertainties that include utility supply and demand and prices of resources.

ECA faces a difficult decision. By means of this research that decision should be supported. This research should clarify the behaviour of the system under various scenarios. Various measures of ECA should be evaluated in the light of possible plant developments of stakeholders in the cluster, as well as energy market developments. Furthermore evaluation should be done from the viewpoint of ECA, but also from the viewpoint of important stakeholder. Reason for this is that negative outcomes for stakeholders could drive them to actions that influence the system. Therefore the outcomes should give a better understanding of the choices made and the effects of those choices on the operation of the BPA. Based on the knowledge gained from this research, ECA should be able to make a decision on how ECA should proceed this project.

2.3 Make-or-buy decision process

Currently CHPX – a joint venture of PCX and Energy Company B – is the main steam producer in site Y. PCX UC is the company that is responsible to meet the steam demand in site Y. Since the spark spread is pressured, the production costs of steam produced by CHPX have gone up. Therefore operating CHPX could be more expensive for PCX UC than buying it from another company with lower production costs. The decision of PCX UC to operate CHPX or to buy from another company can be seen as a make-or-buy decision. PCX UC therefore has to decide to either produce steam itself (with CHPX) or acquire it from another producer. If a firm decides to make an input, it will transact internally with a division or another part of the firm. This is what currently happens with PCX UC and CHPX. However if it decides to buy, it will contract with another organization. The rationale for this sourcing decision is simple. If contracting out parts of the operation is cheaper than doing it yourself, it is a clear case for outsourcing (Fill & Visser, 2000). Whether producing steam with CHPX is cheaper than buying steam from another company depends on resource and electricity prices. Therefore expected (fluctuations in) prices should be taken into account when attempting to understand when PCX UC will decide to outsource steam production.

Besides it should be noticed that the make-or-buy decision is a classic management issue (Fill & Visser, 2000). According to Kremic, Tukel, and Rom (2006) there are three major categories of motivations for outsourcing: costs, strategy and politics. Therefore it is also important to understand the decision criteria behind the sourcing decision by PCX UC to gain insight in what the company will decide. Besides the sourcing decision, based on unit-cost, other (dis)advantages of outsourcing should be taken into consideration when assessing measures.

2.4 Optimization of utility systems

Most companies in industrial clusters consume large amounts of steam, water and electrical resources in the production process. Since the costs of resources have been increasing rapidly, utility networks must be optimized to reduce the overall cost of production of those essential utilities. Recently, many companies have been integrating their processes to achieve better economic performance (Kim, Yoon, Chae, & Park, 2010). The same applies to PCX UC, which is looking for new solutions to obtain cheaper steam. The sourcing decision of PCX UC is thus supported by optimization. By means of this decision, PCX UC aims to maximize its profits. Therefore optimization is needed to represent this behaviour.

Optimization of energy systems that include one or more technologies to meet the requirements of energy systems is extensively studied by many authors. Papoulias and Grossmann (1983) were pioneers in the field by using a mixed-integer linear programming (MILP) approach for performing structural and parameter optimization in the synthesis of utility systems. Years later Marechal and Kalitventzeff (2003) suggested a method to target the optimal integration of the utility system of a production site for multi-period operation. This research effort was quickly followed up by P. Varbanov, Perry, Makwana, Zhu, and Smith (2004) that presented a practical approach for the analysis of industrial utility systems to determine the true value of steam savings and to identify improvements to the utility system. Subsequent Kim et al. (2010) developed a systematic approach to optimize the utility network of an industrial complex. An important feature of this model is the inclusion of realistic operating characteristics of the utility network such as the possibility of selecting alternative raw materials and turning on/off some equipment depending on the seasonal utility demand, fuel price, and so on. This is just a small sample of a topic that has been studied in manifold. Bazmi and Zahedi (2011) provided an extensive overview of the role of optimization modelling techniques in power generation.

To sum up, optimization of integration in utility systems is extensively studied by many authors. However, a systematic procedure including stakeholder plant development plans under uncertain market conditions, is still missing. Therefore in this research an approach is presented that not only assesses stakeholder development plans and uncertainty in market conditions, but also does it interpret the data in order to support the negotiation process.

2.5 Overview approach based on theoretical framework

ECA has to make an investment decision about adjusting its biomass plant for large scale steam production. This decision is difficult, because by producing steam it will enter an industrial cluster that has an integrated utility system. One of the challenges is to investigate long term development plans for such clusters. Since these development plans are uncertain and depend on market conditions, an effort should be made to understand behaviour in the cluster and include this in an analysis. PCX UC is the single steam provider in site Y. Therefore PCX UC gets to decide from whom it purchases the steam it sells in the cluster. PCX UC can either purchase steam from a steam production unit that is also part of PCX, or it can purchase steam from an extern steam producer. The decision of PCX UC from what steam production unit it will purchase steam, depends on a sourcing decision. However other factors can influence this decision as well, which should also be considered in the analysis.

Optimization of utility systems that include one or more technologies to meet the requirements is extensively studied by many authors. For an economic make-or-buy decision that is made by PCX UC, optimization of a utility system is a proven method. However in order to explore whether and under what conditions steam supply by BPA would be beneficial to PCX UC, stakeholder and market developments are included in the analysis. Furthermore the outcomes of the analysis will be used as starting point for the design of a negotiation strategy.

Figure 2 shows a flowchart, which represents the research approach based on the theoretical background provided in section 1 to 4. The flowchart will be discussed in detail in Appendix A.

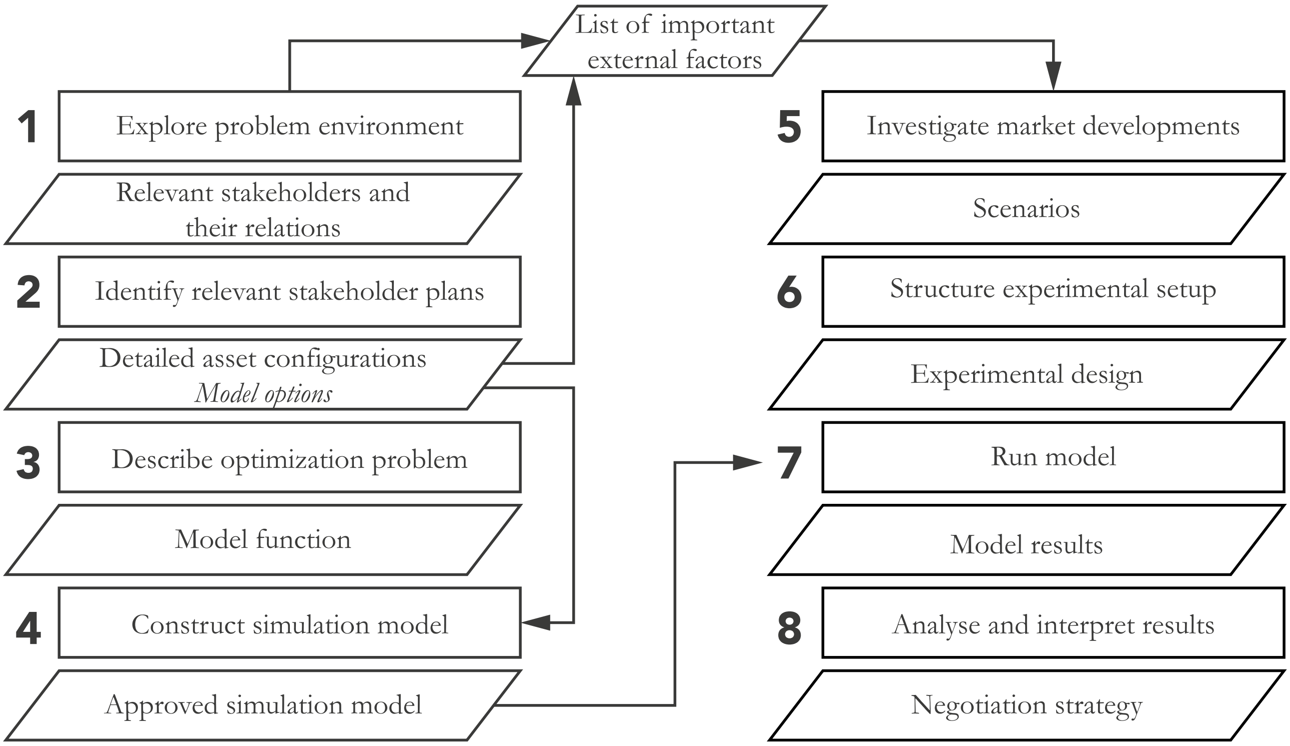


Figure 2: Flow chart of eight-step research approach to support utility producer in its decision to enter an integrated cluster

3. Stakeholder environment

To be able to model the steam system in site Y, it is important to gain insight in the participating companies and the relationship within the cluster. In chapter 1 a schematic overview of the stakeholders of the steam system in site Y was shown. This figure gives an understanding of what the current system looks like. Also a short introduction on the emergence of site Y has been provided in chapter 1. Furthermore in appendix B an introduction to all stakeholders will be given.

In this chapter knowledge about the industrial cluster that ECA wants to enter will be extended. In section 1 the mutual dependencies will be displayed and analysed. Furthermore in section 2, stakeholders in the steam system will be introduced and categorized with regard to their influence on steam production with BPA. The general purpose of stakeholder analysis is to gain such insight in a policy problem that stakeholder strategies can be anticipated (Freeman, 2010). Therefore in section 3 an analysis of future development plans of the stakeholders will be done.

3.1 Cluster integration

For understanding of the interests of the stakeholders in site Y and their position in the cluster, an introduction should first be given about the relationships between the stakeholders. In the figure below, the flows of products that are exchanged between companies in site Y are shown.

In figure 3 it is shown that PCX is a large provider of products within the cluster. Only two companies in the area are not dependent on inputs from PCX. Furthermore as explained in chapter 1, PCX UC is a provider of utilities, such as electricity, steam and water. Therefore PCX has built a network of pipelines in site Y to be able to supply those utilities to its customers. Lastly PCX is still the owner of most of the land in site Y (business manager production site Y, personal communication, May 16, 2014). Therefore all companies that have a plant on land that is owned by PCX need to get permission from PCX for plans on that land.

Due to dependence of PCX for land, utilities and products, for most companies in site Y this means a large dependence. Therefore PCX has a dominant position in the site Y, which gives it the power to set the rules in the cluster.

<figure not attached due to confidentiality reasons>

Figure 3: Integration of product flows in site Y

3.2 Stakeholder types

Considering the participation of ECA in site Y as steam supplier, it is important to find out what stakeholders will be able to influence this project. This will be done according to the theory of Murray-Webster and Simon (2006). When assessing the stakeholders that are involved, three questions are asked to find out whether they are critical stakeholders or not. By critical is meant that those actors have the ability to hinder steam supply of BPA or to make it a success. The three questions to establish the critical stakeholders are the following:

- Do they have power to influence the success of this project?
- Is their attitude positive towards this project?
- Is their interest high to influence this project?

All stakeholders in the steam system in site Y have been mapped according to these three questions. This analysis can be found in appendix B. If a company is influential in the steam system, its attitude is negative towards participation of BPA and its interest is high, then a stakeholder can hinder participation of BPA in the steam system in site Y. However if a company is influential, its attitude is positive and its interest is high, then a company is a saviour. This means that this stakeholder should be involved to be able to support steam production by BPA in site Y.

From the analysis in appendix B can be derived that saviour stakeholders are the Ministry of Economic Affairs and PCX. The ministry is very important, because it decides on the subsidy for bio steam. If ECA will not get a subsidy for bio steam or the subsidy amount will be too low, the project will probably not be profitable. Due to circumstances the political willingness to support improvement in site Y is currently high. Therefore the ministry has a very positive attitude towards supporting steam production of BPA.

Furthermore PCX is the largest consumer of steam in site Y. Since PCX UC is the company that takes care of steam supply in site Y, that is the company that decides what production plant it will purchase steam from. Due to recent developments in the energy market, PCX is very interested in purchasing steam from BPA. PCX is the most important company for ECA to invest in steam production with BPA. ECA will only invest if it will reach an agreement with PCX on the supply of steam.

The other, smaller, companies in site Y are not influential and have a low interest in steam supply by BPA. Reason for this is that all those companies have a steam contract with PCX UC. Therefore if ECA would supply steam to PCX UC, this would not mean that PCX UC would have to change its contracts with its customers. Besides because PCX owns the steam pipelines in site Y, ECA would not be allowed to directly supply steam to the other companies. Furthermore building new pipelines for direct supply of steam from ECA to the smaller companies would be very costly and since PCX owns the land in site Y, this could also be hampered by PCX.

3.3 Analysis of options

In sections 1 and 2 it has been shown that PCX has a dominant position in site Y and that it is therefore a very important stakeholder to involve when entering site Y. In this section an analysis will be done to find out what other options stakeholders have to change their individual situation with regard to steam provision. The need for effective competitive strategy planning has long been recognized to be important. Identification and selection of a robust market strategy by ECA must be based on the anticipation of likely strategies of significant competitors (Dutta & King, 1980). Therefore an analysis of options will be used to identify the options that should be included in the simulation model.

For this purpose meta-game analysis can be used. This analysis reflects on a problem in terms of decision issues, and stakeholders who may exert different options to gain control over these issues. The analysis reveals what likely scenarios exist, and who has the power to control the course of events. The practical application of meta-game theory is based on the analysis of options method (Bots & Hermans, 2003).

The analysis of options method starts with three steps:
1. Review the issues to be decided.
2. Consider who controls the issues.
3. Assess how the stakeholders might control those issues, an inventory of their options (Bots & Hermans, 2003).

Options for every steam customer in site Y have been identified. An overview of the analysis can be viewed in appendix B. Firstly PCX has the option of building a new steam production facility. Reason for this would be that CHPX currently is an expensive unit for the production of steam in site Y due to the pressured spark spread. If PCX would build a new facility, this would probably be a bio boiler or a natural gas boiler. A choice for a boiler that solely produces steam would be made, because electricity prices are low and are not expected to grow much in the future. According to Würzburg et al. (2013) an increased renewable production of electricity crowds out other high(er) marginal-cost technologies and results in lower electricity prices. Besides electricity production is not the core business of PCX and it is expected that the company would rather focus on its core business. Other options for PCX would be to buy steam from ECA or to operate CHPX. Furthermore if other companies in site Y decide to produce steam itself, PCX could buy steam from them as well.

Options for the other steam consuming companies in site Y to improve their conditions under which they buy steam are limited due to the dependency that is explained in the previous sections. However they could decide to jointly build a steam production unit. Individual companies could also decide to build a production unit to produce their own steam. Lastly they could purchase steam from ECA directly. However all of these options are not likely to appear due to the dependence on PCX. For two of the options new steam pipelines would have to be constructed. Furthermore building an own steam production unit is very costly and is therefore not expected to provide a large advantage for individual companies. To conclude it is not expected that other companies in site Y will be building a new facility.

3.4 Conclusions of stakeholder analysis

Two of the PCX plants in site Y are providers of products within the cluster. Only two companies in the area are not dependent on inputs from PCX. Furthermore steam pipelines in site Y are property of PCX. Besides PCX is still the owner of most of the land in site Y (Business manager production site Y, personal communication, May 16, 2014). This means that PCX has a very dominant position in site Y.

From the stakeholder map it was derived that especially the Ministry of Economic Affairs and PCX are very important for ECA to make steam production with BPA a successful project. The ministry is important, because it decides on whether ECA will get subsidy for the production of thermal power as well and if so, what subsidy amount will be assigned. And PCX is very important, because this company will be the main customer of steam from BPA. This is also underpinned by the analysis of options, which lead to the conclusion that it is not expected that other companies than PCX will be responsible for steam production in site Y in the future. However PCX could also decide to build a new facility itself, to produce steam with lower production costs. Therefore this is a significant threat to the steam production alternative of BPA. To cope with this future plant developments of PCX, the options of building a gas or a bio boiler will be taken into account in the simulation model.

4. Specification of steam production units in site Y

In chapter 1 an overview has been given of the companies that currently produce steam to meet the demand in site Y. Subsequently in chapter 3 also other options to produce steam by stakeholders have been introduced. The sourcing decision, which will made about who will produce steam at a certain moment in time, will be based on unit cost. Every steam production unit in site Y has as different unit cost, due to differences in the production specifications of the plant. Therefore in this chapter the production specifications of all the current and identified possible future steam production units in site Y will be viewed. Based on the differences in production specifications the sourcing decision can be made.

In section 1 firstly the specifications of the current configuration of BPA will be described. This will be followed by an introduction of the steam production alternatives that have been identified in a steam export study commissioned by ECA. In the second section of this chapter the specifications of the steam production units that currently produce steam to meet the steam demand in site Y will be laid out. Furthermore this will be followed by a description of the identified possible future production units to be built by PCX. After all the current and possible future steam production units have been introduced, the steam demand in site Y will be investigated. The demand is important, since this is the driving factor of the steam system in site Y. The demand should always be met.

4.1 Alternatives of biomass plant A

4.1.1 Solo electricity alternative

In the current situation the BPA is configured to solely produce electricity. Woodchips enter a Circulating Fluidized Bed (CFB) boiler in which superheated steam is produced. Advantages of using circulating fluidized bed coal combustion technology are wide range fuel application, such as biomass, and low pollution emissions (Tsai, Wu, Huang, & Lee, 2002). Superheated steam that comes out of the CFB boiler then goes into the steam turbine, which causes the turbine to rotate. This work eventually drives the generator in the end, by which green electricity is produced. A conceptual model of this process can be seen in figure C.1 in appendix C.

Characteristics	
Net power	- MW
Type of steam turbine	Condensing
Electrical efficiency	- %
Fuel characteristics	Type: B-wood Energy capacity: 13,5 GJ/ton
Start-up costs CFB	Start-up costs for the CFB of BPA will not be taken into account, because the BPA will be operated at constant maximum load.
Maximum production of superheated steam	- ton/hour
Net Fuel input	- MW In tons: - * 3,6 / 13,5 = - ton/hour

Table 1: Production characteristics BPA (cells left blank for confidentiality reasons)

A large part of the income of BPA consists of subsidy. ECA will get the maximum amount of subsidy for a production of 8000 full load hours per year. Besides biomass plants are not good for flexible operation. Best way to operate a biomass plant is by operating it at maximum capacity. Reason for this is that problems for biomass boilers are fouling, deposits, slagging, corrosion and agglomeration (Saidur et al., 2011). Operating a bio boiler in a flexible way, reduces the optimal configuration of the boiler and can result in a quicker build-up of the issues mentioned above. The combination of the subsidy that ECA wants to receive and the reduced performance of the biomass boiler under suboptimal operations, results in a full-time operation of maximum load.

4.1.2 Pressure Reducing De-Superheater (PRDS) alternative

ECA recently has taken the BPA into operation. This is currently a plant that solely produces electricity, due to the former subsidy regime in Country A which did not favour heat production from biomass. However, since an important action committee came up with the plan to strengthen site Y, ECA is negotiating with the ministry of economic affairs about possible adjustments to the current subsidy scheme. If this will be decided upon, ECA will get subsidy for producing bio steam as well.

From a study on large steam export with the BPA, two alternatives were derived. These alternatives are export steam through a new Pressure Reducing De-Superheater (PRDS) or a new Back-Pressure Steam Turbine (BPST).

The alternative PRDS is a fairly simple option, in which steam is redirected towards a pressure reducing de-superheater, which basically brings the steam to the right pressure and temperature so the steam can be sold. This alternative has a few advantages, which are low investment costs of a little over one million euro and the highest amount of production of steam. However with this option very little electricity will be produced, a part of the heat has to be cooled away. Input- and output data can be found in table 2. Investment costs for both options can be found in appendix C.

4.1.3 Back Pressure Steam Turbine (BPST) alternative

In the second steam production alternative, part of the superheated steam is redirected towards a back pressure turbine, in which electricity is produced from steam and the rest of the steam is bled from the turbine on the right pressure. One of the main advantages of this alternative is that all the energy input that goes in the plant is used to produce steam or electricity, so no excess heat is cooled off. With this alternative there is still a considerable amount of electricity that is being produced. However the investment costs of more than seven million euro are very high compared to the PRDS alternative.

4.1.4 Comparison of steam production alternatives

In table 2 an overview of the in- and output details of both steam production alternatives is shown.

Item	Unit	Alternative BPST			Alternative PRDS		
Process flow	**[%]**	**100**	**50**	**0**	**100**	**50**	**0**
Process flow	[kg/s]	-	-	-	-	-	-
Process heat load	[MW]	-	-	-	-	-	-
Gross power	[MW]	-	-	-	-	-	-
Net power	[MW]	-	-	-	-	-	-
Net Fuel Input (LHV)	[MW]	-	-	-	-	-	-
Net Electric Efficiency	[%]	-	-	-	-	-	-
CHP Efficiency	[%]	-	-	-	-	-	-

Table 2: Overview of in- and output of steam production alternatives BPA (reference not included due to confidentiality reasons) (cells left blank due to confidentiality reasons)

The biggest differences between both options can be found in the ratio between heat and electricity output. Furthermore in the PRDS alternative, part of the heat has to be cooled away, which is a less elegant solution than the BPST alternative. However the PRDS alternative is much less expensive than the BPST alternative.

4.1.5 Implications of steam production alternatives

If ECA decides to (co-)produce steam with the BPA, a pipeline for steam has to be built to connect the BPA to the existing high pressure steam pipeline with large capacity. This pipeline will be approximately 1,6 kilometre. The total investment that has to be made in this connecting BPA to the existing grid is €24 million (reference not included due to confidentiality reasons). This investment is in addition to the investments that already have to be made to adjust the BPA to produce steam. However if this connection would benefit all stakeholders in site Y, site Y authority company (YAC) would be prepared to co-invest in this new pipeline (Business manager production site Y, personal communication, May 16, 2014). A figure of the existing steam grid in site Y and the new steam pipeline, which connects BPA to the existing high pressure steam pipeline, is shown in appendix E.

4.2 Existing steam production units

Steam that is produced by plants that currently operate in this cluster are an important part of the simulation model in which dispatch of all possible configurations of assets are simulated. Therefore it is important to find out what the plant specifications of the current plants are.

4.2.1 CHPX

CHPX is a joint venture between PCX and Energy Company B. This joint venture owns and operates two CHP units, called CHPX 1 and CHPX 2.

CHPX 1

At this moment, the total steam demand of site Y is satisfied by steam production of CHPX 1 and a waste incinerator. As mentioned before CHPX 1 is a CHP. The utilization factor of the ideal CHP plant will strive after 100%. Actual CHP plants have utilization factors as high as 85–90% (large systems provide 40% electrical and 50% thermal energy) (Pilavachi, 2000).

CHPX 1 has a multi-shaft configuration with three gas turbines and HRSGs in series that supply steam through a common header to two separate parallel steam turbines. Exhaust gasses that come out of the gas turbines flow into the HRSGs. In the HRSGs those exhaust gasses are used to heat up water to produce steam. For the use of the HRSGs a decision can be made during operation. The HRSGs can be operated without the supply of extra fuel ('unfired'). If this is the choice, steam will come out of the HRSG at two pressures. The steam flow with high pressure (90 bar) will be directed towards the steam turbine. The steam flow with low pressure will be exported to other companies. The second option is to choose for supplemental fired operation of the HRSGs. If this is the choice, extra fuel will be added to the HRSG, which will be used to produce a larger amount of high pressure steam that goes into the steam turbine. The fully-fired HRSGs are high in cost and also may add to emission considerations as plant siting requirements are evaluated (Chase & Kehoe, 2000). In appendix D a figure is shown in which the production process of CHPX 1 is shown in a schematic way.

Not all information on CHPX 1 is openly available. However in the past years, ECA has collected some information about this plant. Important information that is needed to model CHPX 1 can be found in table 3. According to the business manager production site Y (personal communication, May 16, 2014) CHPX 1 produces 300 ton per hour of high pressure steam at maximum. With the information in table 3, a CHP production profile of CHPX 1 has been calculated. This profile can be found in table 4. The full calculations for the production capacity of CHPX 1 can be found in appendix D.

Gas turbine	• 3 Gas turbines	
	• Electrical output: - MW per unit	
	• Electrical efficiency: - %	
	• Start-up costs per gas turbine: €…,- (calculation is shown in Appendix G)	
HRSG	• 3 HRSGs	
	• *Unfired:*	
	Double pressure	
	Steam production:	- ton/hour for internal processes
		- ton/hour superheated steam
		- ton/hour at low pressure
	• *Supplemental fired:*	
	Single pressure	
	Fuel: natural gas	
	Efficiency: 97,6% (Arrieta & Lora, 2005)	
	Steam production:	- ton/hour for internal processes
		- ton/hour superheated steam
Steam turbine	• 2 Steam turbines	
	• Electrical output: - MW per unit	
	• Type: Extraction Back Pressure (non-condensing)	
	• Steam extraction at high pressure	
	• Low pressure steam extraction	

Table 3: Technical specifications CHPX 1 (information excluded due to confidentiality reasons)

<table not attached due to confidentiality reasons>

Table 4: Production profile CHPX 1

CHPX 2

Since the beginning of 2012 CHPX 2 has been taken out of operation. The reason for this was the heavily pressured spark spread (no reference attached due to confidentiality reasons). Since the total steam demand of site Y can be satisfied by steam production of CHPX 1 and a waste incinerator, it was more expensive to keep CHPX 2 operational than to shut it down. CHPX 2 can only produce low pressure steam and electricity. This steam can only be used by PCX, because the other companies in site Y need higher pressure steam for their operations. The expectation is that CHPX 2 will not be taken into operation in the future anymore. Since the plant has not been running for over two years, the start-up costs will be very high. This will only be done if the electricity prices will increase and the electricity price will stay very high for a longer period in the future. Due to the developments on the electricity market, a steady high electricity price is not to be expected in the future. Therefore CHPX 2 will not be taken into account in the simulation model.

4.2.2 Waste incinerator

The waste incinerator is a plant that is mainly built for the production of steam (business manager production site Y, personal communication, May 16, 2014). Waste is used as fuel to produce superheated steam. The waste incinerator produces 120 tons of steam per hour at medium pressure. Of this amount, 30 ton/hour is supplied to PCB, which is therefore not one of the companies that receives its steam via PCX UC. Furthermore the waste incinerator supplies

60 ton/hour of steam to PCX. This steam is produced at medium pressure, but it is brought down to low pressure to meet the specifications of PCX. The remaining 30 tons of steam hourly are supplied to other companies, that are established on the east side of site Y.

Currently the waste incinerator produces at maximum capacity. Besides the corrosive nature of flue gasses from waste incineration limits the steam parameters to a maximum temperature of approximately 400 °C and a pressure of approximately 40 bar (Rand, Haukohl, & Marxen, 2000). Since these conditions are the maximum input conditions for the steam turbine, it will not be possible for the waste incinerator to produce a large amount of high pressure steam. However steam of the waste incinerator will stay the cheapest in site Y. Reason for this is that it uses waste as input material. the waste incinerator gets a large amount of subsidy for burning waste.

Since the waste incinerator will stay the cheapest producer of steam in site Y, there is no reason to suspect that the current supply contracts of the waste incinerator to PCB and PCX will change in the future. Furthermore since the waste incinerator is not able to produce steam at a higher pressure level, this is no competition for the steam of BPA. Therefore the steam supply of the waste incinerator to PCX and PCB is considered to be fixed. Therefore the waste incinerator will not be modelled in the simulation model.

4.3 New steam production units

From the analysis of options in chapter 3 it has been derived that PCX could also decide to build a gas or a bio boiler to produce steam. Advantages of a gas boiler are that it is very efficient and very flexible. The standard boiler efficiency of a natural gas fired steam boiler is 90% (internal document). Furthermore it can ramp-up in half an hour (Franke & Weidmann, 2008). However the start-up time depends on the time of standstill, which means that if the boiler stands still for a time longer than 3 days, it will take more than an hour to start-up. It is expected that a gas boiler will be used as a flexible unit and it is therefore expected that this unit will be kept standby. This means that a small part of its capacity will always be used to be able to quickly ramp up if needed.

Advantages of a biomass boiler are that it is clean and that biomass prices do not fluctuate as much as fossil fuel prices. If biomass is used for production, the production company is exempted from the European Emission Trading Scheme. Reason for this is the exclusion of installations using 97% or more biomass (fossil fuels may be used for start-up and shut-down)(European Union, 2009). Besides because biomass is easy to store, the purchase of biomass is less dependent on price fluctuations. It can be bought on the market whenever the price is low.

Both of these options will be modelled as possible future options. The boiler size depends on in combination with what other assets it operate. Therefore the boiler size that should be build depends per model option. To cope with the different sizes of boiler that have to be build, in the simulation model a gas and a bio boiler will be included with a very large capacity (400 ton/hr ~ 324 MWth). After the model runs have been done, it is possible to derive from the model results what the boiler size that particular model option should be. The specifications that will be used for the boilers are presented in table 5.

	Gas boiler	Biomass boiler
Efficiency	90% (internal document)	Between 73 – 89% Average 81% (Hebenstreit, Schnetzinger, Ohnmacht, Höftberger, & Haslinger, 2011)
Input characteristics	Natural gas 0,038 GJ/Nm3	A-wood Energy content: 16,5 GJ/ton
Output	400 ton/hr High pressure steam	400 ton/hr High pressure steam
Input needed	360 MWf natural gas ~ 30695 Nm3	400 MWf biomass ~ 87,3 tons of A-wood

Table 5: Production specifications of gas and bio boilers

Both boilers have start-up costs. For a bio boiler it is not desirable to operate at a flexible operation. Furthermore start-up costs are very high for these boilers. The start-up cost for a bio boiler has been estimated on the basis of the start-up costs of the bio boiler in the BPA. The calculation can be found in appendix F. The start-up costs of a bio boiler are estimated at €25.000,-. Secondly the calculation for a gas boiler have been calculated on the basis of an interview with an expert on CHP's. According to plant manager CHP, (personal communication, June 26, 2014) the start-up costs of the bio boiler were estimated well. Furthermore the start-up costs of a gas boiler should be estimated to be around 10% of the start-up costs of a bio boiler, which comes down to €2.500,-.

4.4 Steam demand

4.4.1 PCX large consumption business

The maximum amount of steam that PCX uses is x ton per hour in total (information excluded due to confidentiality reasons). This number has been estimated on the basis of the allocation of free emission rights for the European Emission Trading Scheme (ETS). This scheme will be introduced in appendix M. The allocation of free emission rights is based on the highest median of steam input of PCX in the period of 2005-2008. Therefore this estimation might be too high, since every company wants to receive as much free emission rights as possible. According to project developer biomass (personal communication, May 9, 2014) the regular demand of PCX for low pressure steam is x-y ton per hour (information excluded due to confidentiality reasons). The steam demand of PCX has been checked with two different sources and they are almost similar. Since the estimation on the basis of ETS is expected to be a little overestimated, x-y ton per hour is assumed for the simulation model. PCX gets z ton per hour of steam from the waste incinerator, since PCX is the only company in site Y that uses low pressure steam. The waste incinerator supplies an amount of medium pressure steam to PCB and z ton per hour is converted to low pressure steam after PCB as it goes to PCX. Therefore PCX has to get at least (x-y)-z ton per hour of steam from CHPX at this moment (information left out due to confidentiality reasons).

4.4.2 Small steam consumers

The small steam consumers in site Y are all companies that use steam for their production process, except for PCX large consumption business and PCB. Furthermore small consumers are not obliged to participate in ETS. An introduction to all these companies has been given in appendix B.

The amount of thermal power (steam) delivered to the group of small steam consumers is estimated by the application of CHPX for CO2-rights. To get the highest amount of CO2-rights possible, CHPX claimed the highest accumulated amount of thermal power supplied by CHPX 1 and 2. The period over which CHPX did its calculations is from 2005-2008. From the calculation it is derived that the steam supply of CHPX to the group of small steam consumers in site Y is on average w ton per hour.

4.4.3 Fluctuations

Small steam consumers that get steam from CHPX, are supplied via PCX Utility Company (PCX UC). Those companies have contracts with PCX UC for the supply of this steam. Since not many steam producers are active in site Y and also steam production is not the core business of those companies, the steam contracts in site Y are assumed to be basic. By this is meant that a fixed price per ton steam is set, which is related to the price of natural gas. This assumption is also confirmed by the steam supply contract between the waste incinerator and production company B (no reference included due to confidentiality reasons). Consequently there is no intern steam market within site Y. Therefore prices are not market based on a timely basis.

One of the reasons that an action committee for improvement of site Y was formed is that many of the small steam consumers, that are not part of PCX, were dissatisfied with the conditions under which they received their utilities. Since all those companies were initially founded by PCX, they all get their utilities from PCX UC via pipeline grids that are owned by PCX. Therefore the companies in the cluster have no opportunity to get these utilities elsewhere, because the infrastructure is already there and getting utilities elsewhere would be more expensive due to distance. Because the companies are dependent on PCX UC, the utility company has the power to set the rules. One of those rules is that the steam consuming companies have to consume a fixed amount of steam or they have pay a high price for steam whenever they want to consume it. Reason for this is that CHPX 1 has to keep reserve capacity ready for those companies. Therefore if those companies decide to buy steam at some point, PCX UC asks a high price to compensate for the time it kept back-up reserve. Hence fluctuating demand is very unfavourable for the consuming companies. According to project developer biomass of ECA (personal communication, May 9, 2014) this is the main issue for the steam consuming companies in site Y.

Producer	Consumer(s)	Amount of Steam	Steam pressure
CHPX	PCX large consumption business	(x-y)-z ton/hr	Low pressure
CHPX	Small Steam Consumers	w ton/hr	High pressure
Waste incinerator	PCB	Not relevant	Medium pressure
Waste incinerator	PCX large consumption business	z ton/hr	Low pressure

Table 6: Steam supply and demand in site Y (information excluded due to confidentiality reasons)

5. Model specification

In chapters 3 and 4 interdependencies between stakeholders in site Y have been clarified. Furthermore the specifications of current- and possible future steam production units in site Y have been listed and showed in conceptual models. Now the links between stakeholders and specifications of current- and future possible steam production units have been analysed, a simulation model can be developed. In section 5.1 the goal of the model will be explained. In section 5.2 the optimization problem that that underlies the simulation model will be described. Furthermore in section 5.3 the software that will be used to solve this particular optimization problem will be shown.

5.1 Model purpose and structure

5.1.1 Model goal

The goal of the model is to simulate sourcing behaviour in site Y to meet steam demand. The model will optimize total system profits for the production of steam in site Y to meet the total steam demand in site Y. The profit of steam production depends on asset characteristics, the resource that it uses to produce steam and from possible electricity production of a facility. Therefore in this model resource- and electricity prices will be taken into account, based on which the simulation model makes its decision to operate certain facilities. The total system profits for production of steam in site Y will be calculated for various configurations of steam production units. The model will be optimized under the assumption that all steam producing stakeholders in site Y cooperate to reach the highest total system profits, because it is expected that PCX UC will stay the responsible steam supplier in site Y. Therefore the gains and losses are for the same company. This means that cooperation between steam production units should not be hindered.

Model results will be used to support ECA in its decision making about adjusting the BPA and providing ECA with grips for negotiations with PCX on steam price and selling conditions. For this purpose the model will be used to find out whether steam supply of ECA in site Y would benefit the system from a financial perspective. Also threshold prices for ECA and PCX UC will be determined for steam supplied by ECA. Threshold prices constitute what PCX UC is willing to pay for steam from ECA at maximum and also what ECA asks for its steam at minimum. Therefore these threshold prices are an important part of the negotiation space between PCX UC and ECA. The use of a model is important to find out how the system operates under various circumstances.

5.1.2 Configurations of steam production units

One simulation model will be made in which all assets considered to be important for current- or future steam production in site Y will be modelled. These assets have been introduced in chapter 4. The options represent all possible combinations of assets that can reasonably be expected for site Y in the future. The simulation model will be run for all options. The specific (technical) characteristics and constraints of all individual assets involved have been explained in chapter 4. Those characteristics determine the dispatch of steam production in site Y. In table 7 model options are represented. Model options are combinations of assets.

Option	Name	Biomass plant A Solo-E	Biomass plant A PRDS	Biomass plant A BPST	CHPX 1	Gas boiler	Bio boiler
0	Current	✓			✓		
1	PRDS-CHPX		✓		✓		
2	BPST-CHPX			✓	✓		
3	GB	✓				✓	
4	PRDS-GB		✓			✓	
5	BPST-GB			✓		✓	
6	BB	✓					✓
7	PRDS-BB		✓				✓
8	BPST-BB			✓			✓
9	CHPX-GB	✓			✓	✓	
10	PRDS-CHPX-GB		✓		✓	✓	
11	BPST-CHPX-GB			✓	✓	✓	
12	CHPX-BB	✓			✓		✓

Table 7: Composition of assets per option

Options 0, 1 and 2 are the most realistic options for 2017, since ECA and PCX are already negotiating about steam supply from BPA. Furthermore it is to be expected that on such short notice, no new facility will be built for steam production. However, especially on the longer term these options become more realistic. In options 3 till 8 the addition of a gas- or bio boiler to site Y are considered. For these options it is most realistic that PCX invests in any of the boilers, because it would completely take over the current steam production by CHPX. Furthermore in options 9 till 11 it is expected that PCX UC does not demolish CHPX 1, but that it does place a gas boiler besides CHPX 1. This way PCX UC can operate both facilities in the optimal way, which means operating CHPX 1 when electricity prices are favourable and using the gas boiler with a high efficiency during the rest of the time. The last option considers CHPX 1 in combination with a bio boiler. In this option only solo electricity production by BPA is assumed. Reason for this is that it is not to be expected that PCX UC will buy steam from BPA, which is a biomass plant, and also build a biomass plant itself. Plants on biomass cannot guarantee a yearly 8000 hour production. Therefore having two facilities in the system that run on biomass would provide the system with lower reliability, which is one of the most important aspects of steam supply in site Y.

5.1.3 Model assumptions

Assumptions for the steam system site Y have to be clarified to be able to define the simulation model. Some common assumptions have been made about the steam system site Y. These assumptions have been summarized in table 8.

Assumptions
PCX UC will purchase steam from the producer that produces steam at the lowest unit cost. The cheapest producer might change in time due to price fluctuations of resources and electricity.
BPA will produce constantly at maximum load, independent of the alternative that it operates (investment analyst BPA, personal communication, May 28, 2014).
There is no problem for site Y if one of the combined steam and electricity producers does not produce electricity or less electricity. It will always be possible to get electricity from the net.
Steam demand in site Y does not fluctuate on the basis of steam and electricity prices. It can only fluctuate on the basis of production processes for which steam is needed.
Steam demand in site Y must always be met.
All companies in site Y except for PCX large consumption business and PCB use high pressure steam for their processes.
All steam connections from steam production unit to the grid have to be heated before they can transport steam. Therefore a minimum load of 15 ton/hr has been set for all steam pipelines in site Y. If this lower bound is not met, the particular steam pipeline will temporarily not be used. When it is turned on again, the start-up costs are: €15 (average production cost of a ton steam) * 8 (hours to heat up the pipeline) * 80 (at half capacity, from zero to maximum capacity of the pipeline) = €9600,- This amount is fixed for all steam connections in site Y.
Back pressure and extraction steam turbines have a minimum flow through the end of the turbine of 25%.
No extra water has to be purchased, because it is a closed system, in which water is led back to the producers.
Steam storage is not possible in site Y.
High pressure steam can be converted to low pressure steam if needed.
All low pressure steam can be cooled away if needed, so there is no upper constraint for low pressure steam production.

Table 8: Common assumptions for modelling steam production- and demand in site Y

5.1.4 Model scope

A step that has to be undertaken before constructing a base model is a demarcation, in which a choice will be made about what aspects will be included in the model and what aspects will be left out. The choice for aspects that have been included is based on the model goal. The model will only be used to compare on economic performance between the various options based on marginal costs. The list of aspects that are included in the simulation model can be found in section 5.2.2 in which model parameters are defined.

Some aspects that can also be considered to be important for the steam utility system in site Y will not be modelled in the simulation model. Some of these aspects will be entirely left out of the scope of this project, but some aspects will be discussed in chapter 7. The choice for in- or excluding certain aspects is in line with the aggregation of the model. The model has a high aggregation. It will only be used to gain insight in economic performance of certain compositions of steam production units. Below will be discussed what reasons are for leaving certain aspects outside the scope of the model. Secondly implications of leaving these aspects out will be shortly be discussed.

Not included:

- Prices and amounts of other utilities needed for steam production: The main utility for the production of steam is water. The reason water supply to steam production units will not be considered in this model is because of the assumption that the steam system of site Y is a closed system, in which condensed steam – thus water – is delivered back to steam producers.
- Steam prices: The main driver of the model the steam demand. The optimization that is done when running the model is to reach the highest system profits for the production to meet the steam demand. This is done by calculating what steam production plant can produce steam at the highest profit at a certain moment. This profit consists from production costs plus revenues from electricity production. Therefore steam prices are not relevant in calculating the system profits.
- Individual behaviour of steam producing stakeholders: Individual behaviour of stakeholders has been accounted for by a stakeholder analysis in chapter 3. Therefore the model includes all current- and possible future steam production units in site Y. This will be applied in the model by an experimental design.
- Investment costs in new facilities: The model is used to maximize total system profits to meet the steam demand in site Y under various configurations. However for options in which new steam production units are considered, investment costs are an important part of the profitability of those options. Therefore in chapter 7, results with adjustments to BPA and new steam production units will be considered taking investment costs into account.
- Investment costs in new steam carriers: See 'investment costs in new facilities'.
- Costs for transporting steam in a pipeline: It is expected that costs for transporting steam will not change considerably. Since these costs are expected to stay the same, the costs are not relevant for this model. The model is used to show differences in system profits per configuration of assets under the same circumstances, however costs for transporting the steam will stay the same in all configurations.
- Failure of certain plants: If the reliability of a plant is low, this means that this plant cannot guarantee to be operational 8000 hours per year. There is a higher possibility that an unplanned stop has to take place for those plants. A failure of a plant has a large impact on the entire system, since steam demand always has to be met. Therefore plants that can quickly ramp up and deliver the needed amount of steam should always be available in the system to cope with unplanned outages. In the model it is assumed that all plants will be able to operate (365*24=) 8760 hours per year. However due the a large impact of reliability of certain plants, these considerations will be discussed in chapter 8.
- Unfired HRSG's. In chapter 4 the working of HRSG's in CHPX 1 has been explained. These HRSG's can be operated supplemental fired or unfired. HRSG's of CHPX 1 will be modelled supplemental fired, since this is needed to meet the high pressure steam demand. However in some options this operation might not be needed. Therefore those options will be discussed in chapter 7.
- Ramping constraints: Ramping constraints that limit the generating level of any unit between two consecutive time periods are often included in multi-period scheduling problems. However due to the fact that the units on natural gas in this problem can ramp-up and down within an hour, and the biomass units are expected to operate at a fixed level (as much as possible) these ramping constraints will not be taken into account. However in the model results these constraints can be reviewed. This means that if in the model behaviour it shows that some units are turned on for only two hours, it would not be turned on in reality. These considerations will be done when analysing model results in chapter 7.

5.1.5 Time horizon and time step

The model will be run for the years 2017 and 2025. These periods have been chosen, because 2017 would be the first year that an alternative of steam production with BPA would be operational. Furthermore in this year the new subsidy scheme for the production of electrical and thermal power from biomass will have gone into effect. Therefore this year is a good representation of basic situation in which the BPA will produce steam.

The model will be run for 2025 as well, since this year is further away and subsidy income as well as resource and electricity prices will have changed by that year. Besides the further future is more uncertain and it will be interesting to see what effect different scenarios will have on the outcomes of the simulation model. The scenarios that will be used to explore the outcomes of the model under various circumstances will be discussed in chapter 7.

The model will optimize over a period of 24 hours. This means that the model assumes that every steam producer in the system knows hourly resource- and electricity price for the upcoming 24 hours and bases its decisions upon that knowledge. Optimizing over multiple hours is needed for a system like this, because start-up costs are included. If the model would be optimized per hour, it would be very difficult to earn back start-up costs for an individual SPU. Therefore not many switches between production units would be made. However if you optimize over multiple hours, switching on a steam production unit can be considered with start-up costs, because those costs can be earned back within those 24 hours.

On the basis of electricity- and resource prices assets will be operated or not. The optimization period of one day has been chosen, because of the day-ahead sell and buy electricity market in Country A. Stakeholders can sell- and buy electricity on an electricity market for the next day. Due to the orders of all stakeholders a market price is determined for the next day. A day before the production day, prices can be predicted quite well, due to expected demand-, supply and other conditions. However prices for a longer term, such as a week, are difficult to predict for example due to possible failure of large suppliers- or buyers or changes in the weather. Since resource prices do not fluctuate as heavily, electricity prices are the main driver for system optimization. Therefore the period of 24 hours has been chosen.

The model will be run for a period of a year at the time. A time period of one year is used, because a year is the smallest time period in which all temperature- and weather characteristics are represented. Furthermore the simulation model will be run in time steps of hours. A minimum time step of an hour has been chosen, because for an evaluation of the economic performance of options this is the minimum time step needed. The reason for this is that in an hour the following input- and output variables can be evaluated:

- Variation in heat output
- Variation in electricity output
- Variation in electricity prices

An experimental design will be used to assess the economic performance of various configurations of steam productions units under expected future price and demand, as well as scenarios for a different course of price and demand developments. Since the model options, introduced in section 5.1.2, will be run for the years 2017 and 2025 as well as four scenarios, the experimental design exists from 13 model options and 6 scenarios, resulting in 78 model runs.

5.1.6 Model requirements

A number of requirements should be met by the model to be able to compare the economic performance of various configurations of assets. Functional requirements describe what function it should perform. The simulation model has been constructed to provide results that can be used in decision-making by ECA. The model has not been constructed for common use.

Functional requirements:

- The model should report:
  - maximum total system profits for the production of steam to meet the demand in site Y
  - steam production profits divided per steam production unit
  - optimal dispatch of steam production units based on hourly electricity and resource prices.

5.1.7 Desired output

The BPA project team from ECA requires insight in the economic performance of the steam production system in site Y. Information about costs and revenues of steam production of current and possible future steam production units can form a basis for the investment decision for adjusting the BPA. The assumption is that stakeholders will only be prepared to buy steam if this it costs them less than producing steam. Therefore information about what the threshold value is at which it becomes cheaper to buy steam would be valuable information for ECA. It could also be interesting to see whether different adjustments to the system, such as building a new gas or bio boiler, would give better results than other options. With help of the simulation model, the performance of the steam production system can be assessed under various configurations of steam production units.

The BPA project team of ECA would like to have supportive information on the basis of which it can negotiate about contract conditions with PCX and make an investment decision about adjusting the BPA. As make-or-buy decisions form the basis for PCX to buy steam from another producer, the model aims to represent this decision.

On the basis of the outcomes of the model, it can be derived with what configuration of steam production units in site Y the system would have the highest profits for steam production. The highest profits for steam production result in the lowest production cost for steam. From the improvement in total system profits of a certain option with respect to the current situation, a threshold value for the make-or-buy decision can be determined. However the selling price of steam is also dependent on investment costs for adjusting- or building a new facility and a steam network that has to be build. And in case of BPA also subsidy plays a role. Therefore in chapter 7, steam prices for steam sellers will be calculated on the basis of additional costs and revenues.

Performance indicators per model option are:

- Total system costs under various scenarios
- Change in profits for CHPX 1 compared to option 0, the current situation
- Make-or-buy threshold price for PCX UC

5.2 Optimization problem

Since it is known what the performance indicators are that have to be derived from the model, the economic performance of the total system with various configurations of steam production units can be calculated. To reach a situation in which the steam production in site Y can be done at the highest system profit, optimization is done. If the highest system profit is established, the cost of production of steam is the lowest in the system. In this section the optimization problem will be described. For a detailed mathematical description of the optimization problem, appendix G can be consulted.

5.2.1 Steam production units included in optimization

To start off a visual representation of the system will be given in order to explain the optimization problem. In figure 4, three steam production units are represented. Reason for this is that only those three steam production units – a bio boiler, a gas boiler and CHPX 1 – are included in the optimization function. It is important to notice that biomass plant A is not included in the optimization description. Reason for this is that in an earlier stage it was determined that independent of the alternative BPA operate, it will always operate at maximum capacity. If operation is always at 100% of its capacity, no decision variables apply to a plant. If no decision variables apply to a process, its output can be considered as constant. However in a later stage, in the calculations of the system profits, BPA costs and revenues will be taken into account.

In figure 4 it is shown that low pressure steam and high pressure steam are directed towards low pressure steam demand and high pressure steam demand respectively. The purpose of the steam production system in site Y is to meet those steam demands at all times. Therefore those two model parameters clearly shown in the figure in order to clarify the main priority in the system. Secondly in the figure the process of CHPX 1 is delineated. Reason for this is that the production process of CHPX 1 consists from multiple processes. In appendix G, this process will be looked into in more detail.

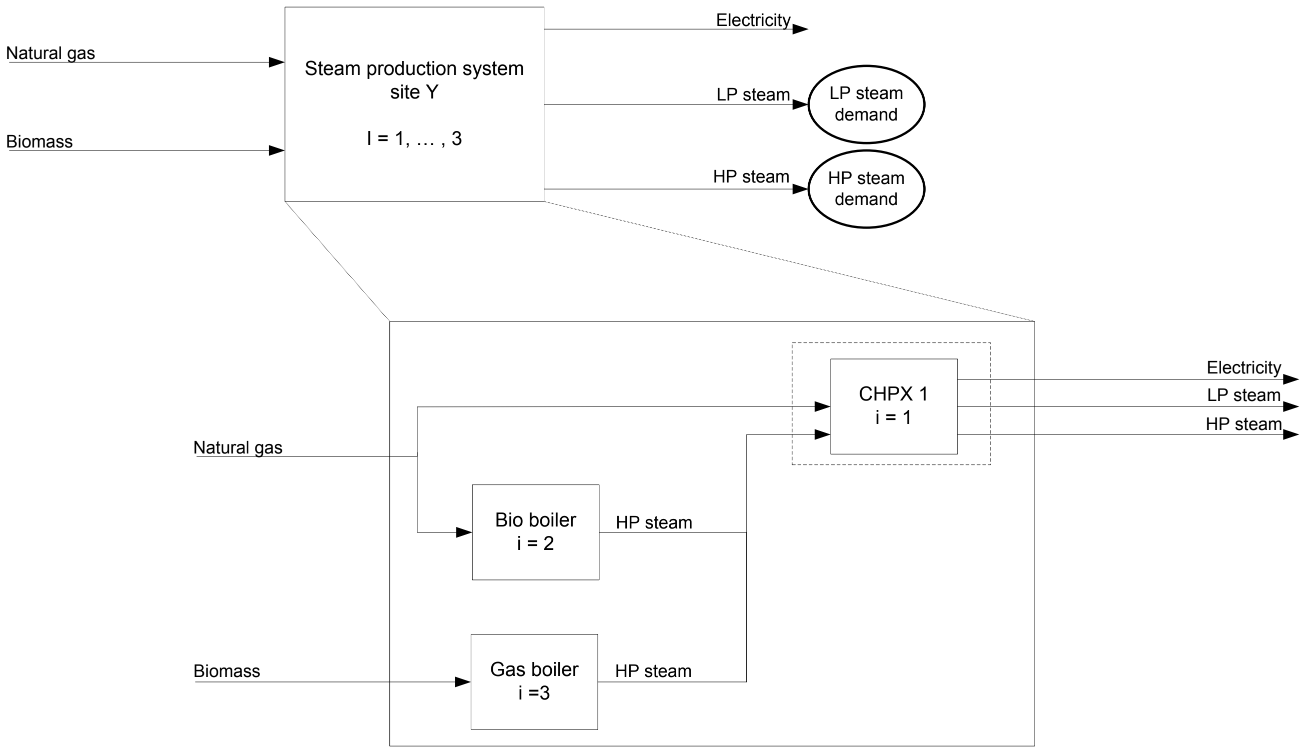


Figure 4: Overview of steam production system to be optimized

5.2.2 Decision variables

The first step in defining the optimization problem is determining the decision variables. Decision variables are variables that can be varied to obtain the optimal outcome for the optimization function. Inputs of the system are resource and electricity prices. Based on those prices, a decision is made about what steam production unit should be operated to meet the steam demand. Since the prices vary, different steam production units become cheaper or more expensive compared to other units. The two boilers – in the figure and in the description of the optimization problem denoted by i = 2 and i = 3 – have little decision variables, because their operation consists from one process. Therefore the decision variables for both boilers concern:

- Whether it is on or off line during time period t {0,1}
- Generating level [%]

However the production process of CHPX 1 consists of more processes. Therefore more decision variables apply to this unit. The decision variables for CHPX 1 will be described below.

Determined for each of the three gas turbines

- Whether it is on line or off line during time period t {0,1}
- Generating level [%]

Determined for each of the two steam turbines

First process of the steam turbine

- Generating level [%]

Second process of the steam turbine

- Generating level of the electricity production part [%]
- Generating level of the heat production part [%]
- Whether the heat production part is on or off line during time period t {0,1}

5.2.3 Model parameters

Secondly model parameters are defined to describe the optimization problem. The model parameters are given in the system, which means that they cannot change during optimization on the basis of outputs of the model. The model parameters will be described below:

- *Hourly selling prices for electricity*;
- *Hourly purchase prices of natural gas*;
- *A fixed purchase price for biomass*. This price is assumed to be fixed, because biomass can easily be stored and can therefore be bought on the market when it is cheap. This means that no large fluctuations in purchase price have to be expected;
- *Constant hourly operational costs* for gas turbines;
- *Constant start-up costs* for boilers and gas turbines;
- *Constant costs for heating up steam pipelines*. It is not possible to instantly transport steam from one end of a pipeline to the other. These pipelines have to be heated. Therefore there is a cost involved for heating up a pipeline;
- Fixed *low pressure steam demand* in site Y in total;
- Fluctuating *high pressure steam demand* in site Y in total;
- *Quantities of resources* required for gas turbines and boilers when operating at maximum capacity;
- *Maximum capacity* of every process of every steam production unit;
- *Minimum load* of every process of every steam production unit.

5.2.4 System model equations

To be able to calculate the desired information described in section 5.1.6, there are two important outcomes needed from the model. The first one is the total system production profit from steam production during time t (P_{Tt}). This is derived by adding up production profits of every individual production unit in the system ($P_{i,t}$). This calculation is represented under (1). Secondly calculations of individual profits from the production of steam during time t are shown under (2). These calculations are needed for equation 1.

$$P_{Tt} = P_{1,t} + P_{2,t} + P_{3,t} \tag{1}$$

$$P_{1,t} = -C_{R1,t} - C_{1,t}^{SU} - C_{1,t}^{HU} - C_{1,t}^{O} + R_{Et}$$

$$P_{i,t} = -C_{Ri,t} - C_{i,t}^{SU} - C_{i,t}^{HU} \quad \forall\, i = 2, 3 \tag{2}$$

The profits per steam production unit ($P_{i,t}$) are constructed from a number of costs and revenues. Below the costs and revenues to calculate individual profits per steam production unit during time t will be described.

- Resource costs $C_{R\,i,t}$

Firstly the cost of resources for the production process of steam production unit i are important. This cost represents the amount of resource used by a steam production unit during time t multiplied with the price of that resource during time t.

- Start-up costs $C_{i,t}^{SU}$

Secondly start-up costs for every steam production unit are being calculated. For boilers and gas turbines it goes that if it has been shut down, start-up costs have to be paid to turn it on again. Start-up costs that have to be paid at the beginning of time t depend on the generating status in time period t-1. If the gas turbine and/or boiler was on [1] at time t-1, then no start-up costs have to be paid. If it was off [0], start-up costs for have to be paid at the beginning of time t.

- Heat-up costs $C_{Si,t}^{HU}$

A similar calculation can be done for heat-up costs of the steam pipeline that connects a production unit to the steam grid. However this applies to a generating unit in total instead of individual parts of a generating unit. If generating unit i was on during time t-1, no heat-up costs have to be paid. However if it was off during time t-1, heat-up costs have to be paid.

- Operational costs Co_i

Operational costs only apply to gas turbines of CHPX 1. For the other processes of CHPX 1 and other steam production units operational costs are be assumed to be zero. The total operational costs will be calculated by multiplying the operational cost per hour per gas turbine with a [0] or [1], which represents whether a gas turbine is online or off line during time t. This calculation will be done for every gas turbine of CHPX 1 in order to calculate total operational costs for CHPX 1 during time t.

- Electricity revenues R_{Et}

As can be derived from figure 4 electricity revenues only apply to steam production unit i=1, which is CHPX 1. The electricity revenues are calculated by the price of electricity during time t multiplied by the electricity production of CHPX 1 during time t.

Production profits will be calculated for every configuration of steam production units that is represented in a model option. If a steam production unit is not present in a certain model option, its production profits will not be taken into account in the calculation of the total system profits for steam production. Equation 1 will be calculated for every model option, given the same set of model parameters.

As explained in section 5.1.4, optimization will be done for 1 day over a period of a year. This means that the optimal production operation will be sought for every 24 hours. Because resource and electricity prices change on a seasonal basis, the results are sought for every day in a year. In order to get a continuing optimization per day during a year, a rolling horizon approach is used. This means that the conditions of time t=24 are used as starting conditions for time t=25.

5.2.5 Objective function

The objective function consists of costs and revenues per production unit bounded by constraints in the system. The index ‘t’ in the summation in the optimization function is the number of hours per day. The years that are simulated reach from 1/1/2017 until 31/12/2017 and from 1/1/2025 until 31/12/2025. The objective function represents the maximum system profits that can be derived from a certain composition of steam production units under given circumstances. Therefore this function will be used for every model option.

The objective function is as follows:

$$MAX \sum_{t=1}^{24} P_{Tt} \qquad (3)$$

Which individual profits are being calculated in the objective function depends on the model option. In every model option a different combination of steam production units is being considered. The highest value of the objective function is the optimal outcome.

5.2.6 Constraints

Besides the optimization function and decision variables, another very important aspect of an optimization problem is defining constraints of the system. The constraints are values that bound parts of the system. All constraints of the system form a space in which the optimal solution should be located. This space is called the feasible region. Values in this feasible region satisfy all constraints of the system. Below constraints for the model will be described:

- Minimum output: The output of every generating part of a steam production unit cannot be lower than its minimum output.
- Maximum output: The output of every generating part of a steam production unit cannot exceed its maximum capacity.
- Low pressure steam demand: The low pressure steam demand in the system should be met at all times by all steam production units combined. The system has a possibility to bleed steam if needed, therefore over production of low pressure steam is possible if this benefits the system in terms of profits.
- High pressure demand: The high pressure steam demand in the system should be met at all times by all steam production units combined. The system has a possibility to expand high pressure steam to low pressure steam. However overproduction of high pressure steam is not possible. Therefore the high pressure steam demand should be met precisely.

5.3 Characteristics optimization problem

In section 5.2 decision variables, model equations and constraints have been specified. From that section it is possible to derive the characteristics of the optimization problem. Furthermore in appendix G all model equations are shown. Based on the following characteristics the choice for Mixed Integer Linear Programming (MILP) has been made:

- The optimization problem contains both continuous and discrete variables. Some variables are restricted to be integers, which can be viewed by the on and off constraints for example. However not all variables are integers, such as the generating levels of all production components. Therefore a Mixed Integer approach is needed.
- Furthermore a number of model equations have a nonlinear character in this optimization problem. This means that nonlinearities exist in the objective function. Therefore a nonlinear problem is represented. However the rest of the equations are linear. As can be viewed in chapter 6, eventually the choice will be made to not include start-up costs in the optimization function. Therefore the nonlinear functions will not be included in the optimization function to derive highest profits. Taking the only two nonlinear equations out of the objective function, results in a linear problem.

5.4 Software

An optimization problem as the one described in this chapter should be calculated with a solver. In this project an industrial production process will be optimized, in which given series of inputs are used to optimize outputs of processes for a pre-defined time period. Therefore the decision has been made to use Linny-R. This is a dedicated tool for optimization of industrial processes. It is an optimization software tool that uses linear programming for industrial process optimization. Furthermore the branch-and-bound algorithm is used to calculate optimal solutions. The branch-and-bound algorithm can be used for integer as well as nonlinear programming. The software has been used to model the system as processes that have products as inputs and outputs (Steep Orbit, 2013). Linny-R has a visual interface, which clarifies the relations between production and consumption of steam in site Y. A visual representation of the system makes model explication to stakeholders involved easier. Therefore this is an applicable tool for this purpose. Furthermore model results can easily be transported to Excel, which makes it easy to interpret the model results due to the extensive application possibilities of Excel. The simulation model, as it is modelled in Linny-R, is shown in appendix I.

5.5 Conclusions of model specification

The purpose of the model is to simulate sourcing behaviour and calculate maximum system profits for the production of steam in site Y. This will be done for every model option to be able to compare between the model options introduced in section 5.1.2. This means that a run to calculate the objective function will be done for every model option, which is based on the same decision variables and model parameters. In conclusion, it can be said that when the model is constructed according to the previous sections, it can be used for this purpose.

The model will also show production profits for individual steam production units, which can be used for the calculation of threshold prices. With help of the simulation model, the improvement of economic performance of steam production in site Y can be assessed. Model option 0 is the option that represents current configuration of steam production units in site Y. This model option will be used as a reference to compare the optimization runs of other model options with and to calculate threshold prices. In the optimization runs, decision variables are varied to maximize total system profits for steam production to meet demand. Hereby the constraints have to be satisfied.

The optimization problem can be solved with help of MILP. The simulation model is constructed in a relatively new software program called Linny-R, that uses a B&B algorithm to calculate the optimal dispatch of assets. Representation of the model can be found in Appendix I. In order to determine whether the model can actually be used to run simulations with, verification and validation tests will be done. Results of these tests will be shown and discussed in chapter 6.

6. Verification and Validation

In this chapter the verification and validation of the simulation model will be discussed. In section 6.1 model verification will be presented. In this section the model will be checked for consistency and correctness. Furthermore a check will be done on whether all demands for the model are met. Section 6.1 includes the validation of the model. This concerns a check of the reliability and sensitivity of the simulation model.

6.1 Verification

Verification of a model is the step to evaluate the consistency and correctness of the model. Numerous inconsistencies are corrected during the development of the model. The modelling process was an iterative process, in which a continuous verification of data and model parameters was done. Feedback and new insights from literature or interviews were incorporated and tested directly. Therefore every time new data were added to the model, it was verified whether this change lead to the desired outcome. In addition to this iterative modelling design process the software automatically checked the simulation model on inconsistencies. Equations that resulted in errors or problems could be traced back, and changed. However one of the downsides of the software used was that model verification via errors or problems was difficult to perform. It was obvious that an error or a problem occurred, but the source of these errors or problems was difficult to trace back.

A dimension analysis is a common method to verify an simulation model. However in case of the software used for construction of this simulation model, dimensions of input and output do not have to be the same. However if there is a discrepancy in dimensions used, the mass- and energy balances have to be correct. Therefore if that is the case mass- and energy balances should be checked.
In this case, input- and output variables of the system have not been modelled in the same dimensions. The reason for this is that this would enhance the ease to understand the model. For example the input of biomass will regularly be given in tons of biomass and the same holds for the price of biomass, which is provided in euro/ton. However the output of the biomass plant in this case consists of steam and electricity. Steam is presented in tons and electricity in MWh, because these dimensions are common dimensions for those products. The discrepancy in dimensions used does not harm the model, but an extra check has been carried out to make sure that the mass- and energy balances are correct. This also implies that the energy content of the input is always larger than that of the output. The differences between energy input and output depend on the efficiencies of the particular plants.
Furthermore if a constraint has not been met, the model reports a 'problem' when it runs. Besides it is shown in the model interface if constraints are not met. Therefore this check has been carried out as well and all constraints are being satisfied during model runs.

6.2 Validation

The validation of a model is considered as a check to see if the model is reliable and gives plausible results. To assess the validity of a model, it should be checked on conceptual model validity, data validity, and operational validity (Sargent, 2005). For the operational validity model runs are carried to discover the behaviour of the model and to see whether it fits the expectation.

6.2.1 Conceptual model- and data validation

Firstly evaluation of conceptual models has continuously been done by keeping the ECA BPA project team closely involved throughout the entire modelling process. The conceptual models of the current production configuration- and steam production alternatives of BPA have been made on the basis of production design drawings for all three options, an ECA BPA large steam export study. The conceptual models of production units that form the basis for the simulation model can be found in appendices E and F. The conceptual model of CHPX 1 has been made on the basis of various internal documents of ECA and a presentation by PCX. These documents and the conceptual model could not be included due to confidentiality reasons. Some essential information for the construction of the simulation model was not available at ECA. Therefore additional research has been done via an interview with the business manager production of site Y. Also production characteristics of the GE combined cycle product line have been investigated, since it was known that CHPX 1 consists of this product line.

Furthermore expert interviews have been held to validate the model. Data and assumptions that have been used for the construction of the simulation model have been discussed with four experts that are closely involved in the project, but all have a very different perspective. The experts that have been consulted are Manager facilities with expertise on CHPs, System Engineer BPA, Manager Development BPA and Investment Analyst BPA. Suggestions made during validations sessions were taken seriously and have been considered taking into account the aggregation of the model and its purpose. A large number of the suggestions made during validation sessions have been implemented in the model directly. Some of the suggestions would not change model behaviour or its outcome. Therefore those suggestions have not been included. Further improvements to the model and decisions about not incorporating certain aspect will be described in the model reflection in chapter 9.

6.2.2 Operational validation

In operational validation a check will be done to find out if the model outcomes correspond to expected behaviour and data from the real world. The following tests will be executed to analyse the validity of the simulation model: an extreme value tests, a sensitivity analysis and a scenario analysis.

Extreme value analysis

The model should have the ability to cope with fluctuations in demand-, resource- and electricity prices. It should react to dynamics in system inputs and optimize per specified time period. Therefore extreme value tests have been done to check whether the model reacts to those fluctuations as expected. In an extreme values test extreme high and low values are used as inputs. Extreme values are used, because with extreme values model reactions are easy to detect. The effect of large changes can easily be measured and compared with how the model is expected to behave. The extreme changes are only applied to extern input variables, on the basis of which the model makes its optimization decisions.

Three extreme value tests on different input variables have been carried out. These tests can be found in appendix G. The extreme value tests can only be done in options in which two or more SPUs are operational that depend on decision variables. Otherwise no difference in reaction to input variables can be detected. One of the extreme values that has been tested is an extremely high electricity price. In an option in which a CHP is operational in combination with a boiler, the CHP should fully operate its capacity to produce as much electricity as possible. The expectation for the model reaction to a high electricity price is fulfilled by the model. If the electricity price gets very high the CHP will produce to its full capacity. However in all cases the plants are firstly bound to produce enough steam to fulfil the steam demand. The model gave a logical outcome in every test and therefore passed the extreme value analysis.

Sensitivity analysis

Besides the extreme value analysis, also a sensitivity analysis has been carried out. This analysis is used to identify which elements greatly affect the outcome of the model. If some constraints have a large impact on the outcomes of the models, assumptions that have been done to estimate these constraints can be reconsidered. Furthermore results gained from the model can be analysed considering the uncertainty of the constraints used.

In an optimization problem with constraints, the shadow price is the change in the objective value of the optimal solution obtained by relaxing the constraint. It could also be described as the marginal utility of relaxing the constraint or the marginal cost of strengthening the constraint. In the sensitivity analysis the effect on the objective function is analysed by slightly adjusting the model constraints. This way it can be noticed whether the model is sensitive to changes in certain constraints. The constraints have been increased and decreased by 10%. In case the output varies more than 10%, this means that the model is more sensitive to a given change. In appendix G can be found that the model does not seem very sensitive to a 10% change in of the most constraints. The high pressure steam production demand and minimum operation load for the steam turbines of CHPX 1 are the most important bounds on the outcomes of the model. For the high pressure steam demand, a check has been done about how the system outcome per model option changes. For some model options, this resulted in other model outcomes. Therefore these results will be discussed in chapter 7.

Due to the outcomes of the sensitivity analysis the system boundary for the steam turbines of CHPX 1 have been discussed with experts from ECA. According to Manager facilities with expertise on CHPs and System Engineer BPA (personal communication, June 26, 2014) the constraints are consistent with characteristics of steam turbines. As a result of the sensitivity analysis it is known what the limiting constraints are for the system and what effect slight changes in these constraints have on the model outcome. Small changes in constraints, within the 20% range, have no significant effect on the model outcomes. Therefore within the scope of this test it can be concluded that the model is not oversensitive for specific changes.

Scenario analysis

Based on the scenario validation in appendix G it can be concluded that the model gives the right model output. In model options in which the most important production unit runs on natural gas, the driving scenario factor is the steam demand. Even if natural gas prices are low, production on natural gas is still more expensive than on biomass. This shows that if it is expected that the steam demand in site Y will decrease in the upcoming years, it would be very smart of PCX to invest in a bio boiler or a collaboration with ECA, in which BPA will produce steam from biomass.

Furthermore it can be viewed from the scenario validation that under various prices, the model reacts differently. If steam demand is the same in scenarios, the model bases it decision on resource and electricity prices. For example all options should always perform better on scenario 2 than on scenario 3. Reason for this is that scenario 2 holds a low biomass price and a high electricity price, while scenario 3 is the other way around. The natural gas price and steam demand are the same in those scenarios. This has been checked and was found to be correct. The same can be applied for scenario 1 and 4. All options should perform better on scenario 4 than on scenario 1. The steam demand and natural gas price are the same in both scenarios, but scenario 4 holds a low biomass price and a high electricity price, while scenario 1 is again the other way around. This has also been checked and found to be correct.

6.3 Model simplification to enhance usability

During the model validation it was noticed that under certain model options, the model runs took a long time. This was noticed for model options in which switching of production was possible between two steam production units. To accelerate the model runs, a number of model simplifications have been executed. These simplifications have been chosen, because the outcomes of the model would still show the model behaviour and under consideration of the model simplifications this behaviour can be analysed.

The following model simplifications are applied:

- Exclusion of start-up costs in objective function of the model runs: Taking into account the start-up costs of every unit significantly increased the time to run the model. However it is also possible to run the model and to see how often the model would switch between production units and to deduct from those data whether that behaviour is reasonable. Therefore start-up costs were taken into account, but were not included in the optimization effort. The exclusion of start-up costs will be discussed in appendix I.
- Decreased efficiencies in part-load: Producing at part-load leads to an efficiency degradation of every production unit. These exact efficiency degradations are not taken into account. It is expected that the efficiency degradations are the largest at the part of CHPX 1, since this plant exists from the most and the oldest turbines. The new gas boiler is not expected to drop drastically in efficiency when operating in part-load. Furthermore for the bio boiler and BPA a fixed load operation is expected and wanted. Therefore efficiency degradation is less important. The reason that efficiency degradation when operating in part-load is not included, is that it significantly reduced the speed at which model runs were carried out. Since efficiency degradation mostly applies to CHPX 1, the benefits for CHPX 1 are underestimated. This should also be taken into account in a later stage of this research.

6.4 Conclusions verification and validation

The outcomes of the verification and validation tests in the previous sections, it can be concluded that the model constructed is sufficiently representative for the situation of future steam production in site Y. When the assumptions in the model are taken into consideration when analysing the results, the model is suitable to simulate a variety of scenarios. Even after verification and validation, the model still has its limitations and uncertainties. These implications of the model are known and therefore the results of the model runs should be interpreted accordingly. This means that caution is necessary.

RESULTS

7. Model results

In chapter 6 the simulation model has been tested on its validity and verification of the model has been done. The model is considered to be valid by the tests and also by experts. Therefore in this chapter the model will be used to derive results on the economic performance of the steam production system in site Y. In section 7.1 the model setup will be explained. Section 7.2 will be used to provide some insights about the model behaviour. If the model behaviour is clear, the outcomes of the base case model in 2017 and 2025 will be shown and interpreted in section 7.3. In section 7.4 scenarios will be presented and applied to the model. Results of model based on scenarios will be presented and conclusions about robustness of the model options will be drawn.

7.1 Model setup

The simulation model is used to predict the economic performance of various configurations of steam production units in site Y to meet the steam demand over time. The developed model is simulated under series of input variables for resource and electricity prices that are expected by ECA and steam demand that is estimated on the basis of interviews and internal documents. The series of expected input variables are constructed for the years 2017 and 2025. The model represents the steam production system in site Y with various configurations of current and possible future plants. A simulation run represents the dispatch of a particular configuration over time.

Since 2025 is in the midterm future, input variables are uncertain. Therefore scenarios will be used to explore how every configuration would behave under different scenarios than the expected input variables. The scenarios will be introduced in section 7.4. For each scenario experiment a different model setup is required to represent a scenario. From the scenario descriptions in section 7.4 the combination of input variables can be derived. These input variables are electricity, natural gas and biomass price and the steam demand in site Y.

In total experiments will be run with input variables for two base case years and for four scenarios. The simulation model will represent thirteen model options. In table 9 the experimental design will be shown, in which every experiment that is simulated will is marked with an '*V*'.

		Model input variables								Model input variables					
Option	*Name*	*2015*	*2025*	*S.1*	*S.2*	*S.3*	*S.4*	*Option*	*Name*	*2015*	*2025*	*S.1*	*S.2*	*S.3*	*S.4*
0	Current	✓	✓	✓	✓	✓	✓	7	PRDS-BB	✓	✓	✓	✓	✓	✓
1	PRDS-CHPX	✓	✓	✓	✓	✓	✓	8	BPST-BB	✓	✓	✓	✓	✓	✓
2	BPST-CHPX	✓	✓	✓	✓	✓	✓	9	CHPX-GB	✓	✓	✓	✓	✓	✓
3	GB	✓	✓	✓	✓	✓	✓	10	PRDS-CHPX-GB	✓	✓	✓	✓	✓	✓
4	PRDS-GB	✓	✓	✓	✓	✓	✓	11	BPST-CHPX-GB	✓	✓	✓	✓	✓	✓
5	BPST-GB	✓	✓	✓	✓	✓	✓	12	CHPX-BB	✓	✓	✓	✓	✓	✓
6	BB	✓	✓	✓	✓	✓	✓			✓	✓	✓	✓	✓	✓

Table 9: Experimental design

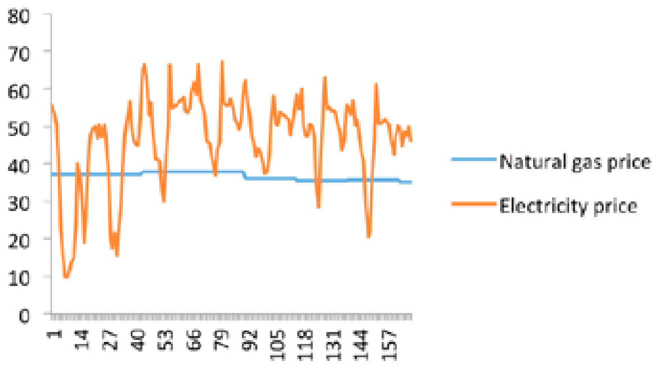
Every '*V*' in table 9 represents an optimization run of the simulation model. Thirteen model options have been identified. Option 0 represents the current situation. This option is included in the experimental design for comparison. If option 0 shows the best results over all, no adjustment to the current situation would benefit the stakeholders. In addition, there are six sets of input variables that will be used for the optimization runs. Therefore the experimental design will exist from thirteen model options times six model parameter sets. This results in seventy-eight optimization runs.

7.2 Model behaviour

Before model results will be analysed and interpreted, first the model behaviour is viewed in order to better understand the model results. The model simulates optimization behaviour of all steam production units combined. Based on given input variables, a dispatch decision is made.

As explained in chapter 5, optimization can only be done with CHPX 1, a natural gas boiler and a bio boiler. Reason for this is that it is assumed that during all runs BPA will produce at maximum capacity. Therefore no decision about different operation with this plant can be made. In order to analyse the model behaviour, only options 9 until 12 will be considered. In these options multiple steam production units that have the ability to switch production pattern are present.

In the figure below the data series will be shown for one week. Input series will be shown for electricity and natural gas prices. Based on those given input variables, model behaviour will be shown for option 9. Model behaviour for options 10 until 12 will be discussed in appendix I.



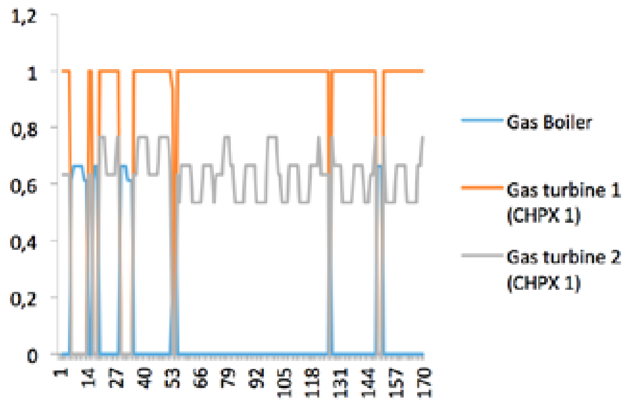


Figure 5 (left): Natural gas and electricity input variables
Figure 6 (right): Production dispatch option 9 based on electricity price in figure 5

In figure 6 it can well be viewed how the model behaves based on given input variables. In figure 5 six large price drops in the electricity price appear. At those drops in the electricity price, it can be viewed in figure 6 that a dispatch decision is made to operate the gas boiler instead of CHPX 1. Reason for this is that CHPX 1 has a lower efficiency than a gas boiler. This means that if the electricity price is below a certain point, it becomes cheaper to produce steam with a gas boiler than with a CHP. However in the simulation model, start-up costs have not been taken into account. Therefore costs of switching are not considered in the optimization function. The behaviour that is presented in figure 6 is not how it would happen in the real world. For a very short time period, no switch would be made due to maintenance reasons and start-up costs.

7.3 Model results in base scenarios

The purpose of the base scenarios is to assess the economic performance of various steam production configurations in site Y under expected electricity and resource prices by ECA. Price series that have been used to assess model results under base scenarios come from ECA. ECA is a company that focuses on production, trade and supply of electricity and natural gas in a number of European countries. Estimating future prices and producing price scenarios is very important for ECA, since its investments highly depend on those prices. Furthermore current installed capacity revenues and costs also highly depend on resource and electricity prices. Therefore many experts on predicting those prices are active at ECA and aim to predict future prices based on historical prices and economic developments. Since ECA is one of the leading companies in production, trade and supply of electricity and natural in Country A, the price series that have been produced by ECA are assumed to be estimated well. However it is not possible to predict the future precisely and therefore different scenarios will be taken into account as well.

Note: For confidentiality reasons all model results are adjusted and therefore results in this chapter do not represent actual model results. These results will be used to show interpretation of the model results.

7.3.1 Model results of base scenario 2017

As explained in chapter 5, the economic performance of different steam production configurations will be checked by the individual and combined total yearly system profits for the production of steam. On the basis of equation 3, the maximum total system profits f or steam production configurations (model options) have been calculated by the simulation model. All model options have been presented and described in chapter 4 and were briefly repeated in section 7.1. Based on the results it is possible to see what steam production configurations would perform best under predicted prices for 2017. However differences in operating expenditures (OPEX) due to investment costs and subsidy incomes have not been taken into account yet. Maximum system profits for the production of steam under a particular model option will be presented in table 9. Options that perform best in terms of total production profits as calculated in chapter 5, are shown in green and options in red perform worst on total system profits.

Steam production profits per steam producer 2017 (in million €)

	Options												
	0	1	2	3	4	5	6	7	8	9	10	11	12
ECA	*0,7*	-2,1	-1,3	*0,7*	-2,1	-1,3	*0,7*	-2,1	-1,3	*0,7*	-2,1	-1,3	*0,7*
CHPX 1	-6,1	-3,9	-5,3							-6,2	-3,7	-5,3	-4,6
Bio boiler							-5,6	-2,9	-3,2				-6,0
Gas boiler				-8,3	-4,2	-4,7				-0,5	-0,4	-0,4	
Total	-6,1	-5,9	-6,6	-8,3	-6,3	-6,0	-5,6	-4,9	-4,5	-6,7	-6,2	-7,0	-10,6

Table 10: Yearly steam production profits divided per operator of an steam production unit

Totals			**Average BPA alternative**	
Average	-6,6		Solo-E	-7,5
St.deviation	1,5		PRDS	-5,8
Minimum	-10,6	Option 12	BPST	-6,0
Maximum	-4,5	Option 8		

Table 11: Model result totals 2017

From the tables it can be drawn that the total profits for steam production to meet the steam demand in site Y are highest in option 8. Option 7, which is also a bio boiler option, performs good as well. For both of these options PCX has to invest in a bio boiler. In options 7 and 8 the entire steam demand in site Y is met by a bio boiler and steam from BPA. In option 8 slightly less steam is produced by BPA, because in this option the BPST alternative is included. However more electricity is produced by BPA than in option 7, therefore the steam production profits of the BPA are a little higher than in option 7. In the system profits in table 10, operating expenditures and subsidy income are not included. Therefore in the next table subsidy and operating expenditures will be added to the model calculations. How these operating costs and subsidies have been calculated will be shown in appendix J. For the calculation of subsidies in 2017 as well as 2025, the concept advice for subsidies as from 2015 by Research Institute A (RIA) (reference not included due to confidentiality reasons) has been used. However it should be noticed that this is a concept advice, which was open for consultation. Even though ECA was allowed to give feedback on the concept of RIA, it is still possible that the subsidy amounts will change differently than expected by ECA.

Steam production profits per steam producer including subsidy and OPEX, 2017 (in million €)													
	Options												
	0	1	2	3	4	5	6	7	8	9	10	11	12
ECA	*6,4*	4,5	4,6	*6,4*	4,5	4,6	*6,4*	4,5	4,6	*6,4*	4,5	4,6	*6,4*
CHPX 1	-6,1	-3,9	-5,3							-6,2	-3,7	-5,3	-4,6
Bio boiler							-0,7	-1,0	-0,8				-5,0
Gas boiler				-9,1	-4,9	-5,3				-0,9	-0,6	-0,7	
Total	-6,1	0,6	-0,6	-9,1	-0,4	-0,7	-0,7	3,5	3,8	-7,1	0,1	-1,3	-9,6

Table 12: Profit of steam production including subsidy income and operating expenses in the year 2017

Totals			**Average BPA alternative**	
Average	-1,8		Solo-E	-6,5
St.deviation	4,2		PRDS	0,9
Minimum	-9,6	Option 12	BPST	0,3
Maximum	3,8	Option 8		

Table 13: Model result totals after inclusion subsidy and OPEX 2017

One of the model outcomes that is striking, is that even if operating expenditures and subsidy are taken into account model option 8 still performs well. Reason for this is that even though operating expenditures are very high, in the RIA consultation report a high subsidy amount is assigned to a boiler on liquid or solid biomass with a capacity that is larger than 5 MW thermal power. Especially in model options 7 and 8 much subsidy is obtained by the steam production system, because both BPA and a new bio boiler run on biomass. Both plants are considered to be using different types of biomass to make sure that they do not outcompete each other for biomass and subsidies.

7.3.2 Model results of base scenario 2025

The first calculations have been done for the year 2017. This would be the first year that ECA's BPA would be delivering steam in site Y. Prices for year 2017 can be predicted quite well, since this year is not very far away from present time. However prices in year 2025 are a lot more difficult to predict, since this is a long time from the decision moment. In 2025 system outcomes may have changed significantly due to large resource and electricity price changes, but also because of a change in the subsidy amount. The reason that there is a difference in the subsidy amount between 2017 and 2025 is that BPA is already participating in a subsidy scheme for production of electricity from biomass. As proposed in the concept advice of RIA, ECA wants to switch its current subsidy scheme towards the one that is newly composed by RIA, which reimburses for electricity as well as thermal power. To make up for the loss in subsidy amount from the old subsidy scheme, the government wants to offer a compensation amount. Therefore in the first years of the new subsidy scheme, ECA will receive more subsidy, which is meant to compensate for the

difference between the old and the new subsidy scheme. After a few years, this difference is fully compensated and the basic subsidy of the new subsidy scheme remains.
In table 14 steam production profits per steam producer including subsidy and OPEX for 2025 are shown. In appendix L also tables without subsidy as well as tables without subsidy and OPEX can be found.

Steam production profits per steam producer including subsidy and OPEX, 2025 (in million €)													
	Options												
	0	1	2	3	4	5	6	7	8	9	10	11	12
ECA	*1,7*	0,1	0,6	*1,7*	0,1	0,6	*1,7*	0,1	0,6	*1,7*	0,1	0,6	*1,7*
CHPX 1	-8,4	-5,0	-6,6							-8,4	-4,5	-6,5	-2,7
Bio boiler							1,9	0,8	0,9				-0,6
Gas boiler				-11,1	-5,8	-6,4				-0,6	-0,2	-0,5	
Total	-8,4	-4,9	-6,0	-11,1	-5,7	-5,8	1,9	0,9	1,5	-8,9	-4,6	-6,4	-3,3

Table 14: Profit of steam production including subsidy income and operating expenses in the year 2025

Totals			**Average BPA alternative**	
Average	-4,4		Solo-E	-6,0
St.deviation	3,9		PRDS	-3,6
Minimum	-11,1	Option 3	BPST	-4,2
Maximum	1,9	Option 6		

Table 15: Model result totals 2025

The average of the total system profits drops between 2017 and 2025, because costs rise. This could be expected, since in the long term prices usually rise. Besides subsidy incomes for BPA decrease between 2017 and 2025. In table 14 can be viewed that option 6 would have the best economic performance in 2025. In option 6, BPA still only produces electricity. However options 7 and 8 still perform very well too. Overall it is possible to state that the PRDS alternative gives the best system results of all three BPA alternatives in various model configurations. Therefore in most cases it would be beneficial for the system if ECA would invest in adjusting the BPA with a PRDS. The BPST outperforms the solo electricity alternative in most options as well. This is the same in 2017. Therefore for the system it would in most cases still be better if ECA would start producing steam and delivering it in site Y. Furthermore it would be interesting to see whether and under what circumstances better performance of steam delivery alternatives of BPA would change. Therefore in section 2 of this chapter scenarios will be applied to the model to see whether different price and demand scenarios would change the model outcomes significantly.

7.3.3 Threshold price calculation

In the previous sections it has become clear that building multiple small sized bio boilers for the production of steam in site Y, possibly in combination with steam production by BPA gives the best economic system outcomes for the cluster. However since building an industrial sized bio boiler demands high investment costs at once, it is not likely that this option will be chosen on short notice. Most likely options in this respect are options 0, 1 and 2. This is proven by the fact that ECA and PCX are already negotiating about steam delivery by BPA. Furthermore ECA is very interested in the threshold price of PCX at which the company is prepared to buy steam from ECA instead of producing steam itself with CHPX 1. Therefore a threshold price estimation will be done for option 0, 1 and 2.

Threshold prices ECA and PCX under base scenarios 2017 and 2025

Differences in revenues for ECA between options 0, 1 and 2 are defined by a different amount of electricity that is produced per BPA alternative and a different subsidy amount that is received by ECA for electricity or a combination of electricity and thermal power. Differences in costs of ECA between options 0, 1 and 2 are defined by different investment costs. In the PRDS alternative more tons of steam are produced compared the solo electricity and the BPST alternatives, however in the BPST alternative more electricity is produced compared to the PRDS option. Obviously in the solo electricity option the most electricity is produced of the three alternatives. The prices in the table are only based on the differences between the various alternatives of BPA. Operational costs and operating expenditures for building the BPA as a whole are assumed to stay the same in all three alternatives. Therefore those costs are not included in the calculations. The same applies to CHPX 1.

If ECA invests in adjusting the BPA to produce steam, it should at least make as much money as they would have with the solo electricity option. Otherwise the investments will be useless and will therefore not support ECA in reaching its goal to operate BPA in a more profitable manner. However PCX will only decide to buy steam from ECA if it benefits PCX. One of the benefits could be economic. If buying steam produced by BPA costs less than producing steam itself with CHPX 1, buying steam from ECA would benefit PCX. The threshold price of PCX means the maximum price it wants to pay for a ton of steam. In table 16 the threshold prices will be shown for which ECA is willing to sell its steam and PCX is willing to buy steam from ECA. Calculations for those prices are shown in appendix K. Furthermore one should note that prices presented in table 16 are based on model outcomes, which are based on expected future resource and electricity prices, including OPEX and subsidies.

Threshold prices		PRDS		BPST	
		2017	2025	2017	2025
PCX	€/ton	2,09	3,19	0,88	1,99
ECA	€/ton	1,77	1,51	1,83	1,22

Table 16: Threshold prices for high pressure steam for PCX and ECA to buy respectively sell steam

PCX and ECA can reach an agreement if the threshold price of PCX is higher than the threshold price of ECA. At that point PCX is willing to pay more money per ton of steam than the price ECA asks per ton of steam at minimum. In table 16 it is visible that the threshold price of ECA is in almost all cases lower than the threshold price of PCX, except for the BPST case in 2017. This would mean that a negotiation window exists to reach an agreement about the price for a ton of steam delivered by ECA.

In the case of the PRDS alternative, CHPX 1 would have the opportunity to shut down one extra gas turbine. Not only would this have an effect on the purchase costs of natural gas for CHPX 1, because steam production by CHPX 1 will drop at that option, but it would also have an effect on the operational costs of CHPX 1. In the calculations in this table, only the purchasing costs of resources are included for CHPX 1, but not the operational costs. Therefore adding those costs could increase the threshold price of PCX. Furthermore many other advantages for PCX when it would buy steam from ECA are important when considering the prices above. In chapter 8 these other advantages will be discussed. Therefore other advantages might even increase the negotiation window.

Threshold prices ECA and PCX under lower steam demand

In the case of the BPST alternative of BPA in 2017, the gap of almost €1,- between the threshold prices of ECA and PCX is very large. Reason for this difference is that in this model option steam delivery by BPA is just a little short for fully shutting down the second gas turbine. Therefore this turbine has to stay stand by to absorb peaks in steam demand in site Y. This results in high start-up costs for the second gas turbine of CHPX 1, which increases the threshold price for PCX.

The high pressure steam demand in site Y has been estimated on the basis of interviews and data from ECA. However this demand is still an estimation and could therefore be incorrect. To check the influence of the high pressure steam demand on the outcomes of model option 2, multiple runs for 2017 have been carried out, in which the high pressure steam demand was varied. It seems that if the high pressure steam demand in 2017 is 15% lower than estimated, this would mean that CHPX 1 could fully shut down one extra gas turbine and would therefore improve its operational and start-up costs. If this lower steam demand would be correct, then the threshold prices for both ECA and PCX would change drastically. New threshold prices under a 15% lower high pressure steam demand will be shown in table 17.

Threshold price at 15% lower steam demand [€/ton]	Option 0	Option 1	Option 2
ECA steam production costs at 15% lower steam demand*	6,4	4,5	4,6
CHPX 1 steam production costs at 15% lower steam demand*	-5,7	-2,8	-3,0
New threshold price ECA		1,77	1,83
New threshold price PCX		2,73	2,84

* including subsidy and OPEX, in million €

Table 17: Threshold prices for ECA and PCX under 15% lower high pressure steam demand

In the table is shown that if the high pressure steam demand is in fact 15% lower than estimated, this would have a large effect on the threshold prices. This would mean that the steam production alternatives of BPA could be a viable alternative, since now the threshold price of ECA is much lower than the threshold price of PCX. Now the production profits of CHPX 1 will be almost the same in options 1 and 2. Reason for this is that it only has to operate 1 gas turbine in both options. However in option 2 it has to produce a little more steam than in option 1, since the PRDS which is operational in option 1 produces a little more steam than the BPST alternative in option 2.

Finally, from an interview with Manager development BPA (personal communication, March 5, 2014) it is derived that the regular steam price depends on the natural gas price. A common number that is used for calculating the steam price is seventy per cent of the natural gas price.

In the table below the natural gas prices and steam prices accordingly, at 70% of the natural gas price of the year before, will be shown. If these prices are higher than the threshold price of ECA, it should negotiate to at least get 70% of the gas price. The gas prices in the table have CO2 emission prices included, because this is the price that CHPX 1 would have to pay for the natural gas it purchases.

<table not attached due to confidentiality reasons>

Table 18: Steam price based on average annual natural gas price of previous year.

From table 17 it is possible to extract that one of the advantages of establishing a steam price that is related to the natural gas price is that the natural gas price is expected to grow in the upcoming years. Therefore the steam price will grow as well. Relating the steam price to the natural gas price would be a good idea considering the threshold prices based on the model outcomes, OPEX and subsidies, and the steam prices based on the expected annual natural gas price. If the threshold prices and prices based on natural gas price are compared, it can be seen that the threshold price of PCX and the steam price based on the natural gas price are almost similar. The threshold price of ECA is a little lower than the steam price based on the natural gas price in most cases.

7.3.4 Unfired HRSG's

In chapter 5 it was discussed that HRSG's would only be included in the system with the supplemental fired operation. In this section it will be discussed whether and how this affects the model results. Firstly the operation of HRSG's concerns the operation of CHPX 1, which means that it is only applicable to model options in which CHPX 1 is represented.

In the years 2017 and 2025 the high pressure steam production of BPA in model options 1 and 2 is not enough to produce enough steam to meet the entire high pressure steam demand. Therefore CHPX 1 always has to be stand-by to produce for the remaining demand. A quick calculation, which can be viewed in appendix D, shows that to be able to produce high pressure steam with the steam turbines, under unfired operation of the HRSG's two gas turbines should be operational. Reason for this is the constraint that at least a 50% flow of the maximum capacity of the steam turbine should flow through the turbine to be able to produce high pressure steam (personal communication, System engineer BPA and plant manager CHP, June 26, 2014). This means that two gas turbines would have to be operational compared to one gas turbine in combination with a HRSG with supplemental firing. This results in a higher cost for operating two gas turbines than one gas turbine and an HRSG with supplemental firing. Therefore unfired operation of HRSGs would not improve economic performance of those options.

Other model options that include CHPX 1 are options 9, 10, 11 and 12. In option 9 most of the time CHPX 1 is fully responsible to meet the high pressure steam demand. To produce large amounts of high pressure steam, supplemental firing is needed as shown in calculations in appendix D. For options 10 and 11 the same calculation is applicable as the one that has been done for options 1 and 2. In option 12 a bio boiler is present in combination with CHPX 1. However from the model results it can be derived that if only a bio boiler would be present, the system would perform better economically. Therefore this configuration of steam production units is not expected. If PCX decides to build a bio boiler, it will not use CHPX 1 anymore, since it will not provide them with large benefits. Therefore it is not necessary to check whether unfired operational of HRSG would improve the results of that model option.

However what is very important to notice is that if at some point the production of BPA will be enough to meet the entire high pressure steam demand in site Y, the unfired operation of HRSGs in CHPX 1 could be a solution to meet the low pressure steam demand with lower costs.

7.4 Scenario application

Since 2025 is more than 10 years away from the decision moment of ECA to invest in a steam alternative for the BPA, input variables used for model runs of 2025 are uncertain. Therefore the same model will be used, but different input variables will be used to see how the system reacts to different resource and electricity prices and to different steam demands. Firstly in section 7.4.1 the scenarios that have been run by the model will be introduced. Secondly model results on the basis of the scenarios will be discussed in section 7.4.2.

7.4.1 Design of scenarios

To explore different future scenarios, four scenarios have been designed in which various combinations of input variables will be used as input for the model options. All model options have been run for all four of the scenarios. In the scenarios biomass, natural gas and electricity prices will be varied as well as the steam demand in site Y. In appendix J is shown from what bandwidth of developments for each driver the designed scenarios have been derived. In the table below an overview of the four scenarios will be given. Each of the scenarios will be briefly described. Furthermore it is shown how much the input variable will be varied in the setup of that particular scenario run. For example if it is stated that a high natural gas price occurs, the series for natural gas price will be 15% higher than the series used for the base case of 2025. For each scenario a different combination of series for input variables is setup.

SCENARIO	ELECTRICITY PRICE low	high	BIOMASS PRICE low	high	GAS PRICE low	high	STEAM DEMAND low	high
	-15%	+15%	-10%	+20%	-15%	+15%	-25%	+25%
1	✓			✓	✓			✓
2		✓	✓			✓	✓	
3	✓			✓		✓	✓	
4		✓	✓		✓			✓

Table 19: Scenarios

Scenario 1: Collaborative international market & national emphasis on renewable energy

In scenario 1 it is assumed that there is a continuous intensification of the social, cultural and economic internationalization or 'globalization' of markets. Under these developments EU natural gas supply would be easier to secure, particularly because it foresees a deeper economic integration with Russia (Correljé and van der Linde (2006). Since natural gas supply is more reliable, prices are lower, because no shortage is expected.

Secondly it is assumed that the government of Country A has put much emphasis on renewable electricity production. This causes the electricity price to drop, since much renewable electricity is being fed into the net. Since electricity produced from renewable sources has low marginal costs, the electricity price will be significantly lower at that point. Furthermore since renewable electricity will be supported, power production from biomass will be probably be supported as well. Since many producers would want to benefit from the subsidy provided for renewable production, more biomass plants will be operated. This would in term increase the biomass price, because of competition. Furthermore a cooperative international environment and low electricity prices improve the investment willingness of investors in site Y. If so, more production plants will be established in site Y, which increases the steam demand in site Y.

Scenario 2: Divided international market & no national emphasis on renewable energy

Scenario 2 assumes a different storyline, in which the world is divided into countries and regions, on the basis of ideology, religion and political arguments. Political and military strategy, bilateralism and regionalism divide the world up into competing US, EU, Russian and Asian spheres of influence. The absence of effective world markets for strategic goods further stimulates the establishment of bilateral trade relationships and treaties, thus reinforcing the formation of more or less integrated blocks with satellite regions that compete for markets and energy resources (Correljé and van der Linde (2006). Since the EU would have a tense relationship with Russia and other gas producing regions, this would mean that supply of natural gas would be insecure. The possibility of deficit would drive the price.

Secondly it is assumed that the government of Country A has stopped or decreased its emphasis on renewable electricity production. Therefore electricity production will largely remain on fossil fuels, which have high prices in this scenario. This means that electricity prices will be high. However since power production from biomass will not be stimulated in this scenario, biomass prices will remain low. Furthermore a hostile international environment and high electricity prices deteriorate the investment willingness of investors in site Y. Therefore steam demand in site Y will decrease.

Scenario 3: Divided international market & national emphasis on renewable energy

Scenario 3 is constructed from parts of scenario 1 and 2. As mentioned in the name of scenario 3, a divided international market is assumed, which results in a high natural gas price. Next political emphasis on renewable electricity is assumed, which ensures low electricity prices and high biomass prices. The combination of the two events causes the steam demand in site Y to drop.

Scenario 4: Collaborative international market & no national emphasis on renewable energy

Just as in scenario 3, scenario 4 is build up from the first two scenarios. However now it is a combination of exactly the two other events. That means an internationalization of markets, which provides for low natural gas prices. Besides no or very little emphasis of the government of Country A on renewable energy, which ensures high electricity prices and low biomass prices. A combination of the two events results in a rise in steam demand in site Y.

7.4.3 Model results based on scenarios

All model options have been optimized with input data from the four scenarios. All results have been supplemented with OPEX and subsidies. The assumption that has been done is that if the initial thermal power capacity of the bio or gas boilers was not enough to fulfil the steam demand in options 3 till 8, the company responsible for meeting the steam demand in site Y, PCX UC at the moment, would have to build additional capacity. In that case the company would decide to build extra gas boilers, because this is a cheap and flexible solution. Therefore for options 3, 5, 6 and 8 extra OPEX have been calculated. In the rest of the options no extra capacity was needed compared to the OPEX calculated for the base cases of 2017 and 2025.

In the tables below a comparison in the economic performance of all model options has been made. In the first table subsidies and OPEX have been added to the system costs. However in table 21 the subsidies are left out. Reason for this is that the exact amount of subsidy and the allocation of subsidy are still uncertain. To check if a model option still performs well if subsidies are subtracted, the second table is shown.

Comparison scenarios on system profits including OPEX and subsidy (in million €)													
	Options												
	0	1	2	3	4	5	6	7	8	9	10	11	12
S1	-9,7	-6,7	-6,0	-11,9	-7,8	-8,1	-1,8	-1,1	-1,2	-10,6	-7,1	-6,8	-11,3
S2	-7,2	-3,8	-3,2	-9,7	-3,1	-3,2	2,1	1,2	2,0	-8,0	-3,3	-3,2	3,0
S3	-8,9	-5,8	-5,5	-9,7	-4,0	-4,4	0,6	-0,3	0,1	-12,0	-5,4	-5,5	1,9
S4	-6,9	-4,1	-3,0	-11,9	-6,8	-6,9	0,8	1,4	1,6	-7,3	-3,9	-3,4	-8,7
Total	-8,2	-5,1	-4,4	-10,8	-5,4	-5,6	0,4	0,3	0,6	-9,5	-4,9	-4,7	-3,8

Table 20: Economic performance including OPEX and subsidies per model option calculated for four scenarios

Totals			**Average per BPA alternative**	
Average	-4,7		Solo-E	-6,4
St.deviation	3,4		PRDS	-3,8
Minimum	-10,8	Option 3	BPST	-3,5
Maximum	0,6	Option 8		

Table 21: Summary of table 20

In table 20 it is well visible that especially the bio boiler options (model options 6, 7 and 8) perform very well in every scenario. Therefore it could be said that these options are robust. However it should first be checked without the addition of subsidies.

Furthermore option 3 is outperformed in every scenario. Besides options 1 and 2 outperform option 0 in every scenario. Therefore it seems like a good idea for PCX to make arrangements with ECA for the supply of steam. Even if at a later stage PCX decides to invest in another steam production unit. However again this should be checked without subsidy, since the subsidy amount and construction are not decided upon until this moment. Of the BPA alternatives the BPST alternative performs best on average when the total system costs are considered. However the PRDS alternative follows on a very close distance.

As mentioned before the subsidies for power production on biomass are still under consultation and are therefore uncertain. To check whether certain options would perform very differently if subsidies will not be granted as expected, the following table has been constructed. This table is the same as the one above, except subsidies are not included.

Comparison scenarios on system profits including OPEX (in million €)													
	Options												
	0	1	2	3	4	5	6	7	8	9	10	11	12
S1	-9,7	-9,2	-8,2	-11,9	-10,2	-10,4	-10,1	-9,1	-9,0	-10,6	-9,6	-9,1	-14,0
S2	-7,2	-6,3	-5,5	-9,7	-5,5	-5,4	-4,6	-3,6	-3,2	-8,0	-5,7	-5,5	-5,4
S3	-8,9	-8,3	-7,7	-9,7	-6,5	-6,6	-6,1	-5,1	-5,0	-12,0	-7,9	-7,7	-6,4
S4	-6,9	-6,5	-5,2	-11,9	-9,3	-9,2	-7,6	-6,6	-6,2	-7,3	-6,4	-5,6	-11,6
Total	-8,2	-7,5	-6,7	-10,8	-7,9	-7,9	-7,1	-6,1	-5,8	-9,5	-7,4	-7,0	-9,3

Table 22: Economic performance including OPEX per model option calculated for four scenarios

Totals			**Average per BPA alternative**	
Average	-7,8		Solo-E	-9,0
St.deviation	1,3		PRDS	-7,2
Minimum	-10,8	Option 3	BPST	-6,8
Maximum	-5,8	Option 8		

Table 23: Summary of table 22

In the tables above it is shown that again option 3 is the option that performs worst in almost every scenario. Option 3 is the option in which the total steam demand in site Y is met by a gas boiler. Furthermore the biomass options 7 and 8, in which BPA produces steam as well, outperform all other options in scenarios 2 and 3. However in scenarios 1 and 4 in which the natural gas price is low, option 2 in which CHPX 1 is active in combination with the BPA with a BPST alternative performs best. Besides options 10 and 11 perform well too. However from the data can be viewed that CHPX 1 produces steam most of the time. Therefore PCX would probably not decide to build a gas boiler together with keeping CHPX 1 operational.

On average, if subsidies are not included, options 7 and 8 perform best. However options 2 and 11 would provide the high system profits for the production of steam to meet the steam demand in site Y as well. Reason for this is that a combination of input resources is used. BPA uses biomass and CHPX 1 and/or a gas boiler use natural gas. Therefore these options are most robust under various circumstances. Besides this option would be a safe option for PCX, since no new investments from their side would be needed.

7.5 Conclusions from model results

In the base scenario of 2017 the system profits from steam production (excluding subsidy and OPEX) to meet the steam demand in site Y were highest in bio boiler options 7 and 8. If operating expenditures and subsidy are taken into account model option 8 still performs best. Reason for this is that even though operating expenditures are very high, in the RIA consultation report a high subsidy amount is assigned to boiler on liquid or solid biomass with a capacity that is larger than 5 MW thermal power. However for both options 7 and 8 PCX would have to make a large investment and there are always risks involved. Lastly in- and excluding subsidy and OPEX, PRDS alternative of BPA would be the best option on a system level in 2017 compared to the other alternatives of BPA.

In the base scenario of 2025 option 6 would have the best economic performance with subsidy and OPEX. In option 6, ECA's BPA still only produces electricity. However options 7 and 8 still perform very well too. It is also possible to derive that the PRDS alternative gives the best system results of all three BPA alternatives in various model configurations for the base scenarios for 2017 and 2025. Therefore in most cases it would be beneficial for the system if ECA would invest in adjusting the BPA with a PRDS.

Furthermore threshold prices have been calculated. It is assumed that PCX and ECA have a good chance of reaching an agreement if the threshold price of PCX is higher than the threshold price of ECA. At that point PCX is willing to pay more money per ton of steam than the price ECA asks per ton of steam at minimum. In 2017 and 2025 almost all threshold prices of PCX were higher than those of ECA, except for the BPST alternative in 2025. Therefore there is a negotiation window for PCX and ECA to reach an agreement about the price.

Furthermore it was shown that if the high pressure steam demand would be 15% (or more) lower than estimated, this would have a large effect on the threshold prices. This would mean that the steam production alternatives of BPA would become even more viable, because the threshold price of PCX increased and the threshold price of ECA stayed the same.

Relating the steam price to the natural gas price would be a good idea considering the threshold prices based on the model outcomes, OPEX and subsidies, and the steam prices based on the expected annual natural gas price. In 2017 the threshold price of ECA is lower than the steam price based on the natural gas price. In 2025 the threshold price of ECA has dropped a little bit, whereas the steam price based on the natural gas price became higher. This means that if ECA can make a deal to get 70% or more of the natural gas price, it would be very beneficial compared to the current business case.

Finally the model options have been optimized under scenarios for 2025. Bio boiler options (model options 6, 7 and 8) performed well in most scenarios. Therefore it could be said that these options are robust. However if PCX would not want to take the risk of a large investment, option 2 would provide high system profits for the production of steam to meet the steam demand in site Y as well. This is an option in which CHPX 1 will still be operated and no new facility will be built by PCX. Only BPA will be adjusted with a BPST. Reason that this option is most robust, is because CHPX 1 runs on natural gas and BPA runs on biomass. Furthermore both plants coproduce electricity. Due to this variety in resources and output, this option is robust under various scenarios.

8. Strategic advice

The reason a simulation model has been constructed was to provide an answer to the question whether steam production by BPA would be advantageous for the stakeholders in site Y in terms of unit cost of steam. An answer is derived by the results from the optimization runs, which have been presented in chapter 7. Those results provide ECA with valuable insight in the performance of the system as it is now and performance of possible alternatives for the future. Furthermore ECA now knows at what price ECA should be willing to sell its steam and it also knows at what price PCX shall be willing to buy steam from ECA. However it is not known how this valuable information can be used in negotiations about steam supply between ECA and PCX. Therefore in this chapter, the results will be used to come up with a strategy for negotiations with PCX.

Firstly in section 1 it will be discussed what other effects steam provision by biomass plant A would have on the steam production system. In this section advantages besides a lower unit cost, will be discussed. In section 2, the negotiation process until this moment will be described and discussed. Lastly, in section 3 these insights will be used in order to design a negotiation strategy.

8.1 Implications of steam supply by ECA in site Y

8.1.1 Advantages of steam production BPA

As explained in chapter 1, it will only be possible to reach an agreement between ECA and PCX if both parties expect to obtain outcomes favourable to their firms. For ECA a favourable outcome lies mainly in the economic aspect. If ECA will be able to get a good price for the steam it sells, the business case of large scale steam production will be better than continuing its current operation of BPA. Hence it should negotiate good selling conditions. The advantage will thus be for ECA that it increases the profitability of its biomass plant. However for PCX, many other advantages besides the economic aspect are important when biomass plant A will produce steam. Advantages of steam supply by BPA for PCX will be described below.

Advantages for PCX:

- Keeping the over allocation of CO_2 rights: This over allocation results in a yearly income of roughly one million euro. Because BPA has to participate in ETS III, PCX will keep this over allocation. Furthermore ECA needs less CO_2 allowances than CHPX 1, because it produces heat from biomass. Since PCX would have to compensate more allowances for CHPX 1 than it would for ECA, this would also result in saving PCX fifty five thousand euro per year. How this works will be explained in appendix M.
- No adjustment to CHPX 1 needed to meet strict new emission rules: In 2010 the European Parliament and Council published a directive for industrial emissions (European Union, 2010). This directive was implemented in 2013 in Country A by the adjustment of the Activities Decree. In this adjusted law stricter emission limits for industries were posed. These new rules went in operation from January 1st 2013. However, due to transitional law old combustion plants – such as CHPX – were exempted from the new rules until January 1st 2016. This deferred date is approaching rapidly and puts pressure on the operations of CHPX 1 in the form of emission limits. This new legislation might impede operations of CHPX 1, which is a CHP built in the 1980's. Therefore cutting down on production might cause CHPX 1 to be able to keep operating within the boundaries of stricter legislation on emissions. Furthermore if it might be able to proceed its operations with only one gas turbine, PCX might only have to adjust one gas turbine to meet the new emission limits.
- Opportunity for gradual decrease production CHPX 1: The combined heat and power plant CHPX 1 was built in the 1980's (no reference due to confidentiality reasons). Due to Research In-

stitute A (no reference included due to confidentiality reasons) the economic lifespan of a CHP is 25 years. This means that CHPX 1 either already reached its economic lifespan or it will reach it soon. This could mean that large maintenance would not only be needed to adjust the CHP to meet emission standards, but also because parts of the system met the end of their lifespan. Therefore it would be wise of PCX to switch to other steam production units to avoid large maintenance and increase reliability of the system.

- Lower operational costs: At current demand, only two gas turbines of CHPX 1 are operated (no reference attached due to confidentiality reasons). Furthermore CHPX stated that if one of those two gas turbines fails, a steam deficit arises in the system. The assumption is that if BPA will produce a part of the steam, PCX can shut down one extra gas turbine. Reason for this assumption is that otherwise PCX would not be very interested in steam production by BPA. Shutting down one extra gas turbine cuts the operation of CHPX 1 to a minimum, which results in minimum operational costs.
- Improving sustainable image: In 2013 PCX became industry group leader in the materials industry in Country A. Furthermore on its website PCX states that it is very committed to making products and processes more sustainable (No reference included due to confidentiality reasons). Utilizing biomass for production of steam offers benefits such conservation of fossil fuel resources and CO2 and NOx emissions reduction (Saidur et al., 2011). Using steam produced from biomass for its production processes would enhance the sustainable image of PCX.

8.1.2 Reliability of steam production in site Y

The option that ECA and PCX are currently negotiating about is the one in which BPA produces steam in combination with CHPX 1. In this option CHPX 1 produces part of the steam needed to meet the demand and it provides back-up capacity for the event that BPA has an unplanned stop.

The BPA runs on biomass. Problems of using biomass in boilers are fouling, deposits, slagging and corrosion issues. Fouling or deposits are commonly known as the layers of materials (ash) collected on the surface of heat transfer equipment. Slagging characterizes deposits on the furnace walls or other surfaces exposed to predominantly radiant heat. Corrosion is the deterioration of intrinsic properties of a material due to reaction with its environment. In boilers, these problems are regarded as a major issue that can affect the design, life time and operation of combustion equipment and increase the operating cost. Furthermore a wood-fired steam plant requires 3-7 times more plant maintenance and operation workers than a coal-fired plant (Saidur et al., 2011). Therefore more (un)planned stops are needed, which results in a lower number of operational hours per year and a lower reliability of steam supply from BPA. Since steam is a very important utility for the production plants in site Y, failures in production should always be absorbed very quickly.

Providing back-up capacity comes at a cost. The start-up times will be kept as short as possible to absorb fluctuations. Since CHPX 1 will always have to make sure that it can quickly ramp up its operation, costs have to be made. Therefore these costs should be compensated as well. Reserve capacity is calculated on the basis of 5% of the second gas turbine capacity of CHPX 1. On the basis of calculations that can be found in appendix K, it was estimated that the cost of keeping back-up reserve amounts around €2,4 million per year in 2017 and €3,2 million per year in 2025. However, as can be viewed in appendix K as well, building gas boilers with enough capacity to absorb plant failures of BPA, will only cost PCX €2,3 million per year in 2017 and €1,6 million per year in 2025. Therefore building gas boiler for back-up would be a cheaper solution for PCX than to keep CHPX 1 as back-up reserve.

8.1.3 Contract conditions for smaller consumers

In an interview with the business manager of production site Y from YAC (personal communication, May 16, 2014) it was mentioned that YAC is very well willing to support plans that improve utility conditions for all companies in site Y. However if a solution only improves the situation of PCX and/or ECA, YAC is not prepared to provide financial resources.

Since it is most likely that in future steam production in site Y will be done by ECA in combination with CHPX 1, it is expected that PCX UC will stay the main steam supplier in site Y. ECA is currently negotiating with PCX, because it has no other option than to sell its steam to PCX. For this reason ECA cannot influence the conditions for smaller consumers in site Y. However ECA can try to convince PCX to provide transparency in the system in order to involve YAC in the project. If this happens, YAC might finance (part of) the steam pipeline between ECA and the current steam grid in site Y.
Whether PCX and ECA should give openness in order to involve YAC in the project depends on how much YAC is willing to invest in the project. This should be weighed against the change in price or conditions that PCX and ECA have to make when providing transparency. The steam prices of ECA to PCX UC and of PCX UC to the small consumers will probably decrease in that case. YAC should only be involved if it yields more than ECA and PCX would lose by lowering the prices due to transparency in the system. Besides the advantage that YAC will partly pay for the connection of BPA to the existing steam grid, another advantage could be that providing better conditions for small consumers will take away a trigger for them to improve their situation. This means that future steam demand will be less likely to decrease if transparency is provided in the system. Advantages and disadvantages should be investigated and compared before starting negotiations with YAC.

8.1.4 Risks for ECA

If ECA and PCX reach an agreement on steam supply by BPA, ECA will invest a large amount of money in the alternative of its choice. Investing large amounts of money always brings risks. The most important risks for ECA when it starts this project have been grouped and will be shown in the table below:

TYPE	RISKS
LEGAL	Risks of outage BPA not sufficiently recorded in contract, which results in high fines for ECA if BPA has low availability
FINANCIAL	PCX goes bankrupt, which will decrease steam demand in site Y and take away ECA's main steam customer
	PCX finds a cheaper alternative and switches from steam supplier
	Stakeholders go bankrupt or decide to produce steam themselves, which causes a decrease in high pressure steam demand
	Commodity prices develop in favour of CHPX 1, which causes steam from CHPX 1 to be cheaper than from BPA
SUBSIDY	Final methodology of calculation new subsidy scheme (NSS) tariffs will be adjusted with a negative outcome for ECA, which causes a change in the business case
	New subsidy scheme not granted to ECA due to too much competition
OPERATIONAL	BPA breakdown or limited availability
	Adjusting BPA takes more time than planned

Table 23: Risks if ECA invests in steam alternatives for BPA

It is important that in the contract between PCX and ECA the absorption of unplanned stops of BPA will be taken care of by PCX, probably in the form of CHPX 1. Furthermore ECA should not be held accountable if outages appear, since the operation of BPA is not fully reliable and due to its short operational period so far, not much data are available on the average availability of the biomass plant. The contract should be very detailed on this point to make sure that ECA does not get large fines when BPA has an unplanned stop. Another important clause in the contract should be on-going compensation of ECA for investment costs and missed income from old subsidy scheme (OSS) or new subsidy scheme (NSS) in the case of breach of contract by PCX. A fine should therefore be included in the contract. Otherwise it gives PCX an incentive to switch suppliers or to move its operations if that favours their business.

Thirdly, an important risk is the new subsidy scheme. In this report all subsidy calculations have been done on the basis of the concept advice of RIA, which was open for consultation. The consultation period has been closed in June. In October the ministry of economic affairs will publish the final NSS. If it turns out that subsidy tariffs will be significantly lower than expected from the concept advice, this might have a negative impact on the viability of steam alternatives of ECA. Therefore ECA should wait with investing in steam alternatives until it has knowledge of the final subsidy scheme.
Lastly a major breakdown or a limited availability of BPA is always a possibility. Therefore it is important that this is well reported in the contract with PCX as explained before. Applying Williamson's (1979) transaction cost theory results in an advice to only perform the activity under the condition that a proper contract would be agreed in respect of the term of supply, reliability, quality, price etc. This is necessary to reduce the threat of opportunism (Fill & Visser, 2000). A large delay in adjusting the BPA can partly be taken care of by good planning from beforehand. It is also possible due to a delayed deliverable from one of the suppliers. This is a possibility in every project and it is important that the project period has some slack time in it. Furthermore good contracts should be prepared. Besides risks in the design and construction phase should be identified and mitigation measures should be considered.

8.2 Considerations before strategy design

In the negotiations between PCX and ECA so far, PCX has shown a competitive style by mentioning that reaching an agreement is more important for ECA than it is for PCX itself. According to PCX the reason for this was that ECA had no other options than to sell its steam to PCX and PCX did have other options to obtain its steam. However in a recent stage of the negotiations, the main negotiator of PCX was replaced by another negotiator, who showed a very different negotiation style. The 'new' negotiator shows PCX to be very well willing to share information and negotiate in a collaborative environment.

The change in negotiation style between the two negotiators of PCX can be reviewed from a viewpoint of negotiation orientation. Brooks and Rose (2004) proposed negotiation orientation as a contextually determined motivational construct that underlies behaviour in negotiations. Based on this negotiation orientation, which is shown in figure 7, the switch in negotiation behaviour can be discussed.

It was derived that the new negotiator showed 'problem-solving behaviour' whereas the old negotiator showed 'aggressive behaviour'. Origin of this behaviour can be found in determinants. Since the switch in negotiation behaviour took place when PCX switched from one negotiator to another, it is expected that the negotiating behaviour (consequence) is determined by personal factors. Since organizational and contextual factors remained the same during the switch, and knowledge between the first negotiator and the second negotiator was probably transferred before the switch, the difference in negotiating behaviour can be explained by personality of the different negotiators. The negotiation style of the negotiator of PCX should be taken into account when designing a negotiation strategy for ECA.

8.3 Design of a negotiation strategy

To overcome numerous barriers stakeholders have when establishing a mutual agreement, a negotiation process precedes the collaboration. Some of the basic points Clopton (1984) made on negotiations in an industrial environment are that long-term relationships are typically sought by both participants, both parties are expected to obtain outcomes favourable to their firms and the goals of buyers and sellers often conflict. Due to the results of this research ECA now has insight in the current performance of the steam production system in site Y and also in the performance of future alternatives for both ECA and PCX. In negotiations with PCX, ECA should decide how to negotiate and how much information it should share.

For the design of a negotiation strategy for ECA, the engineering design approach of Dym, Little, Orwin, and Spjut (2004) will be used to structure the design process. In this section, steps proposed by Dym et al. (2004) will be executed to come up with a negotiation strategy.

8.3.1 Objectives

Firstly it is important to establish what the objectives of ECA are for which a negotiation strategy is used. The aimed outcome for ECA in negotiations with PCX is to reach a contract, in which:

- Steam price is higher than threshold price
- Good conditions under which ECA will provide steam in site Y are included
    - Clause for breaching contract by PCX
    - Fixed amount of steam provided by BPA
    - Limited responsibility ECA for plant failure BPA

8.3.2 Constraints

The main constraint of this negotiation process is that ECA wants to maintain a good relationship with PCX for future collaborations. According to Svendsen (1998) a good relationship with the customer is a very important determinant of long-term corporate profitability. Therefore ECA's negotiation strategy must comply with this constraint.

8.3.3 Functions

The function of the negotiation strategy is the thing that it is meant to do (Dym et al., 2004). In the case of this negotiation strategy it is meant to provide a simple guideline for ECA, which supports ECA's negotiation behavior. Based on this guideline, ECA can decide what tone it should use during negotiations and how much information it should provide.

8.3.4 Design alternatives

On the basis of the two negotiation styles by Perdue et al. (1986), that have been introduced in chapter 2, two design alternatives will be explained to support ECA in reaching its objectives. In both designs, information that ECA has will play a different role.

<u>Collaborative</u>

In the collaborative style, the negotiator attempts to fully satisfy both his/her own concerns and the concerns of the opponent. This is an integrative, "problem-solving" style in which the main objective is the maximization of the joint gain of both parties (Perdue et al., 1986). ECA can apply a collaborative style in two ways. Firstly it could share the simulation model and the results of the optimization runs with PCX. In cooperation with experts from PCX the model will be improved according to the information PCX has. Furthermore input data will be synchronized with the information PCX has and scenarios will be adjusted according to scenario experts from both ECA and PCX. If both companies have verified and validated the model and have sufficient confidence in the ability of the model, new optimization runs will be done with the improved simulation model and the model results will be

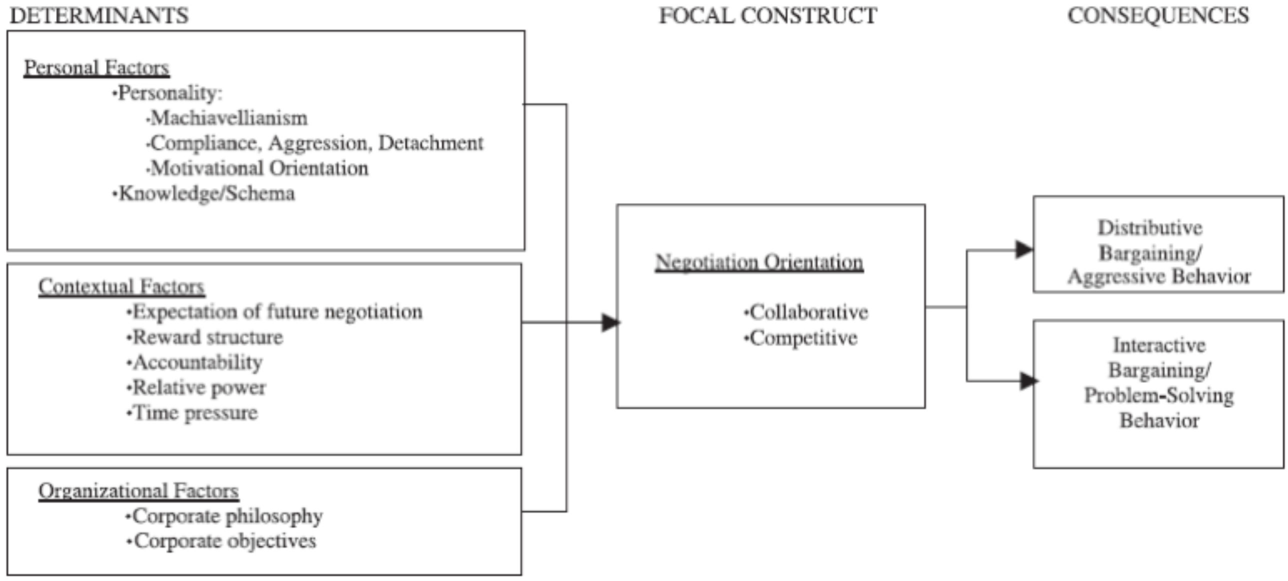


Figure 7: A contextual model of negotiation orientation (adopted from Brooks and Rose (2004))

checked under various scenarios that can be expected in the future. On the basis of the new results, both companies have the same results on the basis of which they can negotiate. However consideration of all other disadvantages and advantages for both companies should be taken into account as well when establishing contractual conditions. This means that both parties should be willing to share all information. If this happens, fair selling conditions can be negotiated on the basis of the model, that both parties are satisfied with.
Secondly, ECA would not have to share the simulation model and the results of the runs, but it could also just share information about its own operations. Since PCX does not know that ECA performed research about the performance of the steam production system in site Y, it would not harm trust between the two companies if ECA would not share this information. If both PCX and ECA will share information about their own operations and side advantages of steam supply by BPA, 'collaborative' negotiations can be performed. In this strategy, the simulation model and its results can be used for control of strategic behaviour of PCX.

Competitive

The second negotiation style is a competitive style of negotiation. In this style of negotiating the negotiator attempts to fully satisfy its own concerns at the expense of the opponent's concerns. This is a "win-lose" style in which the negotiator attempts to enhance its own position relative to the opponent (Perdue et al., 1986). If ECA would use a competitive negotiation style, it would not inform PCX of its attempt to model the steam system in site Y. The effort of modelling the system and the results from the optimization runs have provided ECA with valuable information. ECA has information about the threshold price at which PCX should be willing to buy steam and at what price for steam BPA would become more profitable with a steam production alternative than with its current business case. This information provides ECA with a strong position in the negotiations. Besides ECA would also not share complete information about its own plant operations. It would keep PCX in the dark, in order to get the best outcome for itself. A competitive negotiation style would lead to a bargaining situation on the steam price every company has calculated itself.

8.3.5 Analysis

Collaborative style

One of the advantages of the collaborative style is that if done well, both parties will establish a relationship in which the mutual trust is high and both parties are satisfied with the outcome of the negotiation. This is a solid basis for a good collaboration from which further collaboration in the future is possible, even if the outcome did not result in a collaboration this time.

However it is also possible that one of the two parties does not provide its information honestly. This is strategic behaviour. If a party behaves strategically, it strengthens its own position in the process of discussion and negotiation (De Bruijn & Heuvelhof, 2008). If one of the companies would do this, it would benefit itself and disadvantage the other company. Furthermore one of the companies then has all the information and the other company only has half, which can result in unfair pricing. This could result in a unbalanced relationship, in which trust is damaged.

Competitive style

One of the main advantages of a competitive style is that the risk of providing a lot of information and not getting the amount of the honest information in return does not have to be taken. Furthermore if one company has a lot of information, which it is not allowed to share or does not want to share, a competitive style is the only option.

It can be disadvantageous to use a competitive style if the main aim is to establish a solid relationship. Furthermore it can be more difficult to reach an agreement on the basis of a competitive style, because both companies are scared that the other falsely presents its information and therefore they will be the 'loser' of the game. In a competitive setting none of the participants is willing to give in, therefore it is harder to make a settlement.

8.3.6 Evaluation

Based on the following considerations the choice for a collaborative negotiation style has been made:

- From chapter 7 it was derived that a small negotiation space exists when it comes to threshold prices for steam of PCX and ECA. When a relational experience is competitive, negotiations are more likely to be oriented toward a search for individual gains (Lumineau & Henderson, 2012). Therefore if a competitive style is used, one of the companies will end up disadvantaged. This relational background forms a basis for predictions about future behavior and facilitates inferences about trustworthiness (Lumineau & Henderson, 2012). Since the constraint of the negotiation strategy is that ECA wants its relationship with PCX to be positive for the future, a competitive negotiation style does not seem like a supportive solution to meet its constraint.
- In section 2 of this chapter it was explained how the atmosphere in the negotiations between PCX and ECA was until now. It was derived that the negotiation style of the current negotiator of PCX is collaborative due to personal factors. According to Lumineau and Henderson (2012) cooperative relational experience will more likely steer supply chain partners to seek a "win–win" solution in negotiations. Besides Schneider (2002) stated that problem-solving negotiators make more effective negotiators than hard bargainers. Therefore a collaborative negotiation style could best be answered with the same style to reach the best outcome.
- Lastly, in section 3.5 of this chapter is was explained that a disadvantage of using a collaborative style negotiation strategy is that the opponent could be seduced to behave strategically. It could do this by withholding information or by falsely representing information. However due to this research, much insight was gained in the production process of CHPX 1 and the steam production system of site Y. Therefore this research report could be used to verify information provided by PCX for negotiations.

8.3.7 Strategy

In section 3.6 of this chapter it was established that ECA should use a collaborative negotiation style in negotiations with PCX. Behaviour that fits a collaborative negotiation style is:

- Not act in purely self-serving manner;
- Accurately disclose relevant information when requested;
- Not change supply specifications without consultation;
- Generally act in an ethical manner (Smeltzer, 1997).

However it should be noticed that ECA should only disclose information about its own plant operations. Secondly it should verify information provided by PCX about plant operations of CHPX 1 to arm itself for strategic behaviour of PCX.

8.4 Conclusion on strategic continuation

If ECA and PCX reach an agreement on steam supply by BPA, CHPX 1 would have to provide back-up capacity for the event that BPA has an unplanned stop. Therefore PCX should be compensated for keeping this back-up reserve. However PCX would – besides an economic advantage – have many other advantages from buying steam from BPA, such as the ability to keep the over allocation of CO2 rights, an increased chance to meet strict new emission rules, lower operational costs and a strengthened sustainable image. Those advantages could be enough to compensate for providing back-up capacity for BPA.

Furthermore if ECA invests in adjusting the BPA, some risks appear. Those risks mainly appear in the legal, financial, subsidy and operational categories. Main notifications should be that the contract between PCX and ECA should be very well designed and should leave no room for breaching or putting large fines upon ECA for unplanned stops of BPA. Secondly operational risks should be identified during design and planning phase of adjusting the BPA and mitigating measures should be considered.

In order to get a contract, in which ECA gets a good price for its steam and large risks are being covered, ECA should use a collaborative negotiation strategy. Reason for this is that there is a smaller negotiation space, because threshold prices of PCX and ECA are not far apart. Therefore a satisfying outcome for both companies can only be reached if collaboration takes place. Besides since an important constraint of the negotiation strategy of ECA is that it wants to maintain a good relationship with PCX for the long term, a collaborative style is advised. When using a collaborative negotiation strategy, ECA should disclose relevant information when requested and it should generally act in an ethical manner (Smeltzer, 1997). However it should not share results of this research.

DISCUSSION

9. Conclusion and Recommendations

This chapter addresses the conclusions and recommendations with respect to decision of ECA to invest in large scale steam production with BPA. Also the reflection on the research project itself is provided and suggestions for future research are presented.

9.1 Conclusions

In this research an approach has been proposed to support a utility provider in its investment decision-making to enter an integrated cluster. For that purpose a case study has been done. Firstly in section 1.1 conclusions about the case study will be given. Secondly in section 1.2 conclusions about the approach will be given.

9.1.1 Case study

The main research question that was posed in chapter 1.3 is:

What are the benefits for stakeholders if biomass plant A will supply steam in site Y?

In both simulated years, 2017 and 2025, steam production alternatives of BPA on average score better than the solo electricity alternative of BPA on the total system profits. The same result was derived when four price and demand scenarios were tested on the model. This means that even if PCX decides to build a new facility after it made arrangements with ECA for the purchase of steam, it would still be better off than when it would not get steam supplied by ECA. Therefore independent of its future plans to build new facilities, it would be wise for PCX to make an arrangement with ECA for the purchase of steam.

For the other stakeholders in the system, a reduction in the purchase price of steam by PCX UC could result in a reduction in the selling price of steam by PCX UC to its steam customers. However whether it does result in a reduction in the steam price depends on PCX UC. Therefore an improvement to the steam production system by a steam production alternative of BPA does not necessarily have to benefit other stakeholders in site Y.

For ECA the benefit of producing steam lies mainly in the economic aspect. If ECA will be able to get a good price for the steam it sells, its profits will increase compared to its current operation of BPA. Furthermore whether steam production with BPA benefits ECA depends on the selling conditions it establishes in negotiations with PCX. These conditions will be discussed in section 2 of this chapter.

The increase in total steam production profits is not the only advantage – of steam production by BPA – for PCX. For PCX, many other advantages besides the economic aspect are important when ECA's biomass plant will be producing steam. Advantages of steam supply by BPA to PCX are the following:

- Keeping the over allocation of CO2 rights, result: being able to keep over a million euro per year
- No adjustment to CHPX 1 needed to meet strict new emission rules posed onto CHPX 1 in 2016
- Opportunity for gradual decrease production CHPX 1 to avoid large maintenance due to reaching end of economic lifespan of the CHP
- Lower operational costs due to shutting down of one extra gas turbine (minimum operation)
- Improving sustainable image

The last bullet point applies to other stakeholders as well.

Besides the benefits that steam production by BPA has for PCX and possibly other stakeholders as well, it does have some implications. Biomass plant A runs on biomass. Problems of using biomass in boilers are fouling, deposits, slagging and corrosion issues. Therefore a wood-fired steam plant requires 3-7 times more plant maintenance and operation workers than for example a coal-fired plant (Saidur et al., 2011). This causes more (un)planned stops, which results in a lower number of operational hours per year and a lower reliability of steam supply from BPA. Therefore back-up capacity has to be available at all times. Keeping back-up capacity available induces costs. Since PCX UC is the responsible company for steam supply in site Y, these costs will have to be incurred by PCX UC. Therefore compensation would be needed.

9.1.2 Approach

Cooperation between companies within industrial clusters can strengthen the competitive position of individual companies in those clusters. Localization of production within industrial districts provides opportunities for the industrial district as a whole to secure internal economies of scale and external benefits denied to isolated firms, which causes an improvement in the competitive position of individual firms (Newlands, 2003). Much work has been published on the design and optimization of utility systems in industrial clusters. However non-technical factors are often not taken into account when optimizing an integrated system. In particular, long-term development plans that companies within a cluster make for future development of their own plants limit efficiency gains that could potentially be achieved with integration. This thesis presented a model-based approach to support a utility provider in its investment decision-making to enter an industrial cluster.

By means of this research it was showed that the suggested approach can be used to include development plans of individual stakeholders in an optimization effort of a utility system. It can be used when all information about the technical specifications of the utility plants is available, as well as a case in which information is not fully available. However in that case, as in the case study, step 2 should be done very thoroughly and data validation of the model should be done carefully. Furthermore the shortages of the model should be taken into account when analysing the results.

The conclusion can be drawn that by performing the approach, the main research question is fully answered. Moreover, all the research objectives are met:

- The decision of ECA about whether or not it should invest in adjusting BPA for steam production has been supported;
- The choice of ECA between steam production alternatives BPA has been supported;
- Threshold prices have been defined;
- A negotiation strategy has been proposed.

9.2 Recommendations

9.2.1 Decision for operation alternative BPA

In 2017 the PRDS alternative would be the best alternative of BPA on a system level compared to the other alternatives of BPA. Besides in 2025 the PRDS alternative gave the best system results overall of all three BPA alternatives as well. Therefore it would be beneficial for the system if ECA would invest in adjusting the BPA with a PRDS. However in all four scenarios the BPST alternative to co-produce steam with BPA outperformed the other two alternatives of the BPA. This means that the BPST alternative is most robust under various scenarios. Reason for this is that with the BPST alternative more electricity is produced than with the PRDS alternative. Electricity incomes are the only revenues that are taken into account in the simulation model. Therefore costs for buying biomass remain the same for both alternatives, but the income for electricity with the BPST alternative is higher, since more electricity is produced. This affects the system profits. Furthermore the average system outcomes on the four scenarios for the BPST alternative and the PRDS alternative do not differentiate much. Therefore it is still advised to ECA to invest in the PRDS alternative, since that alternative will provide the best system results on expected price scenarios and will therefore provide ECA with the possibility to get the highest margin on the steam sold. Besides, the PRDS alternative demands the lowest investment costs of the two steam production alternatives. Therefore it would be easier to earn back the investment costs of this adjustment.

9.2.2 Price of steam supplied by BPA

Threshold prices are calculated on the basis of the current business case. It is calculated at what price point ECA or PCX would be better off if BPA would produce steam than their current respective business cases. It is assumed that PCX and ECA will only reach an agreement if the threshold price of PCX is higher than the threshold price of ECA. At that point PCX is willing to pay more money per ton of steam than the price ECA asks per ton of steam at minimum. It is advised to ECA to relate the steam price to the natural gas price. A regular steam price is 70% of the natural gas price. From the results it was derived that there is negotiation space, which means that in most cases the threshold price of PCX is higher than the threshold price of ECA. However due to confidentiality reasons, the exact negotiation space on the basis of threshold prices cannot be defined.
In 2017 the threshold price of ECA and the steam price based on the natural gas price do not vary much. However in 2025 the threshold price of ECA has dropped a little bit, whereas the steam price based on the natural gas price has risen significantly according to model results. Reasons for this is that the natural gas price is expected to increase in upcoming years. This means that in the first few years when the BPA is operational with a steam alternative, ECA might not increase its profits significantly. However in the further future if the natural gas price will keep on rising, ECA will be better off with a steam alternative than keeping its solo electricity operation.

9.2.3 Mitigating risks

If ECA and PCX reach an agreement on steam supply by BPA, ECA will invest a large amount of money in the alternative of its choice. Investing large amounts of money always brings risks. Some very important risks are:

- Breakdown or limited availability of biomass plant A
- New subsidy scheme tariffs will be decreased significantly compared to the concept advise RIA
- PCX finds a cheaper alternative and switches from steam supplier
- PCX goes bankrupt or moves its production to another production location
- Stakeholders build their own steam production units, which decreases steam demand in site Y

To cope with these risks, those topics should be included in a contract with PCX. Firstly ECA should not be held accountable for large breakdowns of BPA. Otherwise this could cause large claims, which would jeopardize the business case of BPA. Secondly an amount of steam supplied to PCX per hour should be agreed on. Otherwise PCX has the opportunity to not use steam from ECA. This could result in a longer or no pay-back of the investment made to adjust the BPA for steam production. Lastly the mother company of PCX in site Y should be held accountable if PCX breaches the contract for steam supply by BPA.

Besides the contract conditions, it is also important that ECA has the final information about how the new subsidy will be calculated and that it will be granted to ECA. Before this affirmation, ECA should not invest in steam production.

9.2.4 Negotiation style

It is recommended to ECA to negotiate with a collaborative style. Reasons for this recommendation are:

- A small negotiation space exists. Both PCX and ECA have not much room for gains or losses. Therefore a collaborative negotiation is the best option to reach a good agreement for both parties. This is important, because an important aspect of the negotiation strategy of ECA is that it wants to maintain a good relationship with PCX.
- In current negotiations, the negotiator of PCX shows a collaborative style. According to Schneider (2002) problem-solving negotiators make more effective negotiators than hard bargainers. Therefore ECA should answer this by showing a collaborative style as well. Both parties could share information about their own operations, to reach a good agreement.
- One of the disadvantages of a collaborative style is that strategic behaviour is possible. However this research provides ECA with knowledge about the steam system in site Y. Therefore ECA has the possibility to compare information provided by PCX with this research. Large differences can point out strategic behaviour. This means that ECA can negotiate with a collaborative style, without taking the risk of being misled.

ECA should not share the simulation model constructed for this research, since the model includes much internal information from ECA. The information provides much insight about the operational specifications of BPA. Also a lot of information about CHPX 1is included in the model. To protect itself from strategic behaviour by PCX, ECA should not show the model. Furthermore showing all the assumptions and information that ECA has collected about CHPX 1 through the years might tense negotiations.

ECA is advised to use a collaborative style in negotiations with PCX. Therefore it should:

- Not act in purely self-serving manner;
- Accurately disclose relevant information when requested;
- Not change supply specifications without consultation;
- Generally act in an ethical manner (Smeltzer, 1997).

9.3 Reflection on research approach

In section 1 is concluded that the proposed approach can be used to include development plans of stakeholders in the optimization of a utility system. Furthermore all the objectives of this research have been met and the main question has been answered sufficiently. However still critical remarks about this research can be made. A list of those remarks can be found below.

<u>Added value of research approach</u>

Future plant developments of stakeholders should be included in an effort towards cluster collaboration, because better success is being achieved by integration of economic, environmental and social dimensions into industrial collaboration activities (Baas, 2008). The fact that each company within a cluster has its own plans for future developments of its plant causes uncertainty for investment decisions. Uncertainty within an utility system due to individual plans of stakeholders can – in the long term – deteriorate the economic performance and competitive position of an industrial cluster.

In this thesis a model-based approach to support a utility provider in its investment decision-making to enter such an integrated cluster has been presented. The approach has been found well suited for the purpose mentioned. It took into account other stakeholder plans and market uncertainties, which provided a robust analysis of the system. Furthermore it is a structured approach, which makes it easily repeatable and provides an ease in interpreting data. The steps that had to be taken to meaningfully answer the main research question were logical and resulted in data that could reliably be interpreted. The added value of this research can be found in a structured approach to include social (non-technical) and economic uncertainties in an optimization effort of an integrated cluster. On this topic a gap in literature exists. This research aimed to accommodate this gap.

Applicability

A point of consideration is that the approach has been tested on just one case study. Since the approach has been conceived to answer the research question of this thesis, the research approach is very much focused on this particular case. Due to limited resources and time the research approach could not be tested for other utility systems. Therefore to be able to provide a definite statement about the applicability of the research approach for other utility systems it should be tested on other case studies as well. However this approach is believed to be flexible and adaptable, due to its structured sequence of steps and the use of widely known methods.

Novelty of research approach

The novelty of this research approach can be found in its application in industrial ecology. All elements of the approach have been widely used for scientific purposes in many different fields. Besides, all elements of the approach have been used in a variety of sequences. Especially simulation modelling and optimization are methods that have been extensively used to achieve economic and environmental efficiencies in industrial clusters. However, when it came to including non-technical or social dimensions into the analysis, literature stranded. In the field of policy analysis, the consideration of social factors in a model-based approach to assess policy measures is extensively researched. This idea has been transplanted to the field of industrial ecology to provide the user with knowledge about the utility system in order to be able to support a negotiation strategy.

9.4 Suggestions for further research

To improve the research approach used in this thesis to support an utility provider in its investment decision-making to enter an industrial cluster, these are suggestions for further research:

- The sequence of steps in the approach could be differentiated by firstly modelling the current system. Then based on the model behaviour and its results, possible stakeholder developments could be proposed and implemented. Conclusions can be drawn about to what extent it is to be expected that stakeholders will invest in a certain technology or in what technologies the entrant in the cluster should invest. This would provide information for the design of a negotiation strategy;
- The research approach could be improved by application of game theory for the design of a negotiation process. The design of a negotiation strategy will then be considered on the basis of two 'rivaling' theories, namely cooperative and non-cooperative game theory. The two branches of game theory differ in how they formalize interdependence among the players. In the non-cooperative theory, a game is a detailed model of all the moves available to the players. By contrast, the cooperative theory abstracts away from this level of detail, and describes only the outcomes that result when the players come together in different combinations (Brandenburger, 2007). By considering both 'games', the optimal outcome can be assessed, which leads to a negotiation strategy.
- Lastly, agent based modelling is a class of computational models for simulating the actions and interactions of autonomous agents (both individual or collective entities such as organizations or groups) with a view to assessing their effects on the system as a whole. Recently agent based modelling has been applied to solve optimization problems whose domains present several inter-related components in a distributed and heterogeneous environment (Barbati, Bruno, & Genovese, 2012). Since agent based modelling could be used to represent actual interactive social behaviour of stakeholders during model runs, this method could well be used for the inclusion of stakeholders plans into an optimization effort. Therefore the use of agent based modelling for the simulation model should be investigated.

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APPENDICES

A. Complement research problem and approach

A.1 Goal tree ECA

To sustain its business in the long term ECA aims to maximize its profits. It can do this by building new assets, which have a promise of profitability. It also has to make sure to preserve its customers and to attract new customers. Furthermore exploiting its current installed capacity in the most profitable way is also one of the things that ECA has to do to reach this goal. ECA can do this by improving the efficiency of the current plants and by investigating whether a different use of a particular plant can increase the profitability of that plant. The goal tree of ECA, which supports the analysis above, can be found in figure A.1.

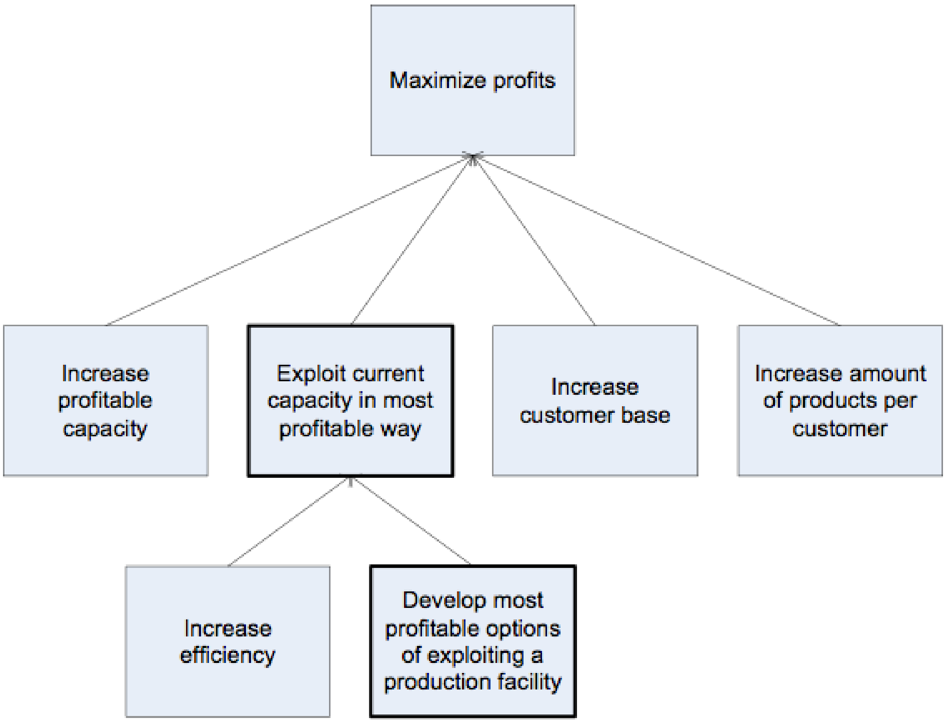


Figure A.1: Goal tree of ECA

ECA is the owner of biomass plant A, which is located in an industrial cluster that is called site Y. The BPA currently solely produces electricity. Since mid-2008 electricity prices in Europe have dropped and experts foresee no drastic improvement in the future. Therefore the BPA does not meet the expectations of ECA in terms of profitability. To reach its main goal, the project team of BPA wants to find out whether exploiting BPA in a different way might lead to increased profits.

A.2 Flow chart of research approach

In chapter 2 a flow chart of the research approach has been presented. In this section some extra information about the steps in the approach is provided. Every step will be discussed on the basis of the actions that have to be taken in order to reach the **outcomes** of the steps.

1) Explore problem environment
Introduction of stakeholders
Mapping of relationships between stakeholders
Stakeholder mapping according to Murray-Webster and Simon (2006)
Establishing what (external) factors influence the utility system
List of stakeholders that will be included in the analysis
List of external factors that will be included in the analysis

2) Identify relevant stakeholder plans
Analysis of options according to Thomas (2003)
Collection of technical specifications of chosen assets
Definition of relevant configurations of assets
Detailed model options

3) Describe optimization problem
Functional requirements of the model
Description of the desired output of the model

4) Construct simulation model
Selection of appropriate software
Implementation in software
Assessment of veracity and validity of the model
Model found sufficient to produce output wanted

5) Investigate market developments
On the basis of identified external factors of importance by problem exploration and stakeholder plans
Construction of relevant scenarios
Scenarios of input variables for the model that influence the system output

6) Structure experimental setup
On the basis of model options and scenarios
Decision of experiments needed for relevant conclusions
Experimental design

7) Run model
Perform all experiments from the experimental design
Model results

8) Analyse and interpret model results
Comparison of results
Conclusions from output data
Assess further system influence enforced by entry of utility provider
Recommendations about negotiation position for entry integrated cluster

B. Detailed stakeholder analysis

To analyse future development plans of stakeholders, it is important to know what the stakeholders are. Therefore in this appendix firstly an introduction will be given to all stakeholders. Secondly all stakeholders will be divided into categories of importance to involve them in the project. Lastly according to the first two analyses, development plans of stakeholders will be outlined.

B.1 Introduction stakeholders - Confidential

An overview of what the system looks like and how the stakeholders relate to each other can be found in chapter 1. Furthermore in this section all stakeholders will be introduced and their goals and therefore interest in possible steam supply by BPA will be discussed.

B.1.1 Regulatory entities

<information not attached due to confidentiality reasons>

B.1.2 Advisory entities

<information not attached due to confidentiality reasons>

B.1.3 Steam suppliers

<information not attached due to confidentiality reasons>

B.1.4 Steam consumers

<information not attached due to confidentiality reasons>

B.2 Mapping of stakeholder types

If a company is influential in terms of this particular project, its attitude is negative towards this project and its interests are high, then a stakeholder can hinder the success of this project. However if a company is influential in terms of this particular project, its attitude is positive towards this project and its interests are high, then a company is a saviour, which means that cooperation of this company is very important to make this project a success. In this project these stakeholders are the Ministry of Economic Affairs and PCX. The ministry is very important, because in the end it gets to decide on the subsidy for steam. If ECA will not get a subsidy for bio steam or the subsidy amount will be too low, the project will probably not be profitable.

Furthermore PCX is the main customer of steam from ECA. Therefore if PCX decides to get its steam from a different supplier or to produce the steam needed for their processes itself, steam from ECA will not be used. If so, ECA would have done large investments and it would not sell its steam.

The stakeholders that will be taken into account in this stakeholder analysis are the ones that have influence on- or will be influenced by steam cluster in site Y. Those stakeholders will be classified in types below.

<table not attached due to confidentiality reasons>

Table B.1: Stakeholder types steam cluster site Y

The most important stakeholders for ECA in this project are the ministry of economic affairs and PCX. The support that ECA needs from the ministry is based on regulatory and monetary terms. ECA is dependent on PCX, because PCX will be the main customer of steam from ECA. Furthermore site Y Authority Company (YAC) is an important stakeholder as well, since it could invest in the new steam network to connect BPA to the existing steam network in site Y. However YAC has mentioned that it will only invest if the investment is beneficiary to all stakeholders. Therefore if steam supply of ECA to PCX only benefits those two companies, YAC will not invest.

Only CHPX could act against steam supply by BPA, because this would mean that CHPX would be operated less. Therefore less employees would be needed and this could mean that part of the employees will be fired. CHPX would want to stay operational. However this will be an intern discussion within PCX, because CHPX is a joint venture of PCX. Furthermore eventually the interest of PCX will be more important.

The waste incinerator does not really have a stake in this situation, since it produces at maximum capacity and will keep doing so, since it will still be the cheapest producer of steam. Furthermore the waste incinerator does not have the possibility to produce high pressure steam, so therefore ECA is not seen as competition.

All companies that currently receive steam from PCX UC, will probably still be receiving their steam from PCX UC. Therefore the steam contracts will probably stay the same even if ECA will produce steam. Those companies will only be very supportive if this would mean that PCX UC would adjust the contracts either with more flexibility or lower prices.

B.3 Detailed analysis of options

According to R. Hackl and Harvey (2013) one of the challenges of optimization in an industrial cluster is to investigate long term development plans for industrial clusters. Each company within a cluster has plans for future development of its own plant and such plans should be included in an effort to improve an utility system. To be able to include such plans, an analysis of options will be done. In this analysis the options that steam customers in site Y have to improve their situation with regard to the conditions under which they purchase steam. This analysis will be presented below.

<table not attached due to confidentiality reasons>

Table B.2: Analysis of options of stakeholders steam cluster site Y

Some of the companies in site Y that get their steam supplied by PCX UC, are not satisfied with the terms on which they obtain their steam. Therefore some of those companies are looking for new ways to obtain steam. Besides PCB's steam demand might increase drastically in due upcoming years. Reason for this is that its capacity is expected to grow significantly. This might give them an incentive to invest in their own steam production. And it is also a possibility that all companies, that get their steam supplied by PCX UC, build a steam production unit together. Furthermore PCX is looking for new ways to obtain steam as well, since steam production with CHPX is very expensive at the moment. Lastly it might also possible that a new investor enters site Y to produce steam for the demanding companies.

However most important conclusions that can be drawn from the table above are that all steam consumers in site Y that currently receive steam from PCX can build a steam production facility together. However it is not likely that this will happen, since the entire steam network in the area is owned by PCX. Also every individual company could build a steam production units for its own steam demand. This is also not likely, since this would take-away economies of scale. Furthermore steam production is not the core business of any of the companies in site Y and it will therefore not be likely that those companies will want to operate a steam production unit. Lastly the option in which the other companies circumnavigate PCX and directly purchase steam from ECA is not to be expected, because the steam network is owned by PCX. This would only be possible if a new steam network would be constructed, however since most of the land on which the other companies operate is owned by PCX, this does not seem to belong to one of the realistic options.
PCX could also decide to quit production in site Y. This would mean that it would not need steam anymore. However since it is currently negotiating with ECA it is not expected that this is the plan of PCX. Therefore this more of PCX is not expected. However it should be considered as one of the risks when ECA decides on investing in steam production.
PCX has more options. Besides buying steam from BPA or producing it itself with CHPX, it can also build a new gas or bio boiler. Any of those options seems like a good solution to circumnavigate the pressured spark spread. Furthermore for a bio boiler option it might be possible to receive subsidy. Therefore these two options will be included in the modelling effort

C. Technical specifications alternatives BPA

In this appendix the conceptual models of all three alternatives of the BPA will be shown. Furthermore investment costs for steam production alternatives will be shown in section 2 of this appendix.

C.1 Alternatives BPA

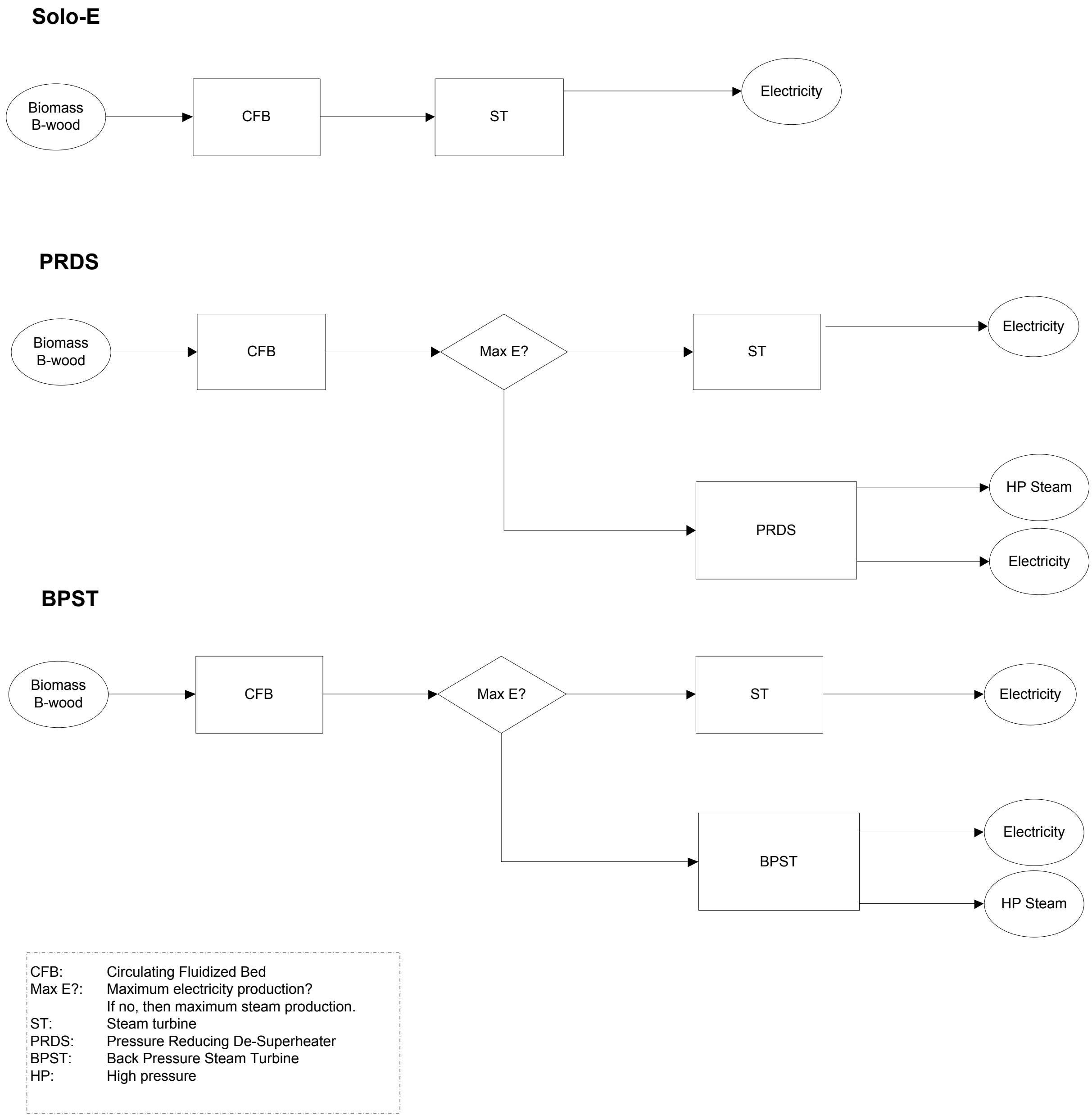


Figure C.1: Conceptual models of alternatives BPA

All input and output specifications can be found in chapter 4.

C.2 Summary investment costs alternatives steam production BPA

Capital Expenditure (CAPEX) estimate (accuracy +/- 20%) for alternatives according to is the following:

Cost estimate CAPEX	Alternative BPST	Alternative PRDS
	€	**€**
Steam turbine	-	-
Process systems	-	-
Electrification	-	-
C&I	-	-
Structures, civil works	-	-
EPCM	-	-
Subtotal	-	-
Contingency	-	-
Total	-	-

Table C.1: CAPEX steam production alternatives BPA (no reference included due to confidentiality reasons) (cells left blank due to confidentiality reasons)

From this table can be derived that the CAPEX for a BPST are significantly higher than for the PRDS. This should be taken in to account when comparing the two alternatives.

D. Technical specifications CHPX 1

In this the process of CHPX 1 and its production specifications will be clarified. In section one an explanation will be given about the characteristics of the Heat Recovery Steam Generator systems in CHPX 1. Furthermore calculations of operation with or without supplemental firing will be shown in section 2, 3 and 4.

D.1 Explanation working HRSGs in CHPX 1

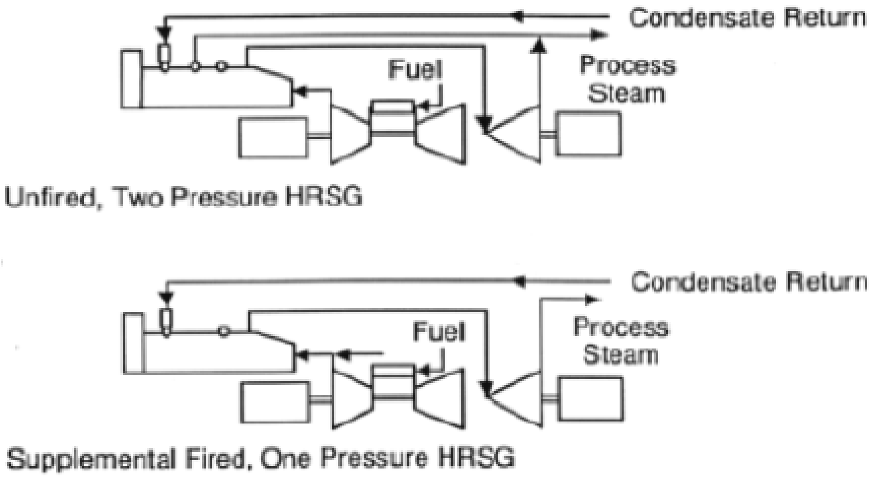


Figure D.1: HRSG options CHPX 1 (Chase & Kehoe, 2000)

Figure D.1 shows combined-cycle cogeneration systems that produce steam with an unfired or supplementary-fired HRSG. HRSG design for supplementary firing provides the maximum process steam energy supply (Chase & Kehoe, 2000). In the figure it is possible to see that the HRSGs in CHPX 1 can be operated in two ways. The first way is unfired, which means that no extra fuel goes into the HRSG. Furthermore since not enough water can be heated to process conditions, two flows of steam come out of the HRSGs at two pressures.

When supplemental firing is added to the HRSGs, extra natural gas is burned to superheat the exhaust gasses that come in from the gas turbine. With this extra heat, all water can be heated up to process conditions, which means that all steam comes out at one pressure to flow into the steam turbine.

D.1.1 Unfired HRSG's

In this section it will be discussed whether and how the decision to only model HRSG's with supplemental firing affects the model results. Firstly the operation of HRSG's concerns the operation of CHPX 1, which means that it is only applicable to model options in which CHPX 1 is represented. In the years 2017 and 2025 the high pressure steam production of BPA in model options 1 and 2 are not enough to produce enough steam to meet the entire high pressure steam demand. Therefore CHPX 1 always has to be stand-by to produce for the remaining demand.

Output of 1 HRSG without Supplemental Firing

2 flows of steam exit the HRSGs: Flow 1 enters the steam turbines and flow 2 exits the plant for export

Pressure steam output HRSG	-	bar
Temperature steam output HRSG	-	°C
Enthalpy steam output HRSG	-	kJ/kg
Flow 1 steam output HRSG w/o SF	-	kg/s
Thermal power flow 1 w/o SF (for STs)	-	MJ/s
Thermal power flow 1 w/o SF (for STs)	-	ton/hour

Output steam turbines at maximum electricity production w/o SF		
Capacity steam turbine	-	ton/hr
Number of steam turbines	2	
Number of steam turbines operational w/o SF	1	
Minimum flow for high pressure steam extraction	50% of	maximum flow
	-	ton/hr

Table D.1: Calculation of high pressure steam production of CHPX 1 with one gas turbine in combination with unfired HRSG (cells left blank due to confidentiality reasons)

A quick calculation shows that to be able to produce high pressure steam with the steam turbines, under unfired operation of the HRSG's two gas turbines should be operational. Reason for this is the constraint that at least a 50% flow of the maximum capacity of the steam turbine should flow through the turbine to be able to produce high pressure steam (personal communication, System engineer BPA and plant manager CHP, June 26, 2014) . However with only one gas turbine operational and with an HRSG with unfired operation, the flow would be too low for high pressure steam production. This means that two gas turbines would have to be operational compared to one gas turbine in combination with a HRSG with supplemental firing. This results in a higher cost for operating two gas turbines than one gas turbine and an HRSG with supplemental firing. Therefore for those options it is not needed to adjust the simulation model.

Other model options that include CHPX 1 are options 9, 10, 11 and 12. In option 9 most of the time CHPX 1 is fully responsible to meet the high pressure steam demand. For options 10 and 11 the same calculation is applicable as the one that has been done for options 1 and 2. In option 12 a bio boiler is present in combination with CHPX 1. However from the model results it can be derived that if only a bio boiler would be present, the system would perform better economically. Therefore it is not expected that this model option will be used in this way. If PCX decides to build a bio boiler, it will not use CHPX 1 anymore, since it will not provide them with large benefits. Therefore it is not necessary to check whether unfired operational of HRSG would improve the results of that model option.

However what is very important to notice is that if at some point the production of BPA will be enough to meet the entire high pressure steam demand in site Y, the unfired operation of HRSGs in CHPX 1 could be a solution to meet the low pressure steam demand with lower costs.

D.2 Totals of inputs and outputs CHPX 1 under operation with and without SF

CHPX 1	Operation			
	Without supplemental firing		*With supplemental firing*	
	Max. e-power	Max. th-power	Max. e-power	Max. th-power
Inputs				
Gas turbines	-	-	-	-
HRSGs			-	-
Total inputs (MW)	-	-	-	-
Outputs				
Gas turbines	-	-	-	-
HRSGs (low pressure steam)	-	-		
Steam turbines				
low pressure steam	-	-	-	-
high pressure steam		-		-
Electricity	-	-	-	-
Total outputs (MW)	-	-	-	-
CHP efficiency	-%	-%	-%	-%

Table D.1: Totals sheet of production process CHPX 1 (cells left blank due to confidentiality reasons)

All inputs and outputs that enter and exit CHPX 1 are delineated in the calculation sheets presented below. The delineated blocks can be traced back in the totals sheet presented above.

D.3 Calculations without supplemental firing

Input gas turbines		
LHV Natural gas	31,7	MJ/m3
Natural gas consumption	-	m3/s
Input gas per gas turbine = LHV Natural gas x Natural gas consumption		
	-	MJ/s
		MWf
Input for 3 gas turbines = Input per gas turbine x 3		
	-	MWf
Output parameters gas turbines		
Electrical efficiency gas turbines	-	%
Electrical output per gas turbine	-	MWe
Electrical output for 3 gas turbines	-	MWe

Flue gas flow	-	kg/hr
Flue gas temperature	-	°C
Flue gas enthalpy	-	kJ/kg
Input HRSGs without supplemental firing		
Flue gas flow from gas turbines	-	kg/hr
Flue gas temperature from gas turbines	-	°C
Flue gas enthalpy from gas turbines	-	kJ/kg
Output HRSGs without SF		
2 flows of steam exit the HRSGs: Flow 1 enters the steam turbines and flow 2 exits the plant for export		
Pressure steam output HRSG	-	Bar
Temperature steam output HRSG	-	°C
Enthalpy steam output HRSG	-	kJ/kg
Flow 1 steam output HRSG w/o SF	-	kg/s
Thermal power flow 1 w/o SF (for STs)	-	MJ/s
Pressure flow 2	-	Bar
Temperature	-	°C
Enthalpy	-	kJ/kg
Flow 2 steam output HRSG	-	kg/s
Thermal power flow 2 (for export)	-	MJ/s
Total thermal power output HRSGs w/o SF	-	MWth
Output steam turbines at maximum electricity production w/o SF		
Capacity steam turbine	-	ton/hr
Number of steam turbines	2	
Number of steam turbines operational w/o SF	1	
Input steam turbines from HRSGs w/o SF = Flow 1 steam output HRSG w/o SF		
Enthalpy inflow	-	kJ/kg
Enthalpy outflow from steam turbine	-	kJ/kg
Delta enthalpy in- and outflow steam turbine	-	kJ/kg
Electrical power output		
Delta enthalpy in- and outflow steam turbine	-	kJ/kg
Input steam turbines from HRSGs if no SF applied	-	kg/s
Max. electrical output = Delta enthalpy in- and outflow ST * Input steam turbines from HRSGs w/o SF		
Maximum electrical output	-	kJ/s
	-	MJ/s

Steam turbine efficiency	-	%
Maximum inflow steam turbine	-	kg/s
Input steam turbines from HRSGs w/o SF	-	kg/s
Efficiency due to part load operation	-	%
Electrical output steam turbine	-	MWe
Output steam turbines from HRSGs w/o SF = Input steam turbines from HRSGs w/o SF		
Output steam turbines from HRSGs w/o SF	-	kg/s
Thermal output: low pressure steam outflow steam turbine		
Pressure	-	bar
Temperature	-	°C
Enthalpy outflow from steam turbine	-	kJ/kg
Thermal output steam turbine	-	kJ/s
	-	MJ/s
Output steam turbines at maximum heat production		
Capacity steam turbine	-	ton/hr
Number of steam turbines	2	
Number of steam turbines operational w/o SF	1	
Input steam turbines from HRSGs w/o SF = Flow 1 steam output HRSG		
Minimum steam outflow from end steam turbine	25%	
	-	ton/hr
	-	kg/s
Outflow from end of steam turbine has ‘characteristics low pressure steam outflow steam turbine’		
Thermal output: low pressure steam outflow steam turbine		
Minimum steam outflow from end steam turbine	-	kg/s
Enthalpy outflow from steam turbine	-	kJ/kg
Thermal output of low pressure steam	-	kJ/s
	-	MJ/s
Thermal output: high pressure steam outflow steam turbine		
Input steam turbines from HRSGs w/o SF = Flow 1 steam output HRSG		
	-	kg/s
Max. high pressure steam production flow = Input ST from HRSGs w/o SF - Min. steam outflow from end ST		
	-	kg/s

Characteristics high pressure steam flow for export		
Pressure	-	bar
Temperature	-	°C
Enthalpy	-	kJ/kg
Thermal output ST high pressure steam =		
Max. high pressure steam production flow from inflow * Enthalpy high pressure export steam flow		
	-	kJ/s
	-	MWth
Electrical output		
Enthalpy inflow	-	kJ/kg
Enthalpy outflow high pressure steam outlet	-	kJ/kg
Enthalpy outflow from steam turbine	-	kJ/kg
Delta 1: enthalpy in- and outflow high pressure steam outlet	-	kJ/kg
Delta 2: enthalpy outflow high pressure steam outlet and outflow steam turbine	-	kJ/kg
Delta 1: enthalpy in- and outflow high pressure steam outlet	-	kJ/kg
Input steam turbines from HRSGs w/o SF	-	kg/s
Max. electrical output = Delta enthalpy in- and outflow ST * Input steam turbines from HRSGs w/o SF		
Maximum electrical output	-	kJ/s
	-	MJ/s
Steam turbine efficiency in first part of steam turbine	-	%
Maximum inflow steam turbine	-	kg/s
Input steam turbines from HRSGs w/o SF	-	kg/s
Efficiency due to part load operation	-	%
Electrical output steam turbine	-	MWe
No electrical output from end part of steam turbine expected, because of significantly reduced flow due to high pressure steam outlet		

Table D.2: CHPX 1 production calculations without supplemental firing (cells left blank due to confidentiality reasons)

D.4 Calculations with supplemental firing

Input gas turbines		
LHV Natural gas	31,7	MJ/m3
Natural gas consumption	-	m3/s
Input gas per gas turbine = LHV Natural gas * Natural gas consumption		
	-	MJ/s
		MWf
Input for 3 gas turbines = Input per gas turbine * 3		
	-	MWf
Output parameters gas turbines		
Electrical efficiency gas turbines	-	%
Electrical output per gas turbine	-	MWe
Electrical output for 3 gas turbines	-	MWe
Flue gas flow	-	kg/hr
Flue gas temperature	-	°C
Flue gas enthalpy	-	kJ/kg
Input HRSGs with supplemental firing		
Flue gas flow from gas turbines	-	kg/hr
Flue gas temperature from gas turbines	-	°C
Flue gas enthalpy from gas turbines	-	kJ/kg
LHV Natural gas	31,7	MJ/m3
Natural gas consumption	-	m3/s
Efficiency supplemental firing	97,6%	
Total thermal power output HRSGs w/o SF	-	MWth
Total thermal power output HRSGs with SF	-	MWth
Difference thermal output HRSGs with or w/o SF	-	MWth
Extra natural gas input needed for SF	-	MWth
Extra natural gas input needed for SF per HRSG	-	MWth

Output HRSGs with SF		
1 flow of superheated steam exits the HRSGs		
Pressure steam output HRSG	-	Bar
Temperature steam output HRSG	-	°C
Enthalpy steam output HRSG	-	kJ/kg
Flow 1 steam output HRSG with SF	-	kg/s
Thermal power flow 1 with SF	-	MJ/s
Total thermal power output HRSGs with SF	-	MWth
Output steam turbines at maximum electricity production with SF		
Capacity steam turbine	-	kg/s
Number of steam turbines	2	
Number of steam turbines operational if SF applied	2	
Input steam turbines from HRSGs with SF = Flow 1 steam output HRSG with SF		
Enthalpy inflow	-	kJ/kg
Enthalpy outflow from steam turbine	-	kJ/kg
Delta enthalpy in- and outflow steam turbine	-	kJ/kg
Electrical power output		
Delta enthalpy in- and outflow steam turbine	-	kJ/kg
Input steam turbines from HRSGs with SF	-	kg/s
Max. electrical output = Delta enthalpy in- and outflow ST * Input STs from HRSGs with SF		
Maximum electrical output	-	kJ/s
	-	MJ/s
Steam turbine efficiency	-	%
Electrical output steam turbines	-	MWe
Output steam turbines from HRSGs with SF = Input steam turbines from HRSGs with SF		
Output steam turbines from HRSGs with SF	-	kg/s
Thermal output: low pressure steam outflow steam turbine		
Pressure	-	bar
Temperature	-	°C
Enthalpy outflow from steam turbine	-	kJ/kg
Thermal output steam turbine	-	kJ/s
	-	MJ/s
		MWth

Output steam turbines at maximum heat production		
Capacity steam turbine	-	ton/hr
Number of steam turbines	2	
Number of steam turbines operational with SF	2	
Input steam turbines from HRSGs with SF = Flow 1 steam output HRSG with SF		
Thermal output: high pressure steam outflow steam turbine		
Maximum high pressure steam flow from 2 STs	-	ton/hr
(personal communication, Business manager production site Y, May 16, 2014)	-	kg/s
Characteristics high pressure steam flow for export		
Pressure	-	Bar
Temperature	-	°C
Enthalpy	-	kJ/kg
Thermal output ST high pressure steam = Max. high pressure steam flow from 2 STs * Enthalpy high pressure steam flow		
	-	MJ/s
Thermal output: low pressure steam outflow steam turbine		
Outflow from end 2 STs = Input STs from HRSGs with SF - Maximum high pressure steam flow from 2 STs		
	-	kg/s
Outflow from end of steam turbine has 'characteristics low pressure steam outflow steam turbine'		
Outflow from end 2 steam turbines	-	kg/s
Enthalpy outflow from steam turbine	-	kJ/kg
Thermal output of low pressure steam	-	kJ/s
	-	MJ/s
Electrical output		
Enthalpy inflow	-	kJ/kg
Enthalpy outflow high pressure steam outlet	-	kJ/kg
Enthalpy outflow from steam turbine	-	kJ/kg
Delta 1: enthalpy in- and outflow high pressure steam outlet	-	kJ/kg
Delta 2: enthalpy outflow high pressure steam outlet and outflow ST	-	kJ/kg
Delta 1: enthalpy in- and outflow high pressure steam outlet	-	kJ/kg
Input steam turbines from HRSGs with SF	-	kg/s
Maximum electrical output = Delta 1 * Input steam turbines from HRSGs with SF		
	-	kJ/s
	-	MJ/s
Steam turbine efficiency in first part of steam turbine	-	%
Electrical output first part of steam turbines	-	MWe

Delta 2: enthalpy outflow high pressure steam outlet and outflow ST	-	kJ/kg
Input 2nd part of STs at max. th. power production =		
Input STs from HRSGs with SF - Max. high pressure steam flow from 2 STs		
	-	kg/s
Electrical output second part of steam turbines =		
Delta 2 * Input 2nd part of STs at max. th.power production		
Electrical output second part of steam turbines	-	kJ/s
	-	MJ/s
Steam turbine efficiency in first part of steam turbine	-	%
Maximum inflow steam turbines	-	kg/s
Input 2nd part of steam turbines after outlet high pressure steam	-	kg/s
Efficiency due to part load operation	-	%
Electrical output second part steam turbine	-	MWe
Total electrical output at max. thermal power production	-	MWe

Table D.3: CHPX 1 production calculations with supplemental firing (cells left blank due to confidentiality reasons)

D.5 Conceptual model of CHPX 1

In figure D.2 the production process of CHPX 1 is described in a conceptual model.

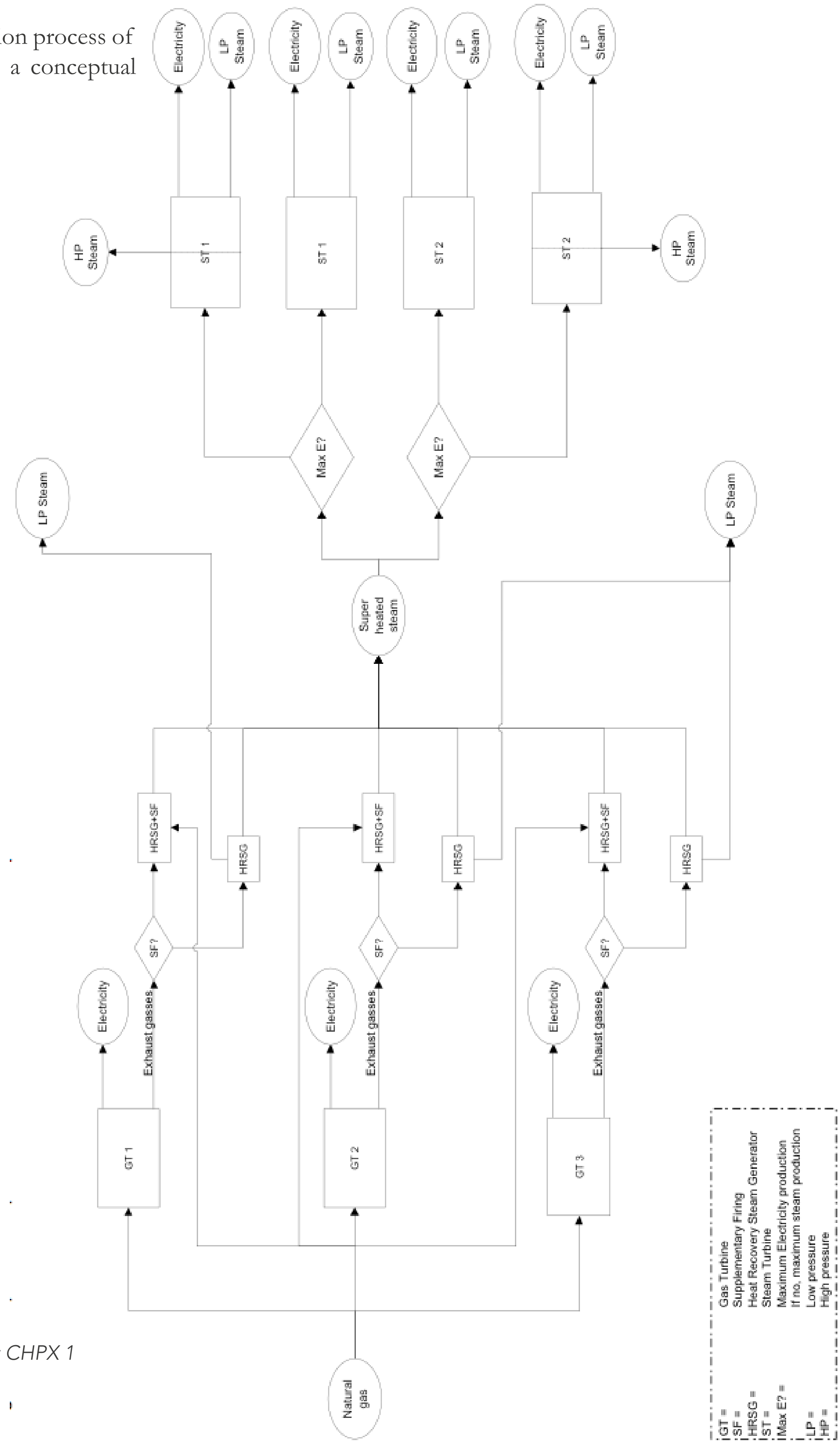


Figure D.2: Production unit CHPX 1

E. Existing and future steam grid site Y

In figure E.1 the steam pipeline that connects BPA to the existing high pressure steam network in site Y. The length of this pipeline should be around 1,6 kilometre. The total investment that has to be made in this connecting BPA to the existing grid is €24 million (no reference attached due to confidentiality reasons).

<figure not attached due to confidentiality reasons>

Figure E.1: Existing steam grid, including steam connection from BPA to existing high pressure steam pipeline.

F. Complementary calculations for model specification

F.1 Steam demand

The amount of thermal power (steam) delivered to the group of small steam consumers is estimated by the application of CHPX for CO2-rights. In order to get the highest amount of CO2-rights possible, CHPX claimed the highest accumulated amount of thermal power supplied by CHPX 1 and 2. The period over which CHPX did its calculations is from 2005-2008.

<calculation not included due to confidentiality reasons>

From the calculation it was derived that w ton/hour is the average steam demand in site Y.

F.2 Boiler start-up costs calculations

Both boilers have start-up costs. For a bio boiler it is not desirable to operate at a flexible operation. Furthermore start-up costs are very high for these boilers. The start-up cost for a bio boiler has been estimated on the basis of the start-up costs of the bio boiler in the BPA.

According to System engineer BPA (personal communication, May 1, 2014) the costs for a start-up for the boiler of BPA consist of 40 ton oil, 70 ton sand and 250 cubic meters of demi water.

Start-up costs of bio boiler

40	Ton oil			
114	$/barrel			
1	barrel	=	0,14	ton oil equivalent
7	barrel	=	1	toe
286	barrel	=	40	toe
32.571	$/40 toe			
23.500	€/40 toe			
70	Ton sand			
15	€/ton			
1.015	€ for sand/start-up			
250	m3 demi water			
3	£/m3			
625	£/start-up			
760	€/start-up			

Total amount for a start-up

25.275	€/start-up

F.3 Start-up costs gas turbine CHPX 1

The start-up costs per gas turbine of CHPX 1 have been calculated on the basis of the start-up costs of a similar unit. This was based on a project that ECA was closely involved in. The start-up costs for the other unit were known and were used to calculate the start-up costs per start-up of a gas turbine of CHPX 1 according to the size of CHPX 1. The data that are used for the calculation have been provided by Investment analyst BPA (personal communication, May 28, 2014) who was the involved from ECA.

Start-up costs gas turbines CHPX 1	Unit	Example plant	CHPX 1
Fuel capacity per gas turbine	MWf	-	-
Natural gas needed for start-up	MWf	-	-
Natural gas price	€/MWh	-	-
		-	-
Inspection cost	€/EOH*	-	-
Cost of start-up	EOH*/start-up	-	-
		-	-
*EOH= Equivalent Operating Hours			
Imbalance risk		-	-
Total	€/start-up	-	-

Table F.1: Start-up costs per gas turbine of CHPX 1 (cells left blank due to confidentiality reasons)

The concept of equivalent operating hours is recommended for determining gas turbine maintenance and repair frequency as well as for its lifetime predicting. Maintenance operations must be performed on the gas turbine at regular intervals. It is the function of maintenance to detect and influence deterioration of the turbine and to repair it. Often starting up and ramping down puts extra pressure on the turbine and will therefore enhance deterioration of the turbine. Therefore EOH are included in the calculation of start-up costs.

Imbalance costs are caused by the difference between the predicted and the actual amount of electricity produced. To cope with this difference, the grid manager has to correct this, which costs money. Furthermore if CHPX 1 ramps down and shuts down any of its gas turbines, this also influences the electricity production of the plant. This causes an electricity imbalance on the electricity net, for which CHPX will be held accountable. This cost also has to be taken into account with start-ups.

G. Description of optimization problem

G.1 Visual representation of optimization problem

To start off a visual representation of the system will be given in order to explain the working of the system. In this representation the decision variables are shown per process in the system. Rectangles show processes in the system. If a decision variable applies to a certain process, the decision variable can be found above the rectangle (representing the process) on the right side. On the basis of the visual representation the optimization problem will be discussed.

It is important to notice that biomass plant A is not included in the optimization description. Reason for this is that in earlier stage it was determined that independent of the alternative BPA operates, it will always operate at maximum capacity. Therefore no decision variables apply to this plant, since operation is always at 100% of its capacity. If no decision variables apply to a process, its output can be considered as constant. However in a later stage, in the calculations of the system profits, BPA costs and revenues will be taken into account. Since BPA is not included in the optimization description, only three steam production units will be taken into account. These are: CHPX 1, a gas boiler and a bio boiler.

In figure G.1, two model parameters are being marked in red. Reason for this is that those parameters represent the steam demand in the system. The purpose of the steam production system in site Y is to meet steam demand at all times. Therefore those two model parameters are accentuated in order to clarify the main priority in the system.

Lastly it is important to notice that every figure forms the basis for the subsequent figure. In figure G.1 the process of CHPX 1 is delineated, which means that this process will be looked into in more detail. Secondly in figure G.2 the process of a steam turbine is delineated, which means that it will be looked into in more detail in figure G.3.

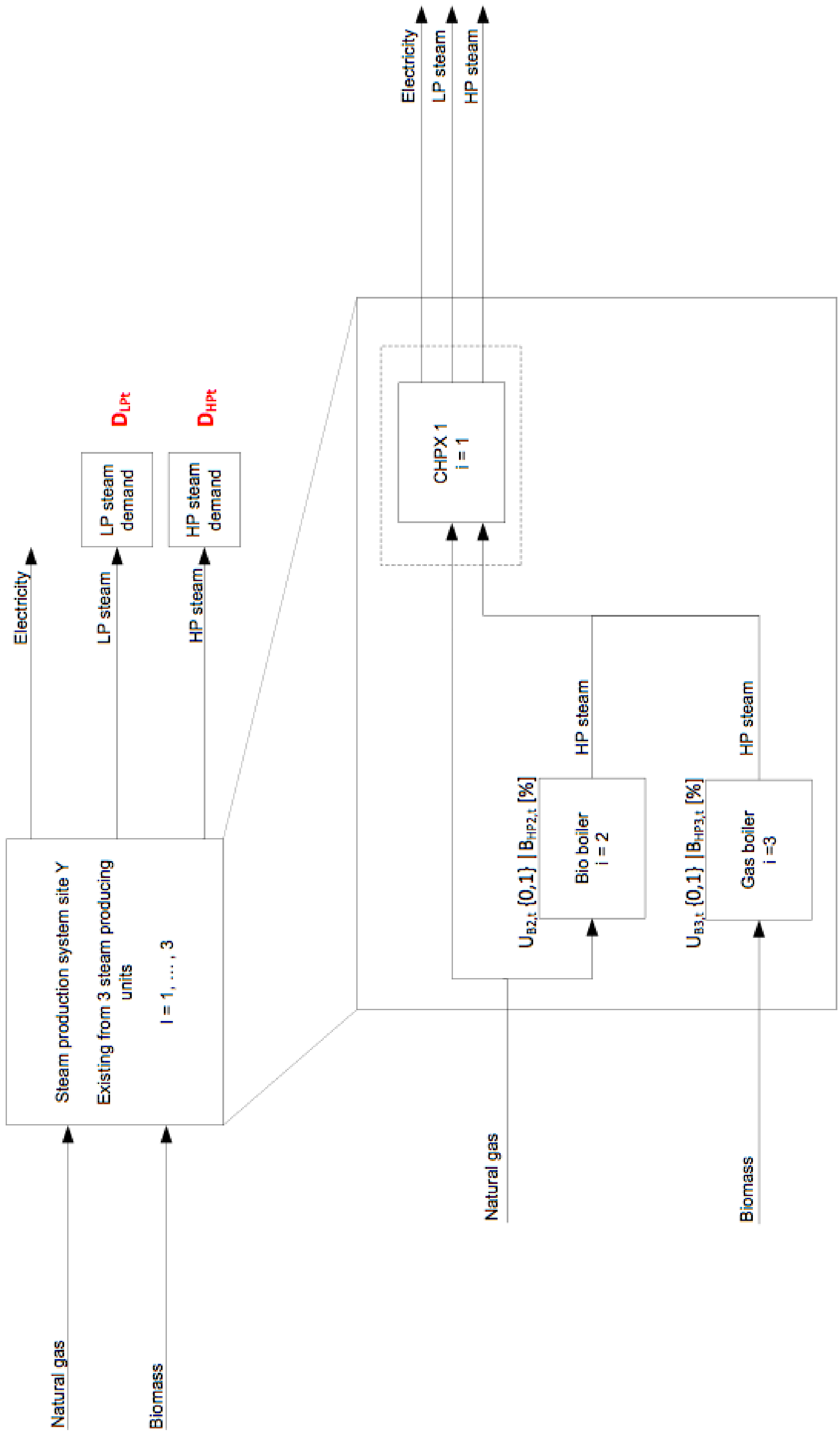


Figure G.1: System overview with decision variables

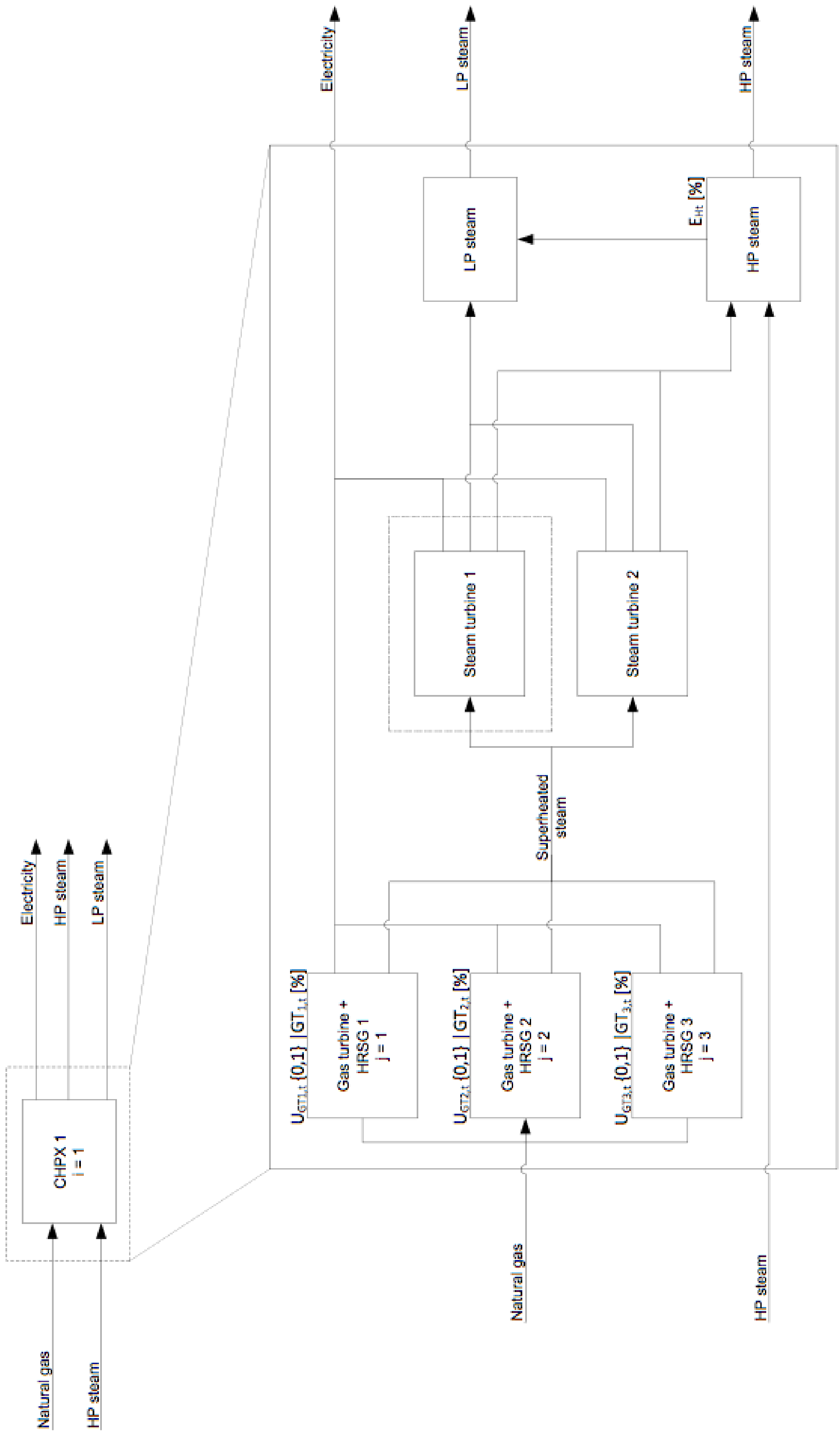


Figure G.2: Overview of production process CHPX 1 with decision variables

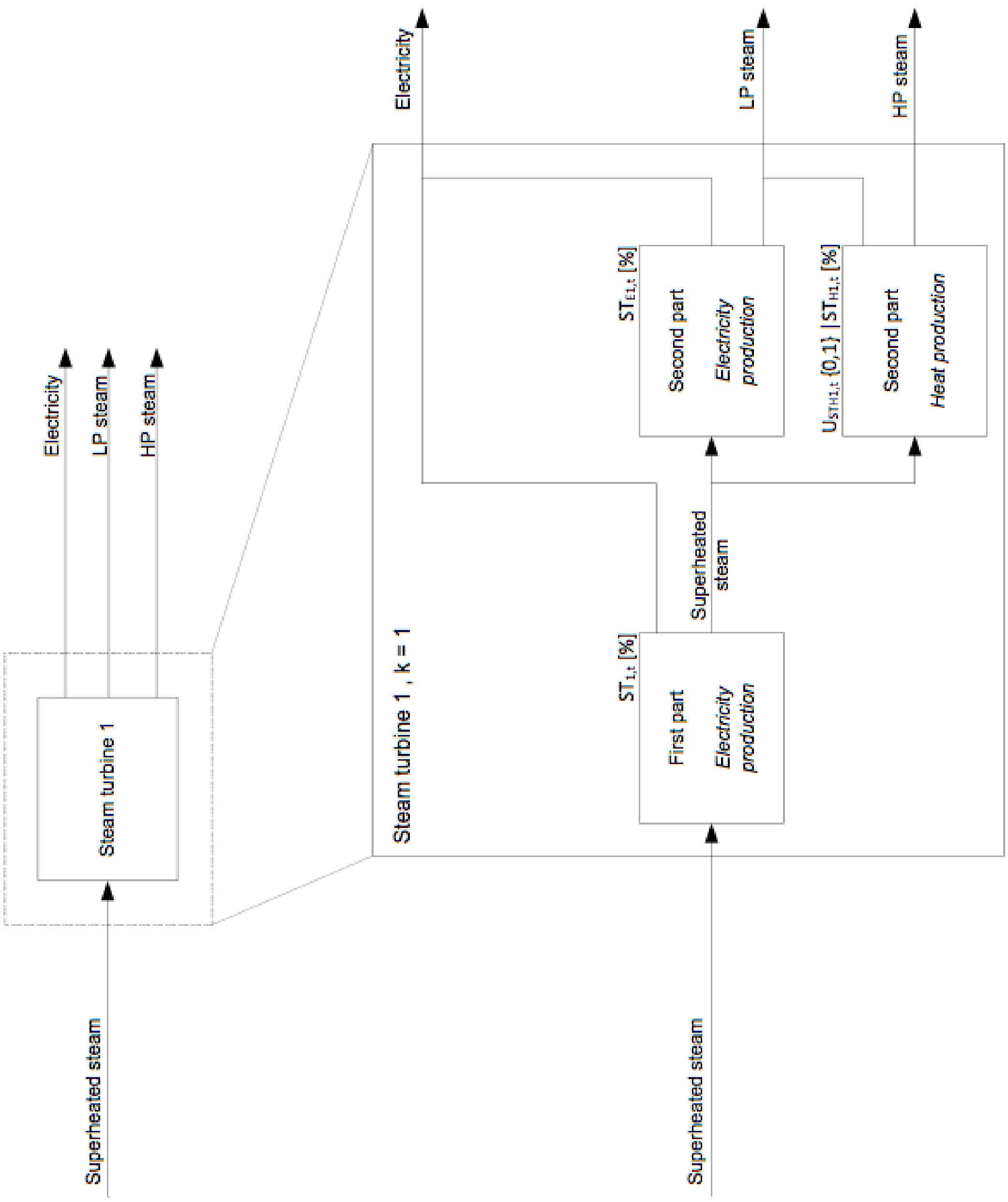


Figure G.3: Overview of steam turbine process with decision variables

G.2 Decision variables

The first step in defining the optimization problem is determining the decision variables. Decision variables are the variables that can be varied to obtain the optimal outcome from the optimization function. Inputs of the system are resource- and electricity prices. Based on those prices, a decision is made about what steam production unit should be operated to meet the steam demand. Since the prices vary, different steam production units become cheaper or more expensive compared to other steam production units.

Specification of decision variables

$i = 1, \dots, 3$

$\forall i = 1$

E_{Ht}	High pressure steam export level during time period t	[%]

$\forall j = 1, \dots, 3$

$GT_{j,t}$	Power generating level of gas turbine *j* during time period t	[%]
$U_{GTt} \in \{0,1\}$	Every boiler or steam turbine *j* can be either on line [1] or offline [0] during time period *t*.	

$\forall k = 1,2$

$ST_{k,t}$	The power generating level of steam turbine *k* during time period t	[%]
$ST_{Ek,t}$	Extra power generating level of steam turbine *k* during time period t	[%]
$ST_{Hk,t}$	High pressure steam generating level of steam turbine *k* during time period t	[%]
$U_{STHk,t} \in \{0,1\}$	Every boiler or steam turbine *j* can be either on line [1] or offline [0] during time period *t*.	

$\forall i = 2,3$

$B_{i,t}$	High pressure steam generating level of generating unit *i* at time t	[%]
$U_{Bi,t} \in \{0,1\}$	Every boiler or steam turbine *j* can be either on line [1] or offline [0] during time period *t*.	

G.3 Model parameters

Secondly the model parameters are defined to describe the optimization problem. The model parameters are given in the system, which means that they cannot change during optimization. The model parameters will be described below:

$\forall i = 1, \dots, 3$

V_{NGt}	Price of natural gas during time *t*	[€/MWh]
V_{BMt}	Price of biomass during time *t*	[€/MWh]
V_{Et}	Electricity price during time *t*	[€/MWh]
C^{HU}	Constant heat up costs to heat up steam pipeline	[€]
D_{HPt}	High pressure steam demand during time t	[MWh]
D_{LPt}	Low pressure steam demand during time t	[MWh]

$\forall i = 1$

Q_{Gt}	Natural gas consumption gas turbine at maximum capacity	[MWh]
$GT^{\max E}$	Power capacity gas turbine	[MWh]
C_{GT}^{SU}	Constant start-up cost gas turbine	[€]
C_{GT}^{O}	Constant operational cost gas turbine	[€]
$ST^{\max E}$	Power capacity of first part steam turbine	[MWh]
$ST_{H}^{\max LP}$	Low pressure steam capacity of heat production process steam turbine	[MWh]
$ST_{H}^{\max HP}$	High pressure steam capacity of heat production process steam turbine	[MWh]
$ST_{E}^{\max LP}$	Low pressure steam capacity of electricity production process steam turbine	[MWh]
$ST_{E}^{\max E}$	Power capacity of electricity production process steam turbine	[MWh]

$\forall i = 2,3$

Q_{Bi}	Input needed for boiler i at maximum capacity	[MWh]
C_{i}^{SU}	Constant start-up cost for boiler i	[€]
$B_{i}^{\max HP}$	High pressure steam capacity boiler i	[MWh]

G.4 System model equation description

To be able to calculate the desired information described in section 5.1.6, there are two important outcomes needed from the model. The first one is the total system production profit ($P_{T\,t}$) from steam production during time t. This means production profits of every individual production are unit added up. This calculation is represented under (1). Secondly the individual profits from the production of steam are calculated under (2). These calculations are needed for equation 1. Subsequently it will be explained how the equations are derived.

$$P_{Tt} = P_{1,t} + P_{2,t} + P_{3,t} \tag{1}$$

$$P_{1,t} = -C_{R1,t} - C_{1,t}^{SU} - C_{1,t}^{HU} - C_{1,t}^{O} + R_{Et} \tag{2}$$

$$P_{2,t} = -C_{R2,t} - C_{2,t}^{SU} - C_{2,t}^{HU}$$

$$P_{3,t} = -C_{R3,t} - C_{3,t}^{SU} - C_{3,t}^{HU}$$

The profits per steam production unit ($P_{i,\,t}$) are constructed from a number of costs and revenues. Firstly equations 3 show the cost of resources for the production process of every steam production unit during time t ($C_{R\,i\,,\,t}$). It is determined by the generating level of each generating part of a production unit that needs a resource (natural gas or biomass) for its process (($G_{j,\,t}$),($B_{i,\,t}$)) multiplied by the amount of resource needed at maximum load of that particular process (($Q_{G\,t}$),($Q_{B\,i}$)) and the price for the needed resource for the particular process during time t (($V_{BM\,t}$),($V_{NG\,t}$)).

Secondly in equations 4 the start-up costs during time t for every production unit ($C_{i,t}^{SU}$) are shown. If a generating unit has been shut down, start-up costs have to be paid to turn it on again. Start-up costs during time t depend on whether a generating unit was turned on in time period t-1 (($U_{GTj,t-1}$),($U_{Bi,t-1}$)). If it was on [1] during time t-1, then no start-up costs have to be paid. If it was off [0] during time t-1, start-up costs for the particular generating unit ((C_{GT}^{SU}), ($C_{B\,i}^{SU}$)) have to be paid at time t.

A similar calculation can be done for heat up costs of the high pressure steam pipeline ($C_{Si,t}^{HU}$) that connects steam production unit i to the steam grid. If production unit i produced high pressure steam during time t-1 (($U_{STH\,t-1}$),($U_{Bi,t-1}$)), no heat up costs have to be paid. However if production unit i was off line during time t-1, heat up costs (C^{HU}) have to be paid. Heat up costs to heat up a steam connection are the same for every steam production unit.

Operational costs ($C_{1,t}^{O}$) only apply to steam production unit i=1. For the other steam production units operational costs are be assumed to be zero. The operational costs for CHPX 1 will be calculated by multiplying constant hourly operational costs for a gas turbine (C_{GT}^{O}) with the operational status of every gas turbine ($U_{GTj,t}$) during time t. As can be derived from figure G.1 electricity revenues only apply to steam production unit i=1. Electricity revenues (R_{Et}) are calculated by the price of electricity at time t (V_{Et}) multiplied with the amount of electricity produced by CHPX 1 during time t. Electricity production during time t is calculated by the maximum electricity generating capacity every electricity generating process of CHPX 1 ($GT^{max\,E}$, $ST^{max\,E}$, $ST_{E}^{max\,E}$) multiplied with the generating level of every electricity generating process of CHPX 1 during time t ($GT_{j,t}$, $ST_{k,t}$, $ST_{Ek,t}$).

Model equations

Resource cost calculations per production unit:

$$C_{R1,t} = \sum_{j=1}^{3} GT_{j,t} \cdot Q_{GT} \cdot V_{NGt} \qquad (3)$$

$$C_{R2,t} = B_{2,t} \cdot Q_{B2} \cdot V_{NGt}$$

$$C_{R3,t} = B_{3,t} \cdot Q_{B3} \cdot V_{BMt}$$

Start-up cost calculations per production unit:

$$C_{1,t}^{SU} = \sum_{j=1}^{3} 0{,}5 \cdot C_{GT}^{SU} \cdot \left(\left(U_{GTj,t} - U_{GTj,t-1} \right) + \left(U_{GTj,t} - U_{GTj,t-1} \right)^2 \right) \qquad (4)$$

$$C_{2,t}^{SU} = 0{,}5 \cdot C_{B2}^{SU} \cdot \left(\left(U_{B2,t} - U_{B2,t-1} \right) + \left(U_{B2,t} - U_{B2,t-1} \right)^2 \right)$$

$$C_{3,t}^{SU} = 0{,}5 \cdot C_{B3}^{SU} \cdot \left(\left(U_{B3,t} - U_{B3,t-1} \right) + \left(U_{B3,t} - U_{B3,t-1} \right)^2 \right)$$

Heat-up cost calculations per production unit:

$$\sum_{k=1}^{2} U_{STHk,t} \geq 1 => U_{STH,t} = 1 \tag{5}$$

$$\sum_{k=1}^{2} U_{STHk,t-1} \geq 1 => U_{STH,t-1} = 1$$

$$C_{1,t}^{HU} = 0{,}5 \cdot C^{HU} \cdot \left((U_{STH,t} - U_{STH,t-1}) + (U_{STH,t} - U_{STH,t-1})^2 \right)$$

$$C_{2,t}^{HU} = 0{,}5 \cdot C^{HU} \cdot \left((U_{B2,t} - U_{B2,t-1}) + (U_{B2,t} - U_{B2,t-1})^2 \right)$$

$$C_{3,t}^{HU} = 0{,}5 \cdot C^{HU} \cdot \left((U_{B3,t} - U_{B3,t-1}) + (U_{B3,t} - U_{B3,t-1})^2 \right)$$

Operational cost calculations for production unit i = 1:

$$C_{1,t}^{O} = \sum_{j=1}^{3} C_{GT}^{O} \cdot U_{GTj,t} \tag{6}$$

Electricity revenue calculations for production unit i = 1:

$$R_{E1,t} = V_{Et} \cdot \left(\sum_{j=1}^{3} (GT_{j,t} \cdot GT^{\max E}) + \sum_{k=1}^{2} (ST_{k,t} \cdot ST^{\max E} + ST_{Ek,t} \cdot ST_{E}^{\max E}) \right) \tag{7}$$

The production profits will be calculated for every steam production that is represented in a model option. If a steam production unit is not present in a certain model option, its production profits will not be taken into account in the calculation of the total system profits for steam production. Equation 1 will be calculated for every model option, given the same set of model parameters.

As explained in section 5.1.4, optimization will be done for 1 day over a period of a year. This means that the optimal production operation will be sought for every 24 hours. Because resource and electricity prices change on a seasonal basis, the results are sought for every day in a year. In order to get a continuing optimization per day during a year, a rolling horizon approach is used. This means that the conditions of time t=24 are used as starting conditions for time t=25.

G.5 Objective function

The objective function consists of costs and revenues per production unit bounded by constraints in the system. The decision variables consist of turning on or off a part of a steam production unit and the generating load of generating parts of the steam production units. The index 't' in the summation in the optimization function is the number of hours per day. The years that are simulated reach from 1/1/2017 until 31/12/2017 and from 1/1/2025 until 31/12/2025. The objective function represents the maximum system profits that can be derived from a certain composition of steam production units. Therefore this function will be used for every model option.

The objective function is as follows:

$$MAX \sum_{t=1}^{24} P_{Tt} \tag{8}$$

Profits for individual steam production units calculated in the objective function depend on the model option. In every model option a different combination of steam production units is being considered. The highest value of the objective function is the optimal outcome.

G.6 Constraints

Besides the optimization function and decision variables, another very important aspect of an optimization problem is defining constraints of the system. The constraints are values that bound parts of the system. All constraints of the system form a space in which the optimal solution should be located. This space is called the feasible region. Values in this feasible region satisfy all constraints of the system. Below constraints for the model will be described:

$\forall i = 1, \dots, 3$

$$\left(ST_{Hk,t}\, ST_{H}^{\max HP} + \sum_{i=2}^{3} B_{i,t}\ B_{i}^{\max HP}\right) \cdot E_{Ht} = D_{HPt}$$

The high pressure steam demand should be met exactly by the steam production system during every time t;

$$\left(ST_{Hk,t}\, ST_{H}^{\max LP} + ST_{Ek,t}\, ST_{E}^{\max LP}\right) + \left(\left(ST_{Hk,t}\, ST_{H}^{\max HP} + \sum_{i=2}^{3} B_{i,t}\ B_{i}^{\max HP}\right) \cdot (1 - E_{Ht})\right) \geq D_{LPt}$$

The low pressure steam demand should be met by the steam production system during every time t.

$\forall i = 1$

$10 \leq GT_{j,t} \leq 100$	The production level of gas turbine j during time t cannot exceed its minimum and maximum level;
$50 \leq ST_{k,t} \leq 100$	The production level of the first part process of steam turbine *k* during time *t* cannot exceed its minimum and maximum level;
$0 \leq ST_{Hk,t} \leq 100$	The production level of the high pressure steam production process of steam turbine *k* during time *t* cannot exceed its minimum and maximum level;
$0 \leq ST_{Ek,t} \leq 100$	The production level of the electricity production process of steam turbine *k* during time *t* cannot exceed its minimum and maximum output;
$\sum_{k=1}^{2} ST_{k,t} = \frac{2}{3} \sum_{j=1}^{3} GT_{j,t}$	The production level of the first part of both steam turbines depends on the production level of the three gas turbines;
$ST_{k,t} = ST_{Ek,t} + ST_{Hk,t}$	The sum of the level of the high pressure steam production and the level electricity production process of steam turbine *k* matches the level of the first part process of steam turbine *k*;
$\sum_{j=1}^{3} U_{GTj,t} = 0 => \sum_{k=1}^{2} U_{STk,t} = 0$	If no gas boilers are turned on during time t [0], then no steam turbines *k* can be turned on [1] during time t;
$\sum_{j=1}^{3} U_{GTj,t} \geq 1 => \sum_{k=1}^{2} U_{STk,t} \geq 1$	If any of the gas boilers *j* is turned on [1] during time t, then any of the steam turbines *k* have to be turned on [1] during time t.

$\forall i = 2, 3$

$0 \leq B_{i,t} \leq 100$	The production level of generating unit *i* during time *t* cannot exceed its minimum and maximum production level.

H. Validation test results

In the operational validation the model is tested on its behaviour. Firstly it will be checked whether model option 0 behaves as is expected from the current situation. Next a test will be done to check whether the model behaves the way it is expected to behave in an extreme value analysis. In this analysis extreme input variables will be used to view how the system behaves under these values. For example a very high cost price of a resource is used as input for the model. The expectation is then that a production unit will only want to meet its constraints and after that produce at the lowest load to keep its production costs at the lowest rate. Thirdly in section 3 of this appendix a sensitivity analysis will be done. This is to check what constraints are critical in the model and to see whether slight changes in these constraints would heavily influence the system outcomes. If this is the case, the assumptions on which those constraints are based should be reviewed very carefully. Furthermore system outcomes should be considered according to assumptions on those constraints. Lastly on the basis of the scenario results a validation will be done. Scenarios show varieties in resource and electricity prices as well as demand. Due to the composition of various developments, the scenario results are expected to vary in a certain direction. It will be checked whether the results match the expectations.

H.1 Comparison to current situation

Current situation (option 0):

- The BPA produces electricity at maximum capacity.
- CHPX 1 operates only two gas turbines (no reference included due to confidentiality reasons) since electricity prices are low and natural gas prices are high, therefore it is not expected that CHPX 1 would want to produce at maximum capacity. It will only want to satisfy the steam demand.

The model outcomes satisfy the expectations drawn from the current situation. However this test does not say much yet, since the model constraint is that ECA BPA should be operating at 100%. Therefore the only conclusion that can be drawn from this test is that the range of steam demand is sufficient, since it corresponds to the real world data

H.2 Extreme value analysis

The extreme value analysis should be done on an option in which two SPU's are operational that can fluctuate on the basis fluctuating inputs. Only in those options it is possible to see how the model reacts to various inputs.

Extremely high and low biomass price
The first test was done with model 12. A very high and a very low biomass price were used to see whether the bio boiler or CHPX 1 would be supplying steam in the site Y. As can be seen in figure H.1 at the point that the biomass price decreased drastically, the bio boiler became fully responsible to meet the full steam demand in site Y. However before, at a very low biomass price, CHPX 1 produced steam to meet the steam demand.

Model option 12:

- Biomass boiler
- CHPX 1
- First period (0-84) biomass price of 5 €/ton
- Second period (85-168) biomass price of 1000 €/ton

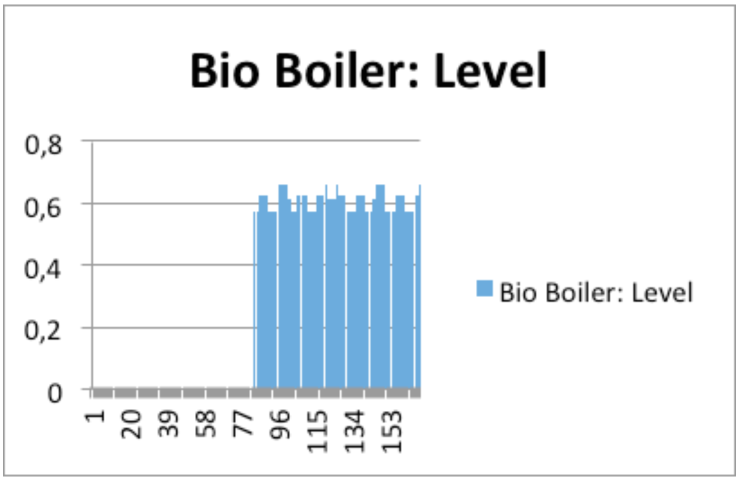


Figure H.1: Production of the bio boiler at very high and very low biomass price

Extremely low and high natural gas price
The second test was done with model 12 as well. Extreme natural gas prices were used to see whether the bio boiler or CHPX 1 would be supplying steam in the site Y. As can be seen in figure H.4 at the point that the natural gas price was very low, CHPX 1 became fully responsible to meet the full steam demand in site Y. However at a very high natural gas price the bio boiler produced steam to meet the steam demand in site Y. Also it can be viewed in figure H.2 and H.4 that at a very low electricity price in time steps 7 and 8, a drop in production by CHPX 1 appeared.

Model option 12

First period (0-84) natural gas price of 2 €/ton
Second period (85-168) biomass price of 1000 €/ton

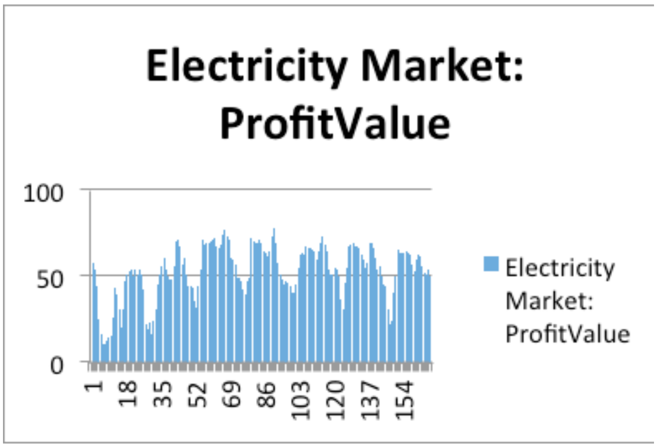


Figure H.2: Input electricity price

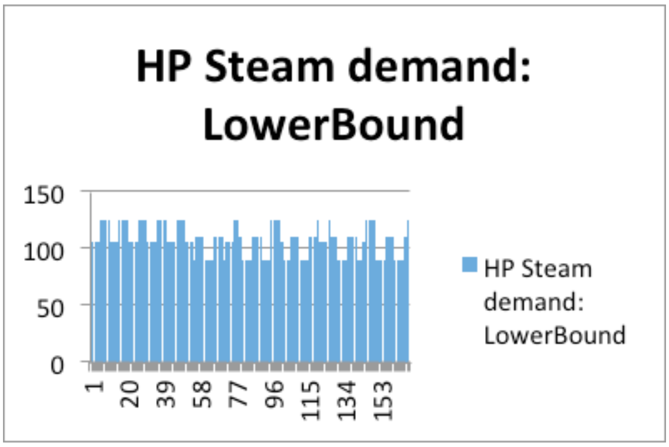


Figure H.3: Input high pressure steam demand

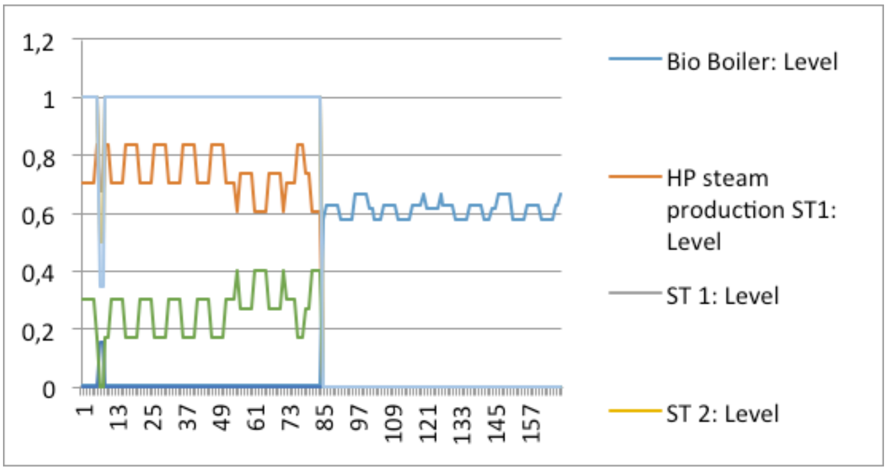


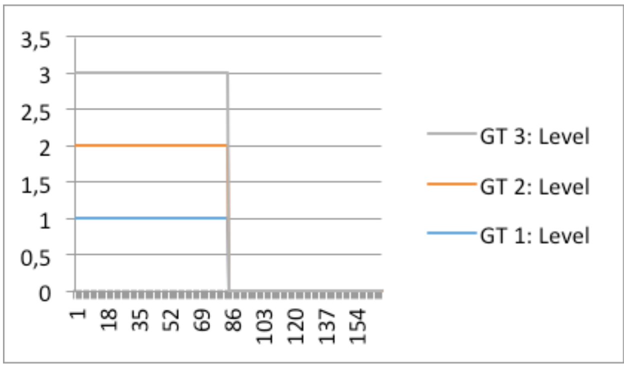
Figure H.4: Output production decision between bio boiler and CHPX 1 at varying natural gas price

Extremely low and high electricity price

The third and final test was done with model option 9. Extreme natural gas prices were used to see whether the gas boiler or CHPX 1 would be supplying steam in the site Y. As can be seen in figure H.5 at the point that the natural gas price was very low, CHPX 1 became fully responsible to meet the full steam demand in site Y. However at a very high natural gas price the gas boiler produced steam to meet the steam demand in site Y.

Model option 9:

Solo electricity production by BPA
Steam production by CHPX 1 and a gas boiler
First period (0-84) electricity price of 1000 €/MWh
Second period (85-168) electricity price of 2 €/MWh



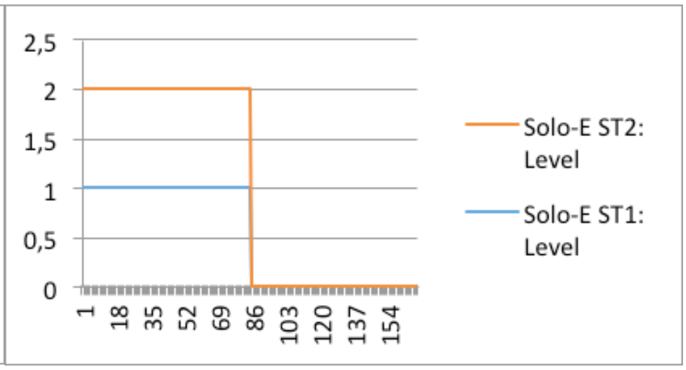


Figure H.5 (left): Output production level gas turbines 1,2 and 3 of CHPX 1
Figure H.6 (right): Output production level maximum electricity production of steam turbines 1 and 2 of CHPX 1

From figures H.5 and H.6 it is possible to derive that when the electricity price is very high, CHPX 1 is operated to produce as much electricity as possible. The gas boiler is then used to meet the residual steam demand. Furthermore when the electricity price changes and gets very low, the gas boiler is operated to meet the entire steam demand in site Y and CHPX 1 is shut down.

In all three tests with different variables, the model behaves exactly as expected. Therefore the model has passed the extreme value test.

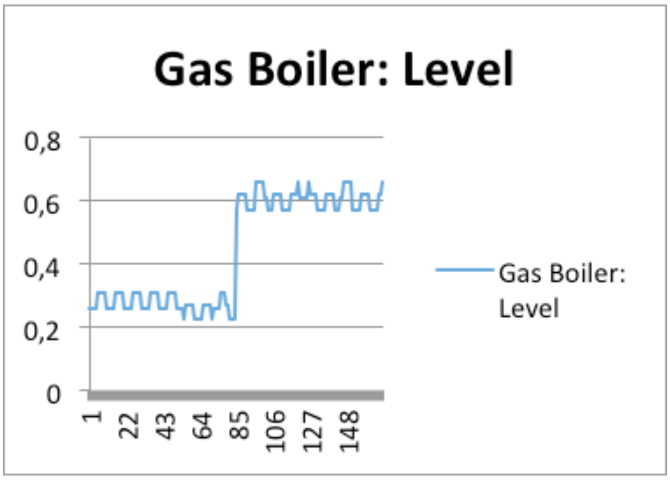


Figure H.7: Output production level of gas boiler

G.2 Sensitivity analysis

A sensitivity analysis will be done to check what constraints are critical in the model and to see whether slight changes in these constraints would heavily influence the system outcomes. Below all constraints will be considered and individually judged on its bounds on the model behaviour and outcomes.

The high pressure steam production of all SPUs "i" should meet the total high pressure steam demand;

- ➢ This constraint only affects CHPX 1, since with a significantly lower steam demand it could be operated with only 1 gas turbine. With a significantly higher steam demand is has to be operated with 3 gas turbines. It is known that CHPX 1 only operates 2 gas turbines at the moment. It is also known that if one of those gas turbines fails, not enough high pressure steam will be produced to meet the demand in site Y.
- ➢ The high pressure steam constraint only changes model outcomes if it changes the decision for CHPX 1 how many gas turbines it should operate.
- ➢ Therefore it is shown in a model with significantly lower steam demand that addition of BPA steam production to the system would lead to significant system cost decrease.

The low pressure steam production of all SPU "i" should at least meet the total low pressure steam demand;

- ➢ This constraint especially influences CHPX 1. However an adjustment of 10% higher and lower does not change model behaviour. It does change model outcomes.
- ➢ If the low pressure steam demand in- or decreases by 10% no significant changes in model behaviour and outcomes appear.
- ➢ This constraint is obtained from an interview with the development manager BPA. Since CHPX is a joint venture of PCX and Energy Company B, it is assumed that PCX and CHPX closely cooperate. Therefore if the low pressure steam demand of PCX would threshold the steam production of CHPX to operate an extra gas turbine, PCX would lower its low pressure steam demand. Therefore it is expected that the low pressure steam demand as estimated approaches the real demand.

The load of gas turbines j' cannot be lower than 10% and not higher than 100%;

- ➢ With slight changes in the lower bound of the gas turbines, no large model outcome and behaviour occur. Reason for this is that the process is mainly bound by the minimum loads of the steam turbines. To meet those demands, gas turbine should be operating at a higher load than 10% anyway, so therefore this constraint is never a driving constraint.

The load of steam turbine k cannot be lower than 50% and not higher than 100%;

- ➢ This is one of the most limiting constraints in the system. Any change in this constraint has an effect on the model outcomes. However slight changes do not have a large impact on the model behaviour.
- ➢ From an interview with Manager facilities with expertise on CHPs and System Engineer BPA (personal communication, June 26, 2014) it has become clear that it is not possible to produce high pressure steam with a steam turbine if it operates below 50% of maximum capacity.

The boiler load of a gas boiler cannot be lower than 0% and not higher than 100%;
The boiler load of a bio boiler cannot be lower than 0% and not higher than 100%;

- ➢ Both boilers can operate between 0 and 100%. In reality for one bio boiler a minimum of 70% is maintained to keep the steam produced at desired conditions. For a gas boiler this percentage is considerably lower, only 25%. However for this model, it is assumed that not one very large boiler will be built, but multiple smaller one. Reason for this is redundancy in the system.
- ➢ In the optimization model both boiler have been modelled as one boiler. However since large redundancy between multiple smaller units is assumed, a minimum of 0% is applied in the model.
- ➢ The minimum of 0% is rarely approached in solutions.

H.3 Scenario analysis

The scenario analysis is similar to the extreme value analysis, however in this test the scenario results are used to validate whether the model behaves as can be expected from the scenarios. For example if in a particular scenario the natural gas price is high and the electricity price is low, this would mean that CHPX 1 would have higher operating costs. Therefore this plant should either be run to a minimum, or the production costs for CHPX 1 and thus the total system costs in that particular model option should rise significantly.

Firstly below the scenario table is shown to be able to view the different scenarios and couple them to the results. Secondly the model results per scenario are shown in the next table. Then the results are analysed according to the scenarios.

	ELECTRICITY PRICE		BIOMASS PRICE		GAS PRICE		STEAM DEMAND	
SCENARIO	low	high	low	high	low	high	low	high
	-15%	+15%	-10%	+20%	-15%	+15%	-25%	+25%
1	✓			✓	✓			✓
2		✓	✓			✓	✓	
3	✓			✓		✓	✓	
4		✓	✓		✓			✓

Table H.1: Scenarios

Comparison scenarios on system profits (in million €)													
	Options												
	0	1	2	3	4	5	6	7	8	9	10	11	12
S1	-9,7	-9,1	-8,1	-11,6	-10,0	-9,8	-10,1	-9,1	-8,9	-10,6	-9,6	-8,9	-14,0
S2	-7,2	-6,2	-5,4	-9,4	-5,2	-5,1	-4,6	-3,6	-3,0	-8,0	-5,7	-5,4	-5,4
S3	-8,9	-8,2	-7,6	-9,4	-6,2	-6,3	-6,1	-5,0	-4,9	-12,0	-7,8	-7,6	-6,4
S4	-6,9	-6,5	-5,1	-11,6	-9,0	-8,7	-7,6	-6,6	-6,1	-7,3	-6,3	-5,5	-11,6

Table H.2: Model results based on scenarios

Option 0

RANK	EXPECTATION	RESULT	EXPLANATION
1	S4	S4	
2	S2	S2	
3	S1	S3	The steam demand in S3 is low, which gives a better result.
4	S3	S1	

Table H.3: Option 0 result expectations based on scenarios

In option 0 only CHPX 1 is operational. From the table can be seen that in scenarios 1 and 3 the system profits are lower than in options 2 and 4. Reason for this is that in those option the electricity price is low. However in scenario 1 the natural gas price is low, but the steam demand is high. Therefore the total operating profits are still lower than in scenario 3, in which the gas price is high, but the steam demand is low.

The same holds for scenarios 2 and 4. Both options have a high electricity price, which results in higher steam production profits. However in scenario 2 the gas price is high, which should result in lower production profits than in scenario 4, which has a low natural gas price. But this is compensated, because in scenario 2 the steam demand is low and in option 4 the steam demand is high. Due to this difference, the steam production profits in scenario 2 are higher than the steam production profits in scenario 4.

Option 1

RANK	EXPECTATION	RESULT	EXPLANATION
1	S4	S2	
2	S2	S4	
3	S1	S3	
4	S3	S1	

Table H.4: Option 1 result expectations based on scenarios

For option 1 the same applies as for option 0. However in this option also the biomass plays a role. Therefore it is expected that scenarios 2 and 4 score even better compared to scenario 1 and 3 than for option 0. This can indeed be viewed in the table.

Option 2

RANK	EXPECTATION	RESULT	EXPLANATION
1	S4	S4	
2	S2	S2	
3	S1	S3	
4	S3	S1	

Table H.5: Option 2 result expectations based on scenarios

The reason why a difference appears for option 2 compared to option 1 is that in option 2, the BPA produces more electricity. In scenario table H.1 it can be viewed that the electricity prices increases by 15%, but the biomass price only decreases by 10%. Therefore in this option, the electricity revenues transcend the biomass costs. This results in scenario 4 giving the best results for option 2.

For scenario's 1 and 3 the same holds as for option 1. Even though the natural gas price is high in scenario 4, it does not outweigh the fact that the steam demand is low. Reason for this is that the steam demand decreases by 25% and the natural gas price only increases by 15%.

Option 3

RANK	EXPECTATION	RESULT	EXPLANATION
1	S2 & S3	S2 & S3	
2			
3	S1 & S4	S1 & S4	
4			

Table H.6: Option 3 result expectations based on scenarios

In this option a gas boiler fulfils the entire steam demand. Therefore profit of production is only determined by costs based on steam demand and the natural gas price. In scenarios S1 and S4 the natural gas price is low and the steam demand is high. However the natural gas price got 15% lower and the steam demand 25% higher. Therefore even though the gas price is low, much more steam has to be produced, which results in higher system costs.

Option 4

RANK	EXPECTATION	RESULT	EXPLANATION
1	S4	S2	Low steam demand, which compensates for the high natural gas price, since CHPX 1 does not have to produce much steam anymore.
2	S2	S3	Again a low steam demand. Since the biomass price, even though it is high, is still better than the natural gas price, this results in a good solution.
3	S1	S4	On both scenarios with a high steam demand option 4 performs worst. Of those two scenarios, scenario 4 has better input conditions, such as a low NG price, low biomass price and high electricity price.
4	S3	S1	

Table H.7: Option 4 result expectations based on scenarios

In option 4, the steam demand is most important for the economic performance of this system. If the steam demand is low, the model performs best. Reason for this is that BPA produces the same amount of steam in every scenario. If the steam demand is low, just a little part of the production has to be done by a gas boiler. The gas boiler produces very expensive. Even if the biomass price is high and the NG price is low, BPA still produces cheaper than a gas boiler. Therefore if the steam demand is low, least costs have to be made by the gas boiler.

Option 5

RANK	EXPECTATION	RESULT	EXPLANATION
1	S2	S2	
2	S3	S3	
3	S4	S4	
4	S1	S1	

Table H.8: Option 5 result expectations based on scenarios

Option 5 is expected to perform almost the same as option 4. These options are almost the same, except that in this option BPA produces a little more steam and less electricity.
From the table can be derived that this expectation is correct. Again the steam demand is determinative.

Option 6

RANK	EXPECTATION	RESULT	EXPLANATION
1	S2	S2	
2	S4	S3	Scenario 3 has a low steam demand, which results in lower production costs, even though the biomass price is higher than in scenario 4.
3	S3	S4	
4	S1	S1	

Table H.9: Option 6 result expectations based on scenarios

In option 6, the steam demand is met by only steam production of a bio boiler. Therefore it was expected that scenarios in which the biomass price was low would give the best results. However from the table it can be derived that the steam demand is more determinative for the system performance. This can easily be calculated:
€72 * 1625625 = €117,0 million
€54 * 2709375 = €146,3 million

This is a difference of €29,3 million. Therefore the model calculated it right.

Option 7

RANK	EXPECTATION	RESULT	EXPLANATION
1	S2	S2	
2	S3	S3	
3	S4	S4	
4	S1	S1	

Table H.10: Option 7 result expectations based on scenarios

Due to the results of option 6, it is expected that option 7 will perform better on scenario 3 than on scenario 4, even though scenario 4 has a low biomass price and a high electricity price. Reason for this is again the steam demand. Now it can be calculated if the electricity income compensates the difference calculated for option 6.

In option 7, BPA produces 5,6 MWh of electricity. This amount will be produced every hour, since BPA always produces at maximum capacity. Therefore the hourly high electricity price used in scenario 4 has been multiplied by 5,6 MWh. This resulted in €3,6 million. This is not enough to compensate for the difference of €29,3 that has been calculated in the previous section.

Option 8

RANK	EXPECTATION	RESULT	EXPLANATION
1	S2	S2	
2	S3	S3	
3	S4	S4	
4	S1	S1	

Table H.11: Option 8 result expectations based on scenarios

For option 8 the explanation for the scenario results can be given as for options 6 and 7.

Option 9

RANK	EXPECTATION	RESULT	EXPLANATION
1	S4	S4	
2	S2	S2	
3	S1	S1	
4	S3	S3	

Table H.12: Option 9 result expectations based on scenarios

In option 9 both CHPX 1 and a gas boiler are operational. It was expected that this option would perform well with a low NG price, high electricity price and a low steam demand. However, there are no scenarios in which a low NG price and a low steam demand occur. Therefore the expectation was that it would perform best on the option in which the NG price was low and the electricity price was high, but the steam demand was high too. This is correct. Furthermore the second best scenario was the one in which the steam demand was low and the electricity price was high, but the natural gas price was high. Option 9 performed worst in scenario 3, which has a low steam demand, but a high NG price and a low electricity price.

Option 10

RANK	EXPECTATION	RESULT	EXPLANATION
1	S4	S2	
2	S2	S4	
3	S3	S3	
4	S1	S1	

Table H.13: Option 10 result expectations based on scenarios

In this option three steam production units are operational, which are CHPX 1, a gas boiler and the BPA. This option would perform best under a low NG price, low biomass price, high electricity price and a low steam demand.

However this combination of developments has not been included in the scenarios. Furthermore again in this option, a low steam demand outweighs a high natural gas price.

Option 11

RANK	EXPECTATION	RESULT	EXPLANATION
1	S2	S2	
2	S3	S4	
3	S4	S3	
4	S1	S1	

Table H.14: Option 11 result expectation based on scenarios

For option 11 the same conclusions can be drawn as for option 10. The difference should be that at a high electricity price, the system costs for option 10 should be higher than for option 11, since in option 11 BPA operates the BPST alternative which produces more electricity. This has been checked and this is correct.

Option 12

RANK	EXPECTATION	RESULT	EXPLANATION
1	S2	S2	
2	S3	S3	
3	S4	S4	
4	S1	S1	

Table H.15: Option 12 result expectations based on scenarios

In this option two steam production units are operational, which are CHPX 1 and a bio boiler. This option would perform best under a low NG price, low biomass price, high electricity price and a low steam demand. However, it is expected that a low biomass price would be driving, because then CHPX 1 would not have to be operational. Besides the biomass price, again the steam demand would be driving, because it would be the same calculation as is done for option 6. According to the table, these expectations are correct. The steam demand is more important than the biomass price, since the biomass price only increases with 20% and the steam demand decreases with 25%.

Conclusions of scenario validation

Based on the scenarios it can be concluded that the model gives the right model output. In model options in which the most important production unit runs on natural gas, the driving scenario factor is the steam demand. Even if natural gas prices are low, production on natural gas is still more expensive than on biomass. This shows that if it is expected that the steam demand in site Y will decrease in the upcoming years, it would be very smart of PCX to invest in a bio boiler or a collaboration with ECA, in which BPA will produce steam from biomass.

Furthermore it can be viewed from the scenario validation that under various prices, the model reacts differently. If steam demand is the same in scenarios, the model bases it decision on resource and electricity prices. For example all options should always perform better on scenario 2 than on scenario 3. Reason for this is that scenario 2 holds a low biomass price and a high electricity price, while scenario 3 is the other way around. The NG price and steam demand are the same in those scenarios. This has been checked and was found to be correct. The same can be applied for scenario 1 and 4. All options should perform better on scenario 4 than on scenario 1. The steam demand and natural gas price are the same in both scenarios, but scenario 4 holds a low biomass price and a high electricity price, while scenario 1 is again the other way around. This has also been checked and found to be correct.

I. Simulation model

I.1 Repesentation of simulation model

< figure not included due to confidentiality reasons >

Figure I.1: Simulation model including all possible steam production units in site Y

I.2 Explanation of simulation model

Figure I.1 shows the simulation model in which all possible steam production units are modelled. The simulation model is modelled in Linny-R. In Linny-R there are two types of nodes: products and processes. This was also shown in the conceptual models. A process is denoted with a rectangle. A product is denoted with an ellipse. Products are either the input or the output for/of a process. If this is the case, this relation is to be indicated with an arrow. For every node, the used has to provide information. This information bounds the solution of the optimization runs. Furthermore the information that is used to construct this model can be found in chapter 4.

In the upperpart of the model, CHPX 1 is represented. To understand this model, it would be advised to have a look at the conceptual model that can be found in appendix D. The process that can be viewed in figure I.1 is that CHPX 1 has three gas turbines, which are placed in parallel with three heat recovery steam generators (HRSGs), that are operated with supplemental firing. From the HRSGs an amount of process steam continues to two steam generators. The steam generators can be operated in two ways: 1. For maximum electricity production, or 2. For maximum high pressure steam production. This choice depends on the steam demand and the other steam producers in the system. In the middle part of the model, the gas and the bio boiler are represented. The processes of those production units are simple: resource comes in and steam comes out of the boiler process. Each of the boiler have their own efficiency.
Lastly at the bottom part of the model, ECA BPA is represented with three alternatives. Firstly the circulating fluidized bed (CFB) boiler is shown. Here process steam is produced, which continues towards any of the three alternatives. Only the PRDS and the BPST processes produce steam. The steam turbine (ST) solely produces electricity. The reason that the process of BPA is not modelled similar to the gas and bio boiler is that at a later stage this model can be used to switch between BPA alternatives. If the model will be used for that purpose, it has to be possible in the model to make a choice between either using the process steam that comes from the CFB to operate the BPST (or PRDS) or to direct it through the steam turbine to produce the maximum amount of electricity.

I.3 Model behaviour

Model behaviour should be viewed to better understand the model results. The model simulates optimization behaviour of all steam production units combined. Based on given input variables, a dispatch decision is made.
Optimization can only be done with CHPX 1, a natural gas boiler and a bio boiler. Reason for this is that it is assumed that during all runs BPA will produce at maximum capacity. Therefore no decision about different operation with this plant can be made. In chapter 7, model behaviour of option 9 was presented and analysed. In this section 10 until 12 will be considered.

In the figure below the data series will be shown for one week. Input series will be shown for electricity, biomass and natural gas prices. Based on those given input variables, model behaviour will be shown for option 10 until 12.

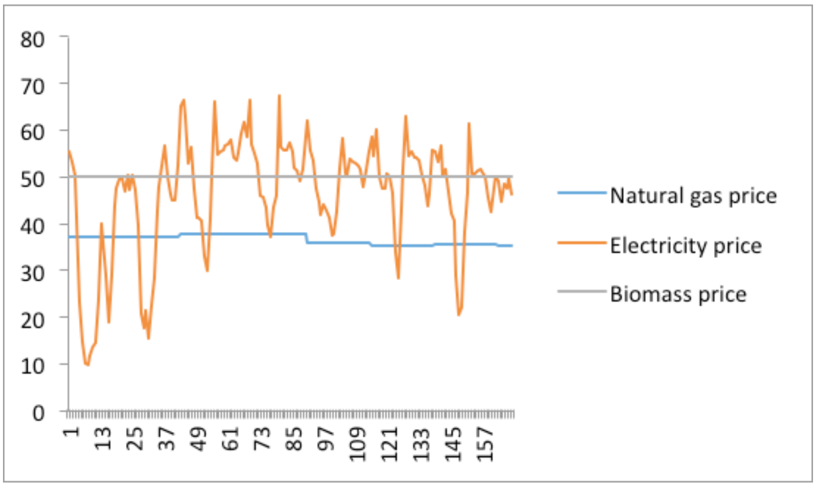


Figure I.2: Given resource and electricity prices for optimization runs

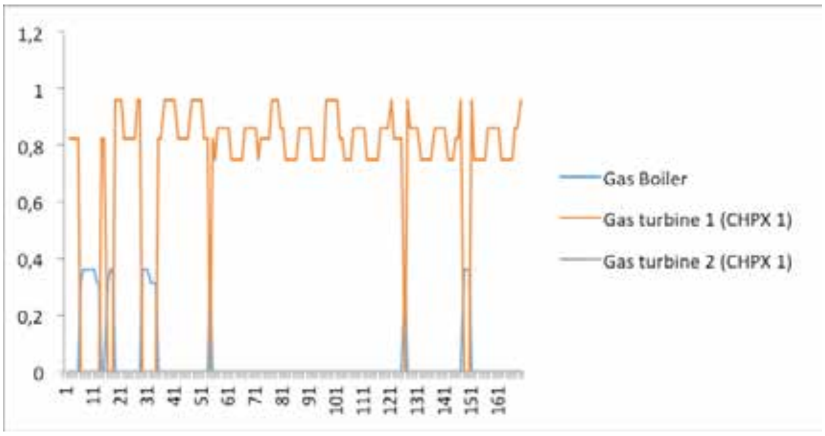


Figure I.3 : Production profile option 10 under given input variables figure I.2

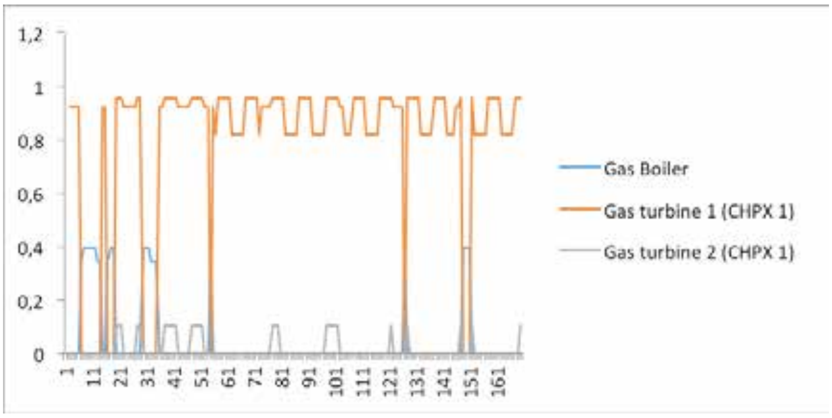


Figure I.4: Production profile option 11 under given input variables figure I.2

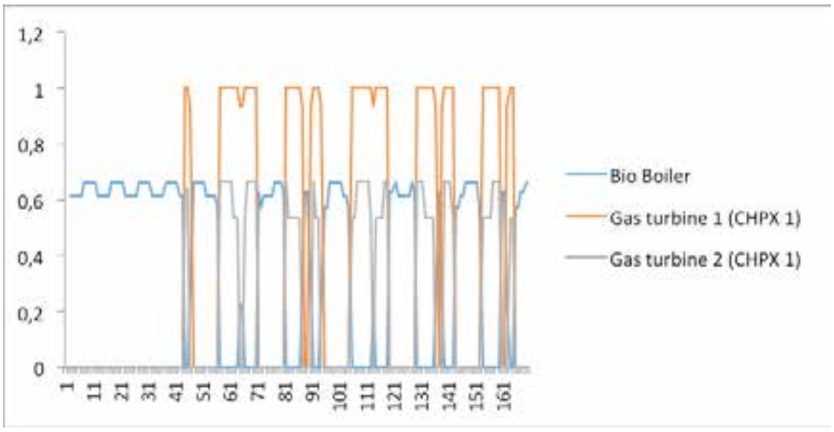


Figure I.5: Production profile option 12 under given input variables figure I.2

For options 10 and 11 the same production profiles can be viewed as for option 9. When the electricity price drops, the gas boiler takes over production from CHPX 1. Reason for this is that the efficiency of a gas boiler is much higher than of a CHP. Therefore if at a certain point the electricity price is too low to make up for the difference in efficiency, the gas boiler produces steam at a lower cost than the CHP.

Option 11 consists from a gas boiler, a bio boiler and the BPST alternative of BPA. Compared to option 10, it can be viewed that option 11 sometimes has to operate its second gas boiler, whereas in option 10 this is not necessary. Reason for this is that in option 10 the PRDS alternative is present. This alternative produces more steam than the BPST alternative. It can be viewed that the BPST alternative produces slightly not enough steam in order to fully shut down the second gas turbine of CHPX 1.

For option 12 a different production profile can be viewed, because now it is the other way around. In the beginning the bio boiler produces steam at the lowest cost. However it can be viewed that if the electricity price reaches over a certain threshold point, steam production of the CHP becomes cheaper. At that point production switches. This behaviour is not how it would work in the real world. Especially for bio boiler, a steady production is wanted for maintenance reasons. Besides, since start-up costs are very high for a bio boiler, switching would only happen for a long time period. However, based on the production profile above, it can be viewed how often any of the two production units would be operational and therefore a choice could be made between both production units.

I.4 Exclusion of start-up and heat-up costs

In model options in which steam demand is met by multiple steam production units that are taken into account in the optimization function, start-up costs play a large role. This is applicable for options 9 (CHPX-GB), 10 (PRDS-CHPX-GB), 11 (BPST-CHPX-GB) and 12 (CHPX-BB).

For every model option, this impact will shortly be discussed:

- Option 9: In 2017, the gas boiler is only switched on for 400 hours of the 8760 hours in a year. Therefore it is not expected that a gas boiler will be built next to CHPX 1. This means that the results are more likely to be like in option 0, which represent the current situation. In this situation the entire steam demand in site Y is met by CHPX 1.
- In 2025, the gas boiler is only switched on for 473 hours per year. Therefore the same conclusion can be drawn as the one for 2017. Likely results can be obtained from option 0 in year 2025.
- Option 10: In 2017, the gas boiler is according to the results of the optimization runs, only switched on for 441 hours of the 8760 in a year. This is only 5% of the time. Therefore it is not expected that if PCX contracts ECA for the production of steam, it will also build a gas boiler for the production of steam itself.

Unless is wants to get rid of CHPX 1, but then the results can be drawn from option 4.

- In 2025 it can be viewed that the gas boiler would only even be on for 256 hours. This is even less than in 2017. Therefore the same conclusions can be drawn.
- Option 11: As expected, this option shows almost the same results as option 10. Since this option includes the same production units, but in this option BPA produces a little less steam. Therefore the gas boiler in switched on a little more hours than in option 10, but it still does not exceed the 5% much. Therefore results of option 5 are more likely to appear.
- Option 12: In 2017, it can be viewed that the bio boiler is switched on for 5724 hours of the total 8760. This is over 65% of the time. Therefore this could be a viable option. However, problems for biomass boilers are fouling, deposits, slagging, corrosion and agglomeration (Saidur et al., 2011). Operating a bio boiler in a flexible way, reduces the optimal configuration of the boiler and can result in a quicker build-up of the issues mentioned. Therefore this operation of a bio-boiler is not to be expected. Since the bio boiler is switched on more than half of the time and from the results it can be viewed that solo bio boiler options (option 6, 7 and 8) perform better than options 0 (in which CHPX 1 is the only steam production unit in the system), it can be expected that if PCX decides to build a bio boiler, it will shut down CHPX 1. Besides, it can be viewed in the results of 2025 that the bio boiler will expectedly be operational for 8111 hours of the total 8760. This result also supports the conclusion drawn above.

From the analysis of the results, it can be drawn that the exclusion of start-up and heat-up costs does not affect the relevant conclusions that are drawn about the system.

J. Scenario construction

The simulation model will be run for the years 2017 and 2025. The circumstances of steam production in site Y will be assumed to not show a large variation. However the year 2025 is in the further future and many things can have happened in the meantime. Therefore it is important to analyse possible future developments and to incorporate various changes in circumstances in the simulation. This way alternatives can be weighed under various circumstances.

J.1 National politics on renewable energy

One of the problems with policy on renewable energy that has occurred in the past is that changing policy of governments has led to a slowdown of the sustainable energy transition. Renewable electricity policies have been complex in Europe. Due to Agnolucci (2007) a source of complexity has been the number of policies that have been introduced to the market to help the transition towards renewable electricity. The government of country A has experimented with different approaches both in terms of policy instruments (renewable quota vs. feed-in tariff) and in terms of the focus of the policy (demand side vs. supply side). As a consequence of this, many policies were adopted and contemporaneously implemented. These policy changes increase the risk for investments. These uncertainties have had a negative effect on the investments in sustainable energy (Gudde, 2011). Due to the unpredictability of policy on renewable energy in the long term, it is important to consider different developments in policy with regard to renewable energy.

Subsidy on renewable electricity production

The government of country A came up with policy to make sustainable energy techniques more profitable on the short- and long term. In the long term the goal is to reach a CO2 poor society in country A. On the short(er) term, the government wants to increase the percentage of renewable energy in the energy. However renewable energy techniques are still very expensive at the moment. Therefore the government has established a subsidy for the cheapest renewable solutions to reach its goals (source not included due to confidentiality reasons). If subsidies on renewable energy remain or even increase in amount, this will boost the installed renewable capacity. The amount of installed renewable capacity influences the electricity price.

The paper of Sáenz de Miera, del Río González, and Vizcaíno (2008) analysed the reduction in the wholesale price of electricity as a result of more renewable electricity being fed into the grid. The paper showed that this reduction is greater than the increase in the costs for the consumers arising from the renewable electricity support scheme (the feed-in tariffs), which are charged to the final consumer. Therefore, a net reduction in the retail electricity price results, which is positive from a consumer point of view. Also in Germany this wholesale electricity price reduction has been noticed. The German feed-in support of electricity generation from renewable energy sources has led to high growth rates of the supported technologies. The paper of Sensfuß, Ragwitz, and Genoese (2008) analysed the impact of privileged renewable electricity generation on the electricity market in Germany. The results indicate that the financial volume of the price reduction is considerable. In the short run, this gives rise to a distributional effect which creates savings for the demand side by reducing generator profits.

Subsidy on bio-based economy

Bio-energy is seen as one of the top four energy carriers that is most suitable to reach energy goals of country A. Biomass is the source for this bio-energy. It can be used for the production of electricity, gas, heat or as bio-fuel for vehicles. One of the cheapest renewable solutions is co-firing biomass in coal plants. The government is currently examining whether this could be a good solution. At the moment electricity produced from biomass gets subsidy. Furthermore currently a subsidy amount on thermal power produced from biomass is being discussed between the ministry of economic affairs and stakeholders involved, such as ECA. However the potential of the bio-economy extends well beyond bio-energy (Langeveld, Dixon, & Jaworski, 2010). Biomass could also be used for the production of non-fuel bio-products, such as chemicals, pharmaceuticals and biopolymers. There is no subsidy on the production of non-fuel bio-products yet. If the government decides to put more emphasis on the bio-based economy, more subsidy would be provided for production of biofuels, bio power and non-fuel bio products. According to the business manager production site Y (personal communication, May 16, 2014) an increase in subsidy for bio-based economy could have a positive effect on investments in site Y. However it could also mean an increase in competition on the biomass market, which would increase the purchase price for biomass.

J.2 Geopolitics

World demand for natural gas is commonly expected to grow over foreseeable future. The report of the IEA (International Energy Agency, 2011) describes a bright future for the European gas market with a gas reserve for a possible consumption of another 120 years. However, proven reserves of natural gas are rather unevenly distributed and only a few countries and regions will remain surplus exporting producers in the future. Security of gas supply largely depends on stable deliveries from Russia and Algeria. The break-up of the former Soviet Union has increased the number of transit countries and enhanced the political and commercial risk of projects in the area. Countries respond to the evolving situation in the energy market, adopting reflexive strategies and taking account of each other (Correljé & van der Linde, 2006). Due to Bilgin (2010) the term "European energy security" goes beyond the European Union's 27 member states and concerns many other countries. Therefore it is important to look at the future gas system from a broad perspective. Analyses on the European energy security focus on risks that might arise from:

1. The Russian state's control in the Russian energy sector
2. The illiberal market conditions and extensive centralization in Russia
3. The consequences of the asymmetry between the liberal understanding of the energy sector in Europe and the illiberal environment in Russia
4. Geopolitical concerns stemming from European energy supply security
5. Turkey's emerging role in a new energy corridor.

In the paper of Correljé and van der Linde (2006) the authors propose two storylines for security of energy supply to the European Union (EU). The Markets and Institutions storyline assumes that there is a continuous intensification of the social, cultural and economic internationalization or 'globalization' of markets.
This also implies an enduring cooperation in the international political and economic institutions, supporting a constant development of the multilateral system that governs international relations. Under a growing risk of disruptions of supply, in the Markets and Institutions storyline, EU natural gas supply would be easier to secure, particularly because it foresees a deeper economic integration with Russia.

The Regions and Empire storyline elaborated a more pessimistic view on the international political and economic system. It involves, essentially, a division of the world into countries and regions, on the basis of ideology, religion and political arguments. Political and military strategy, bilateralism and regionalism divide the world up into competing US, EU, Russian and Asian spheres of influence. The absence of effective world markets for strategic goods further stimulates the establishment of bilateral trade relationships and treaties, thus reinforcing the formation of more or less integrated blocks with satellite regions that compete for markets and energy resources.

J.3 Economic situation and competitive landscape

A major shift in the competitive landscape of the worldwide industry currently taking place. New players from oil- and gas-producing countries and the high-growth developing markets of China and India join the industry's top ranks in sales. These newcomers are better placed to benefit from two of the key dynamics driving the industry's future: control of advantaged feed stocks in a high-oil-price world, and privileged access to the most attractive consumer-growth markets (Budde, 2011).

Since the economic slowdown of the past years, the global industry has seen major changes. According to Budde (2011) two of those major changes are energy-price dynamics and shift in growth of global (chemical) demand. Firstly, the industry is confronted with fuel price volatility. In addition, energy prices are significantly higher than they have been for the past two decades—and they are higher than they were coming out of previous recessions. Overall, the degrees of cost advantage and disadvantage among regions have increased.

Second, the economic downturn has highlighted the accelerating shift in the growth of global (chemical) demand from developed economies to the developing world. While demand in Europe and the United States has not returned to pre-crisis levels and seems unlikely to do so until 2012, China's chemical demand increased by 6.4 percent in 2009 and by over 15 percent in 2010. Meanwhile, new petrochemical capacity in the Middle East continues to expand, while plant-closure announcements have multiplied in Europe, Japan, and the United States.

Besides the shift in the competitive landscape of the worldwide industry, also the economic environment of Europe plays a role in the investment readiness of new entrants to build production plants in site Y. Since the financial crisis Europe has had a huge economic setback. However recent European Commission's (2014) forecast pointed to a continuing economic recovery in the European Union following its emergence from recession.

The expectation is that if the European- and global economy will be characterized by a significant growth in the upcoming years, this will increase the demand in Europe and the United States to at least pre-crisis levels. European and US demand for chemicals requests a high quality standard of chemicals with a short delivery time. It is expected that this demand and a better investment climate will boost the European and American chemicals' industry.

J.4 Scenario testing on simulation model

The simulation model will be run for various scenarios. The combinations of developments that will be run, will be shown in the table J.1. Data for electricity-, biomass- and natural gas prices will be provided by ECA.

SCENARIO	ELECTRICITY PRICE		BIOMASS PRICE		GAS PRICE		STEAM DEMAND	
	low	high	low	high	low	high	low	high
	-15%	+15%	-10%	+20%	-15%	+15%	-25%	+25%
1	✓			✓	✓			✓
2		✓	✓			✓	✓	
3	✓			✓		✓	✓	
4		✓	✓		✓			✓

Table J.1: Scenarios

<u>Developments</u>

	D.1: Subsidy on renewable electricity production	**Effect**	**Result**
a.	Drastic increase in subsidy on renewable electricity production	Increase in installed renewable capacity	Low electricity price + 15%
b.	No significant changes	-	-
c.	Drastic decrease in subsidy on renewable electricity production	Decrease in new investments renewable capacity	High electricity price - 15%

Table J.2: Possible developments for subsidy on renewable electricity production

	D.2: Subsidy on bio-based economy	**Effect**	**Result**
a.	Drastic increase in subsidy on bio-based production	Increase in plants on biomass	High biomass price + 20%
b.	No significant changes	-	-
c.	Drastic decrease in subsidy on bio-based production	Decrease in new investments biomass plants	Low biomass price - 10%

Table J.3: Possible developments for subsidy on bio-based economy

D.3: Natural gas price		Effect	Result
a.	Markets and institutions	Natural gas price market driver	Low natural gas price - 15%
b.	No significant changes	-	-
c.	Regions and empires	Natural gas price driven by political power and bilateral contracts	High natural gas price + 15%

Table J.4: Possible developments for natural gas price

D.4: Economic developments		Effect	Result
a.	Increased economic growth Increased high quality chemicals' demand in Europe and America	Increase in chemicals' demand Increase in production site Y	High steam demand + 25%
b.	No significant changes	-	-
c.	Stagnated economic growth Emphasis on chemicals'	Decrease in chemicals' demand Decrease in production site Y	Low steam demand - 25%

Table J.5: Possible developments for economic developments

<u>Explanation of bandwidth effects</u>

ELECTRICITY PRICE		BIOMASS PRICE		GAS PRICE		STEAM DEMAND	
LOW	high	low	high	low	high	low	high
-15%	+15%	-10%	+20%	-15%	+15%	-25%	+25%

Table J.6: Bandwidth of developments

Scenarios have been constructed to test how the system performs under different scenarios than the base scenario in 2025. For all four identified variables that will be varied, a bandwidth is defined for the developments. For some of the variables a larger bandwidth is defined. In this section the choice for the bandwidth is explained.

To test outcomes on developments, these scenarios should be significantly different from the base case. For the gas price and electricity price a bandwidth of 30% (15% higher and 15% lower) around the expected pricing has been chosen. Reason for this is that ECA is very experienced in the natural gas and electricity market. The experts that have produced the price series for electricity and gas are very experienced. Therefore not an extremely large variation has been chosen, but a reasonable range within the pricing will probably be.

For the biomass price another consideration has been made. In the year 2017 a biomass price of €50,- per ton is assumed (personal communication, investment analyst BPA, April 29, 2014). With a regular price increase due to inflation rate of 2%, since inflation in country A usually fluctuates between 0,9% and 3,1% (no reference included due to confidentiality reasons), the expected price in 2025 is €60,-. If the same bandwidth would be used as for natural gas and electricity prices, the biomass price in 2025 would be lower than in 2017. However this does not seem likely. It seems more likely that the biomass prices will increase a lot more. Therefore a bandwidth of -10% – +20% has been chosen.

Lastly the steam demand is very much unknown. According to the business manager production site Y (personal communication, May 16, 2014) in the most ideal situation the available land on site Y (400 hectares) will be entirely sold to new investors. However he mentioned that this is an almost unreachable situation. YAC does have a target of selling 9 hectares per year, but some years this goes better than other years. Furthermore he mentioned that the installations of PCX are becoming old (from the '60s), which could also be a large cause for change in site Y. So, all in all it is very difficult to make a prediction about the steam demand in site Y. Therefore a quite large bandwidth has been chosen.

K. Calculations complementary to model results

K.1 Operating expenditure calculations

In 2008 ECA requested a quote for a gas boiler (internal document). A few years later, in 2013, ECA requested a price quote for a bio boiler. The assumption that has been made is that if PCX, will invest in a boiler, it will probably do so in 2015. Therefore prices from the quotas have been calculated with an inflation rate of 2% over the years till 2015. An inflation rate of x% has been used, since inflation in country A usually fluctuates between 0,9% and 3,1% (no reference included due to confidentiality reasons). Therefore a standard of 2% has been assumed. Furthermore a sales tax of x% has been assumed. In country A this sales tax is raised on most products. Some products are exempted from sales tax or have a lower sales tax. However that does not apply to these boilers (no reference included due to confidentiality reasons).

Gas and Bio boiler prices	
Inflation rate	2 %
Sales tax	- %
Gas boiler	
Size	4 boilers of 30 MWth = 120 MWth
Investment cost 2007	€ -
Investment cost 2015 incl. inflation	€ -
Investment cost 2015 incl. sales tax	€ -
Bio boiler	
Size	39 MWth
Investment cost 2013	€ -
Investment cost 2015 incl. inflation	€ -
Investment cost 2015 incl. sales tax	€ -

Table K.1: Gas and bio boiler prices (cells left blank due to confidentiality reasons)

Depending on the model option a different amount of gas- or bio boilers is needed. It is expected that the boiler will be built after a decision about the BPA alternative has been made. Therefore the size of the boilers depends on the BPA alternative and whether or not CHPX 1 will still be operated.

The size of the boiler needed per model option is determined on the basis of the model results. For options 3 till 8 it is assumed that three extra gas boiler will be built for back-up power if some production units or the BPA have an unplanned stop. Three extra gas boilers have an extra capacity of 90 MW, which is about 110 tons of steam. Reason why not more back-up capacity is built into the system is because it is expected that PCX can adjust its steam consumption to cope with unforeseen circumstances as well. Therefore the combination of the reduction of steam consumption of PCX and the extra back-up capacity are expected to be enough to make sure that no large steam disruptions will appear in site Y.

For the calculation of yearly OPEX, the annuity is used. The annuity is a fixed amount that has to be paid per year. Annuity is used for periodically payments that make up for a large one-time payment, such as the investments mentioned in the table. The annuity consists of a part redemption and a part interest. The annuity stays the same for the period that is established to pay back the investment. That pay-back period differs between PCX and ECA. For ECA the period of 12 years has been chosen for an investment like this according to project developer BPA (personal communication, July 11, 2014). However for PCX the period of maximum 3 years is common according to the business manager production site Y (personal communication, May 16, 2014). The differences in period provide a large difference between the OPEX costs that have to be paid per option.

$$T = \frac{i \cdot P}{1 - (1 + i)^{-n}}$$

T	Annuïty	[€/year]
P	Initial investment	[€]
i	Interest rate	[%]
n	Payback period	[year]

Furthermore the OPEX are also determined by maintenance costs. These imputed costs are determined as a percentage of the replacement asset value. According to Project developer biomass (personal communication, July 11, 2014) this percentage is only 2% for any of the adjustments to the BPA. However he estimated the percentages for a gas boiler at 3,5% and for a bio boiler, a sensitive piece of equipment and therefore maintenance sensitive, a maintenance percentage of 5% has been estimated.

Percentage maintenance of investment	
Bio boiler	5%
Gas boiler	3,50%
BPST and PRDS	2%

Table K.2: Percentage of the replacement asset value

One thing that should be noticed is that operational costs are not taken into account. Reason for this is that for options in which the solo electricity alternative of BPA is replaced by a steam production alternative the operational costs will probably not change very much. This is because at the moment BPA is fully operated as well. The same reason is applicable to options in which a bio or gas boiler replaces CHPX 1. It is expected that operational cost will most likely not change very much, however if so it is expected that operational costs will more likely decrease than increase, since CHPX 1 is a very large plant with many different components. Therefore operational costs have not been included for these options. However for the options in which CHPX 1 is not replaced, but a gas or bio boiler is simply built beside CHPX 1, operational costs are likely to increases. This consideration should be made when evaluating the economic performance of the model options.

Due to the fact that operating costs of rent, employees etcetera are not taken into account, the OPEX in this case are called Δ OPEX. In the table on the next page a summary of the assumptions and calculations to get to yearly Δ OPEX are shown.

Δ OPEX calculations		Options											
		1	2	3	4	5	6	7	8	9	10	11	12
Capacity needed PCX	MWth			240	150	150	234	156	156	210	120	120	234
Back-up size	MWth			90	90	90	90	90	90				
Investment cost ECA (PRDS & PRDS) *	mln €	-	-		-	-		-	-		-	-	
Investment cost PCX *	mln €			-	-	-	-	-	-	-	-	-	-
**incl. inflation & sales tax*													
Investments costs back-up capacity*	mln €			-	-	-	-	-	-				
**incl. inflation & sales tax*													
Total investment costs PCX	mln €			-	-	-	-	-	-	-	-	-	-
Annuity ECA	mln € / year	-	-		-	-		-	-		-	-	
Annuity PCX	mln € / year			-	-	-	-	-	-	-	-	-	-
Annuity back-up capacity	mln € / year			-	-	-	-	-	-				
90% gas boiler efficiency	MWhf	*90 MWh (output) / 0,9 = 100 MWhf (input needed)*											
5% of back-up reserve capacity	MWhf	*0,05 * 100 (MWhf input) = 5 MWhf (input to stay stand-by)*											
Average natural gas price 2017	€/MWh	-											
Average natural gas price 2025	€/MWh	-											
Cost for keeping reserve capacity stand-by in 2017	mln € / year			-	-	-	-	-	-				
Cost for keeping reserve capacity stand-by in 2025	mln € / year			-	-	-	-	-	-				
Total Δ OPEX ECA 2017	mln € / year	-	-		-	-		-	-		-	-	
Total Δ OPEX PCX 2017	mln € / year			-	-	-	-	-	-	-	-	-	-
Total Δ OPEX ECA 2025	mln € / year	-	-		-	-		-	-		-	-	
Total Δ OPEX PCX 2025	mln € / year			-	-	-	-	-	-				

Table K.3: Delta OPEX calculations for new to build steam production units (cells left blank due to confidentiality reasons)

K.2 Subsidy calculations

Subsidy calculations for BPA steam alternatives

At this moment ECA receives a subsidy amount per kWh electricity produced with BPA, because it is a plant that runs on biomass. For confidentiality reasons, this subsidy scheme will be called the 'Old subsidy scheme' (OSS). ECA would get this subsidy for 12 years, which would end in 2021. After 2021 it would then apply for another subsidy, that would be significantly lower. However ECA is now considering steam production alternatives for the BPA. In that case the BPA would have to be adjusted. If ECA will do so, it will produce a large amount of steam, for which at this point no subsidy scheme exists. Since political willingness for improvement of the site Y area is very high at the moment, as explained in chapter 1, the government is willing to adjust the subsidy scheme on the basis of a proposal of RIA. Therefore the government asked RIA to calculate new subsidy amounts for this new category. RIA published a conceptual advice in which calculations for new subsidy categories were shown (no reference included due to confidentiality reasons). This advice was open for consultation, after which the new subsidy categories and its calculations would be established. The final subsidy amounts will not be published before this research will be finished. Therefore for subsidy calculations the number from the conceptual advice of RIA will be used.

For the calculations of the subsidy amount for ECA's BPA the advice from RIA was used. It considers a biomass plant that produces electricity as well as thermal power. Furthermore it is for plants that still receive the OSS at the moment. The plant owner will receive a higher base amount if it aborts its OSS to get the NSS before the end of its OSS period. The more years its stops before the end of its OSS period, the higher the base amount is to compensate for the lost OSS subsidy income. If a plant is adjusted for the production of electrical as well as thermal power, it will receive subsidy for 4429 full load hours per year.

The associated calculations will be shown below. Determination of yearly maximum NSS-subsidy amount for combined heat- and electricity production with a biomass plant on B-wood:

<subsidy calculations are not included due to confidentiality reasons>

The next three tables contain the assumptions on which subsidy calculations are based.

		Old situation	PRDS	BPST
Gross electricity output	MW	-	-	-
Net electricity output	MW	-	-	-
Gross thermal output	MW	none	-	-
Net thermal output	MW	none	-	-
Full load hours electricity	hour/year	8.000	8.000	8.000
Full load hours thermal	hour/year	-	8.000	8.000

Table K.4: Output data BPA alternatives (cells left blank due to confidentiality reasons)

<table not included due to confidentiality reasons>

Table K.5: Assumptions for NSS subsidy calculations

		2017	2025
Electricity price	€/MWh	-	-
Natural gas price	€/MWh	-	-

Table K.6: Average electricity and gas price 2017 and 2025 based on model input data (cells left blank due to confidentiality reasons)

An example calculation will be shown of NSS subsidy calculations for the BPST alternative of BPA in 2017. The calculations are based on the tables above.

<calculation not included due to confidentiality reasons>

Besides the NSS regular income, also an amount will be granted for the loss of OSS subsidy income. This amount will only be granted in the first few years of the new subsidy scheme. The amount of losses that will be compensated depends on the amount of years ECA quits its old subsidy scheme before it would regularly end. If the OSS subsidy would not be stopped before its end term it would last until 2021. However if ECA decides to switch to the new subsidy scheme in 2017, it would quit its OSS subsidy 4 years early. This means that 4 years of the OSS subsidy should be compensated. After 2021, no compensation will be granted anymore. Therefore the subsidy amount will decrease drastically after 2021. The yearly OSS compensation is calculated as follows:

<calculation not included due to confidentiality reasons>

An example of that calculation is as follows:

<calculation not included due to confidentiality reasons>

Subsidy for bio boilers

Besides ECA, other operators could receive subsidy as well if steam would be produced in a sustainable manner. Therefore in the options in which a new bio boiler will be built, subsidy should be taken into account. Since a bio boiler solely produces steam, a different subsidy calculation is used. Furthermore no OSS compensation will be given, since it involves a new plant. This subsidy category was included in the concept advice of RIA for consultation as well. In the table below the subsidy amounts will be shown. The amounts are based on the concept advice of RIA.

<table not included due to confidentiality reasons>

Table K.7: NSS subsidy amounts to calculate subsidy for a bio boiler

The same gas price scenario for 2017 and 2025 as used for calculating NSS correction amount for the BPA alternatives will be used for calculating the NSS correction amount for a bio boiler as well. The NSS subsidy calculation for a bio boiler on a wood is as follows:

<calculation not included due to confidentiality reasons>

Every option has a different boiler size. Reason for this is that it is expected that PCX will only decide to invest after it knows what the decision with ECA was. Therefore PCX will know what the size of the bio boiler it builds should be. Therefore the boiler size will fit the option.

The actual operational hours of a plant is determined on the basis of the model output per model option. From the model output it is possible to derive how many hours the bio boiler have been running at full capacity or part load. Therefore the total net produced heat output can be determined.

	option 6	option 7	option 8	option 12
Gross Th. Power Bio boiler	234 MWth	156 MWth	156 MWth	234 MWth
Maximum subsidy income 2017	- mln €	- mln €	- mln €	- mln €
Maximum subsidy income 2025	- mln €	- mln €	- mln €	- mln €
Operational hours per option	-	-	-	- hours 2017 - hours 2025
NSS subsidy income 2017	- mln €	- mln €	- mln €	- mln €
NSS subsidy income 2017	- mln €	- mln €	- mln €	- mln €

Table K.8: NSS subsidy income for bio boilers

For every scenario the NSS income has been calculated too. The outcomes can be found in the table below.

	option 6	option 7	option 8	option 12
Operational hours bio boiler S1	-	-	-	-
Operational hours bio boiler S2	-	-	-	-
Operational hours bio boiler S3	-	-	-	-
Operational hours bio boiler S4	-	-	-	-
NSS income per option S1	- mln €	- mln €	- mln €	- mln €
NSS income per option S2	- mln €	- mln €	- mln €	- mln €
NSS income per option S3	- mln €	- mln €	- mln €	- mln €
NSS income per option S4	- mln €	- mln €	- mln €	- mln €

Table K.9: NSS subsidy income for bio boilers under scenarios (cells left blank due to confidentiality reasons)

K.3 Threshold price calculations

Threshold prices ECA and PCX for steam in 2017

The threshold price for ECA is based on the comparison to the business case as it is right now. So only the difference between the alternatives of not doing anything or investing in a steam production alternative will be taken into account. Therefore if the threshold price is met, it does not make sure that an alternative is actually profitable. It only means that it is from that threshold price more profitable than it would be with keeping the current business case, which is solely producing electricity. The costs of CHPX and BPA that are used to calculate the threshold price are the costs with subsidy and Δ OPEX included.

PRDS alternative

$$\text{Threshold price per ton of steam for PCX: } \frac{\Delta\, \text{Profits CHPX 1 in option 0 and option 1}}{\text{Tons of steam delivered by BPA}} = \frac{€}{ton}$$

$$\text{Threshold price per ton of steam for ECA: } \frac{\Delta\, \text{Profits BPA in option 0 and option 1}}{\text{Tons of steam delivered by BPA}} = \frac{€}{ton}$$

BPST alternative

$$\text{Threshold price per ton of steam for PCX: } \frac{\Delta\, \text{Profits CHPX 1 in option 0 and option 2}}{\text{Tons of steam delivered by BPA}} = \frac{€}{ton}$$

$$\text{Threshold price per ton of steam for ECA: } \frac{\Delta\, \text{Profits BPA in option 0 and option 2}}{\text{Tons of steam delivered by BPA}} = \frac{€}{ton}$$

In the table below the threshold prices in €/ton will be converted to €/MWh.

Conversion table			
	€/ton	Conversion	€/MWh
PRDS		*)	
Threshold price PCX	-		-
Threshold price ECA	-		-
BPST			
Threshold price PCX	-		-
Threshold price ECA	-		-

Table K.10: Table for converting threshold prices from €/ton to €/MWh (cells left blank due to confidentiality reasons)

Threshold prices ECA and PCX for steam in 2025

For 2025 the same calculations will be done, but with the 2025 model results.

K.4 Cost of reserve capacity CHPX 1

Similarly to the reserve capacity calculations in table K.3, reserve capacity of CHPX 1 is calculated. The cost of keeping reserve capacity is calculated on the basis of keeping 5% of the second gas turbine capacity ready for operation all times. At this rate, the gas turbine can ramp up in case of emergency. On the basis of these assumptions, the following estimated cost for keeping reserve capacity is calculated in table K.11.

	Calculation		Unit
Input needed for back-up reserve		-	MWhf
5% of back-up reserve capacity	*0,05 * -*	-	MWhf
Average natural gas price 2017		-	€/MWh
Average natural gas price 2025		-	€/MWh
Cost for keeping reserve capacity stand-by in 2017	-	2,4	mln € / year
Cost for keeping reserve capacity stand-by in 2025	-	3,2	mln € / year

Table K.11: Table for reserve capacity calculations CHPX 1 in mln €/year (cells left blank due to confidentiality reasons)

L. Model results

In this appendix all model results will be shown and interpreted. Furthermore it will be shown for all results how the costs have been calculated. The calculations that lead to these tables have been shown in appendix J.

L.1 Model results including calculated subsidy and OPEX 2017

Steam production profits per steam producer 2017 (in million €)													
	Options												
	0	1	2	3	4	5	6	7	8	9	10	11	12
ECA	*0,7*	-2,1	-1,3	*0,7*	-2,1	-1,3	*0,7*	-2,1	-1,3	*0,7*	-2,1	-1,3	*0,7*
CHPX 1	-6,1	-3,9	-5,3							-6,2	-3,7	-5,3	-4,6
Bio boiler							-5,6	-2,9	-3,2				-6,0
Gas boiler				-8,3	-4,2	-4,7				-0,5	-0,4	-0,4	
Total	-6,1	-5,9	-6,6	-8,3	-6,3	-6,0	-5,6	-4,9	-4,5	-6,7	-6,2	-7,0	-10,6

Table L.1: Steam production profits per steam production unit in 2017

Totals			**Average BPA alternative**	
Average	-6,6		Solo-E	-7,5
St.deviation	1,5		PRDS	-5,8
Minimum	-10,6	Option 12	BPST	-6,0
Maximum	-4,5	Option 8		

Table L.2: Summary of table L.1

In tables L.1 and L.2 it is possible to see that especially the biomass options perform well. However option 0, the options in which no adjustments are made compared to the current situation, performs best. Furthermore it is possible to derive that the PRDS alternative of BPA performs best of the three BPA alternatives. However it shows a small difference with the average of the BPST alternative.

Another very striking results is that option 12 performs worst, while option 6 performs quite well. Options 6 and 12 are the same options, in which BPA produces electricity and biomass boiler produces steam. However in option 12 CHPX 1 is added to the system. Reason that option 12 does not perform better than option 6 is that start-up costs and ramping constraints are not included in the model. Therefore every time CHPX 1 can – on the basis of the natural gas price and the electricity – produce at a lower cost than the bio boiler, production switches. However start-up costs are very high for as well heating up the steam pipelines as starting up the separate turbines. Therefore option 12 becomes a very expensive option. What can be derived from this outcome is that building a bio boiler besides CHPX 1 would not be much more profitable than just using a bio boiler solo. Therefore option 12 is not a viable option.

Subsidy per operator per option 2017													
	Options												
	0	1	2	3	4	5	6	7	8	9	10	11	12
ECA													
CHPX 1													
Bio boiler													
Gas boiler													

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Δ OPEX 2017													
	Options												
	0	1	2	3	4	5	6	7	8	9	10	11	12
ECA													
CHPX 1													
Bio boiler													
Gas boiler													

<cells left blank due to confidentiality reasons>

Steam production profits per steam producer including subsidy and OPEX 2017 (in million €)													
	Options												
	0	1	2	3	4	5	6	7	8	9	10	11	12
ECA	*6,4*	4,5	4,6	*6,4*	4,5	4,6	*6,4*	4,5	4,6	*6,4*	4,5	4,6	*6,4*
CHPX 1	-6,1	-3,9	-5,3							-6,2	-3,7	-5,3	-4,6
Bio boiler							-0,7	-1,0	-0,8				-5,0
Gas boiler				-9,1	-4,9	-5,3				-0,9	-0,6	-0,7	
Total	-6,1	0,6	-0,6	-9,1	-0,4	-0,7	-0,7	3,5	3,8	-7,1	0,1	-1,3	-9,6

Table L.3: Steam production profits per steam production unit in 2017 including subsidy and OPE

Totals			**Average BPA alternative**	
Average	-1,8		Solo-E	-6,5
St.deviation	4,2		PRDS	0,9
Minimum	-9,6	Option 12	BPST	0,3
Maximum	3,8	Option 8		

Table L.4: Summary of totals table L.3

In tables L.3 and L.4 it can be seen that even when delta OPEX and subsidy are included, the biomass options still perform well. Reason for this is that subsidy for a bio boiler is calculated to be very high. However it is not sure yet whether such a large amount of subsidy will be granted to a bio boiler in site Y.

Still PRDS performs best on average of the three BPA alternatives. Besides the gap between the average performance of the PRDS alternative and the BPST alternative has increased. This can be explained by the higher amount of subsidy with the PRDS alternative. Reason for this is that more MWh are produced when the PRDS alternative is operational, because more steam is being produced.

The bio boiler options perform very well when it comes down to steam production profits and the steam production profits including delta OPEX and subsidy. However one of the main considerations whether PCX will want to invest in a bio boiler is the high investment cost. Furthermore it is not sure yet whether it will receive subsidy for steam production with a bio boiler. Therefore below a table will be shown in which only steam production costs and delta OPEX are included.

Steam production profits per steam producer including OPEX 2017 (in million €)													
	Options												
	0	1	2	3	4	5	6	7	8	9	10	11	12
ECA	*0,7*	-2,1	-1,4	*0,7*	-2,1	-1,4	*0,7*	-2,1	-1,4	*0,7*	-2,1	-1,4	*0,7*
CHPX 1	-6,1	-3,9	-5,3							-6,2	-3,7	-5,3	-4,6
Bio boiler							-9,4	-5,5	-5,8				-9,4
Gas boiler				-9,1	-4,9	-5,3				-0,9	-0,6	-0,7	
Total	-6,1	-6,0	-6,7	-9,1	-7,0	-6,8	-9,4	-7,6	-7,2	-7,1	-6,4	-7,4	-14,0

Table L.5: Steam production profits per steam production unit in 2017 including subsidy and OPEX

Totals			**Average BPA alternative**	
Average	-7,9		Solo-E	-9,1
St.deviation	2,1		PRDS	-6,7
Minimum	-14,0	Option 12	BPST	-7,0
Maximum	-6,0	Option 1		

Table L.6: Summary of totals table L.5

In the tables L.5 and L.6 it is shown that the bio boiler options – options 6, 7 and 8 – do indeed not outperform all the other options anymore. This means that if PCX will not get subsidy for the steam produced with a bio boiler, it would be better off with a steam contract with ECA. Option 0 performs best when subsidy is excluded. This means that it would be best to continue the current configuration of assets, which means that still only CHPX 1 will be producing steam in site Y.

M.2 Model results including calculated subsidy and OPEX 2025

All model options have been run for 2017 as well as 2025. For 2025 different price series were the input for the simulation model. The price series were derived from ECA. Due to different price series, different model outcomes can be derived. However this is not necessarily the case.

Steam production profits per steam producer 2025 (in million €)													
	Options												
	0	1	2	3	4	5	6	7	8	9	10	11	12
ECA	*0,9*	-2,3	-1,5	*0,9*	-2,3	-1,5	*0,9*	-2,3	-1,5	*0,9*	-2,3	-1,5	*0,9*
CHPX 1	-8,4	-5,0	-6,6							-8,4	-4,5	-6,5	-2,7
Bio boiler							-6,7	-3,4	-3,8				-7,4
Gas boiler				-10,9	-5,6	-6,2				-0,6	-0,2	-0,5	
Total	-8,4	-7,3	-8,1	-10,9	-7,9	-7,7	-6,7	-5,8	-5,4	-8,9	-7,1	-8,6	-10,2

Table L.7: Steam production profits per steam production unit in 2025

Totals			**Average BPA alternative**	
Average	-7,9		Solo-E	-9,0
St.deviation	1,6		PRDS	-7,0
Minimum	-10,9	Option 3	BPST	-7,4
Maximum	-5,4	Option 8		

Table L.8: Summary of totals table L.7

It can be viewed in tables L.7 and L.8 that no large differences appear from the year 2017. Again the bio boiler options perform very well. Off course this depends on the price for biomass that is used in the model, which is significantly lower than the natural gas price for the same production. Still the PRDS alternative performs best of the BPA alternatives.

Option 3 performs worst in terms of steam production profits. Reason for this is that the natural gas price is expected to be high. Since a gas boiler does not produce electricity, but only steam, the steam price becomes almost similar to the natural gas price.

In 2025 PCX does not really benefit from the BPST alternative of the BPA compared to the current situation. However, this would be the case with the PRDS option.

Subsidy per operator per option 2025													
	Options												
	0	1	2	3	4	5	6	7	8	9	10	11	12
ECA													
CHPX 1													
Bio boiler													
Gas boiler													

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Δ OPEX 2025	Options												
	0	1	2	3	4	5	6	7	8	9	10	11	12
ECA													
CHPX 1													
Bio boiler													
Gas boiler													

<cells left blank due to confidentiality reasons>

Steam production profits per steam producer including subsidy and OPEX, 2025 (in million €)	Options												
	0	1	2	3	4	5	6	7	8	9	10	11	12
ECA	*1,7*	0,1	0,6	*1,7*	0,1	0,6	*1,7*	0,1	0,6	*1,7*	0,1	0,6	*1,7*
CHPX 1	-8,4	-5,0	-6,6							-8,4	-4,5	-6,5	-2,7
Bio boiler							1,9	0,8	0,9				-0,6
Gas boiler				-11,1	-5,8	-6,4				-0,6	-0,2	-0,5	
Total	-8,4	-4,9	-6,0	-11,1	-5,7	-5,8	1,9	0,9	1,5	-8,9	-4,6	-6,4	-3,3

Table L.9: Steam production profits per steam production unit in 2025

Totals			Average BPA alternative	
Average	-4,4		Solo-E	-6,0
St.deviation	3,9		PRDS	-3,6
Minimum	-11,1	Option 3	BPST	-4,2
Maximum	1,9	Option 6		

Table L.10: Summary of totals table L.9

In tables L.9 and L.10 it can be viewed that even if OPEX and subsidies are taken into account, the bio boiler options 6, 7 and 8 still perform very well. As can be viewed from the tables above, the delta OPEX are very high. However the expected subsidy for steam produced by a bio boiler are very high as well. Options in which no bio production is present perform worst in this table. Reason for this is that natural gas alternatives do not receive subsidy.

To check to what extent options that performed well in tables L.7 and L.9 are dependent on subsidies, a table will be shown without the inclusion of subsidies, but with the inclusion of delta OPEX.

Steam production profits per steam producer including OPEX, 2025 (in million €)													
	Options												
	0	1	2	3	4	5	6	7	8	9	10	11	12
ECA	*0,9*	-2,3	-1,7	*0,9*	-2,3	-1,7	*0,9*	-2,3	-1,7	*0,9*	-2,3	-1,7	*0,9*
CHPX 1	-8,4	-5,0	-6,6							-8,4	-4,5	-6,5	-2,7
Bio boiler							-6,7	-3,4	-3,8				-7,4
Gas boiler				-11,1	-5,8	-6,4				-0,6	-0,2	-0,5	
Total	-8,4	-7,4	-8,2	-11,1	-8,1	-8,1	-6,7	-5,8	-5,5	-8,9	-7,1	-8,7	-10,2

Table L.11: Steam production profits per steam production unit in 2017 including subsidy and OPEX

Totals			**Average BPA alternative**	
Average	-8,0		Solo-E	-9,1
St.deviation	1,6		PRDS	-7,1
Minimum	-11,1	Option 3	BPST	-7,6
Maximum	-5,5	Option 8		

Table L.12: Summary of totals table L.11

In tables L.11 and L.12 can be seen that options in which (part of) the production is done by units on biomass, still perform very well. This means that even if subsidies disappoint, the system will still benefit. However another reason that options 6, 7 and 8 perform well is that the investment costs for building a new bio boiler are assumed to be paid off in 3 years. Therefore in 2025 delta OPEX are much lower than in 2017.

L.3 Model results under scenarios 2025

To see whether certain model options still perform well if price do not develop as expected, a scenario analysis will be done. Furthermore for ECA it is important to see whether under what circumstances certain alternatives of BPA perform very well. Based on the exploration of various uncertain variables on the system, a more robust decision can be made.

The scenario construction can be seen in appendix I. Below the scenarios will be shortly introduced in table L.13.

SCENARIO	ELECTRICITY PRICE low	ELECTRICITY PRICE high	BIOMASS PRICE low	BIOMASS PRICE high	GAS PRICE low	GAS PRICE high	STEAM DEMAND low	STEAM DEMAND high
	-15%	+15%	-10%	+20%	-15%	+15%	-25%	+25%
1	✓			✓	✓			✓
2		✓	✓			✓	✓	
3	✓			✓		✓	✓	
4		✓	✓		✓			✓

Table L.13: Scenarios

The price and demand series used for the model runs of 2025 are varied on the basis of the scenarios above. All model options have been run under the new price and demand series. The results can be found below. Since the changes in price and demand series only affect the production costs of the system, these are the only tables that will be shown for comparison.

Scenario 1

In scenario 1 the electricity price is low, as well as the natural gas price. However the biomass price is high and the steam demand too. Therefore it could be expected that production on natural gas would become cheaper than production on biomass. Furthermore since the electricity price is lower and the natural gas price is low, it is expected that the gas boiler does not perform as bad as in the base scenario for 2025.

Scenario 1: Steam production profits (in million €)													
	Options												
	0	1	2	3	4	5	6	7	8	9	10	11	12
ECA	-0,2	-2,9	-2,3	-0,2	-2,9	-2,3	-0,2	-2,9	-2,3	-0,2	-2,9	-2,3	-0,2
CHPX 1	-9,7	-6,2	-5,8							-9,8	-6,0	-6,0	-9,4
Bio boiler							-10,1	-6,2	-6,6				-4,6
Gas boiler				-11,6	-7,1	-7,6				-0,9	-0,6	-0,6	
Total	-9,7	-9,1	-8,1	-11,6	-10,0	-9,8	-10,1	-9,1	-8,9	-10,6	-9,6	-8,9	-14,0

Table L.14: Steam production profits per steam production unit in 2025 under price and demand series of scenario 1

Totals			Average per BPA alternative	
Average	-10,0		Solo-E	-11,2
St.deviation	1,4		PRDS	-9,4
Minimum	-14,0	Option 12	BPST	-9,0
Maximum	-8,1	Option 2		

Table L.15: Summary of totals table L.14

From tables L.14 and L.15 it can be derived that under scenario 1 the BPST alternative performs better than the PRDS alternative on total system profits. Reason for this is that part of the production in done by CHPX 1 and part of the production is done by BPA with a BPST alternative. Since the natural gas price is low, CHPX 1 has low production costs. Besides with the BPST alternative, more revenues from electricity will be earned than with the PRDS alternative.

Bio boiler options 7 and 8 as well as gas boiler option 11 perform well under this scenario. Even though the biomass price is high, it is still better than the natural gas price. Option 11 has the same profile as option 2, but then it only switches production between CHPX 1 and a gas boiler when the electricity price is very low.

Scenario 2

In scenario 2 the electricity price is high, as well as the natural gas price. However the biomass price is now low and the steam demand too. Therefore the production costs of the gas boiler would rise. The production profits of CHPX 1 do not have to decrease, because the electricity price is high. Since the biomass price is low, it is expected that options with units that run on biomass now even perform better. Especially the BPST alternative should perform well, because the biomass price is low and the electricity price is high.

Scenario 2: Steam production profits (in million €)													
	Options												
	0	1	2	3	4	5	6	7	8	9	10	11	12
ECA	1,7	-2,0	-1,1	1,7	-2,0	-1,1	1,7	-2,0	-1,1	1,7	-2,0	-1,1	1,7
CHPX 1	-7,2	-4,3	-4,3							-7,3	-3,8	-4,3	-0,6
Bio boiler							-4,6	-1,6	-1,9				-4,8
Gas boiler				-9,4	-3,3	-4,0				-0,7	0,0	0,0	
Total	-7,2	-6,2	-5,4	-9,4	-5,2	-5,1	-4,6	-3,6	-3,0	-8,0	-5,7	-5,4	-5,4

Table L.16: Steam production profits per steam production unit in 2025 under price and demand series of scenario 2

Totals			**Average per BPA alternative**	
Average	-5,7		Solo-E	-6,9
St.deviation	1,7		PRDS	-5,2
Minimum	-9,4	Option 3	BPST	-4,7
Maximum	-3,0	Option 8		

Table L.17: Summary of totals table L.16

From tables L.16 and L.17 can be drawn that indeed the BPST alternative performs best of the three BPA alternatives. Besides the biomass options perform very well. It can also be derived from table L.16 that it is the first time that option 12 does not perform poorly. Reason for this is that the price difference between the natural gas price and biomass price got so high that the system could easily decide to let the bio boiler produce the steam. Therefore not much switches (start-up costs) were needed.

In conclusion can be said that if the biomass price goes down, the bio boiler options perform well. If the electricity price will be high and the high pressure steam production of BPA would be enough to meet the entire high pressure steam demand in site Y, the production profits of CHPX 1 will increase drastically.

Scenario 3

In scenario 3 the electricity price is low, as well as the steam demand. However the biomass price is high and so is the natural gas price. Due to this change in prices and demand, it is expected that the total system profits will be low compared to 2. All production units will now have a hard time to produce at low costs. Since both the natural gas price and the biomass price are high, it is expected that the biomass options will perform better.

Scenario 3: Steam production profits (in million €)

	Options												
	0	1	2	3	4	5	6	7	8	9	10	11	12
ECA	-0,2	-2,9	-2,3	-0,2	-2,9	-2,3	-0,2	-2,9	-2,3	-0,2	-2,9	-2,3	-0,2
CHPX 1	-8,9	-5,3	-5,3							-8,6	-4,9	-5,3	-0,3
Bio boiler							-6,1	-2,1	-2,6				-6,2
Gas boiler				-9,4	-3,3	-4,0				-3,3	0,0	0,0	
Total	-8,9	-8,2	-7,6	-9,4	-6,2	-6,3	-6,1	-5,0	-4,9	-12,0	-7,8	-7,6	-6,4

Table L.18: Steam production profits per steam production unit in 2025 under price and demand series of scenario 3

Totals			Average per BPA alternative	
Average	-7,4		Solo-E	-8,6
St.deviation	1,9		PRDS	-6,8
Minimum	-12,0	Option 9	BPST	-6,6
Maximum	-4,9	Option 8		

Table L.19: Summary of totals table L.18

From tables L.18 and L.19 that indeed the bio boiler options perform well. However also the gas boiler options in combination with steam production alternatives of BPA show good results. Reason for this is that not much extra steam has to be produced by the gas boiler. However CHPX 1 still has some electricity income, but not much since the electricity price is low. This means that at a low electricity price and if only low pressure steam has to be produced, a gas boiler has a better efficiency than CHPX 1.

Scenario 4

In scenario 4 the electricity price is high, as well as the steam demand. However the biomass price is low and so is the natural gas price. Due to this change in prices and demand, it is expected that especially the production profits of CHPX 1 should increase as well as production profits of the BPST alternative of BPA.

Scenario 4: Steam production profits (in million €)

	Options												
	0	1	2	3	4	5	6	7	8	9	10	11	12
ECA	1,7	-2,0	-1,1	1,7	-2,0	-1,1	1,7	-2,0	-1,1	1,7	-2,0	-1,1	1,7
CHPX 1	-6,9	-4,5	-4,0							-6,9	-4,1	-4,1	-7,2
Bio boiler							-7,6	-4,6	-5,0				-4,3
Gas boiler				-11,6	-7,1	-7,6				-0,4	-0,3	-0,3	
Total	-6,9	-6,5	-5,1	-11,6	-9,0	-8,7	-7,6	-6,6	-6,1	-7,3	-6,3	-5,5	-11,6

Table L.20: Steam production profits per steam production unit in 2025 under price and demand series of scenario 4

Totals			Average per BPA alternative	
Average	-7,6		Solo-E	-9,0
St.deviation	2,0		PRDS	-7,1
Minimum	-11,6	Option 12	BPST	-6,3
Maximum	-5,1	Option 2		

Table L.21: Summary of totals table L.20

From tables L.20 and L.21 can be derived that especially the options in which CHPX 1 is present perform well. Reason for this is that the natural gas price is low and the electricity price is high. If this scenario occurs, CHPX 1 would be the best production unit. However it also performs very well in combination with a steam production alternative of BPA as well as with a gas boiler.

Scenario results comparison

For a quick overview of the results, the following tables have been produced. In the tables below all total system profits can be viewed. Furthermore it can be derived under what conditions what options perform best.

Comparison scenarios on system profits (in million €)

	Options												
	0	1	2	3	4	5	6	7	8	9	10	11	12
2017	-6,1	-5,9	-6,6	-8,3	-6,3	-6,0	-5,6	-4,9	-4,5	-6,7	-6,2	-7,0	-10,6
2025	-8,4	-7,3	-8,1	-10,9	-7,9	-7,7	-6,7	-5,8	-5,4	-8,9	-7,1	-8,6	-10,2
S1	-9,7	-9,1	-8,1	-11,6	-10,0	-9,8	-10,1	-9,1	-8,9	-10,6	-9,6	-8,9	-14,0
S2	-7,2	-6,2	-5,4	-9,4	-5,2	-5,1	-4,6	-3,6	-3,0	-8,0	-5,7	-5,4	-5,4
S3	-8,9	-8,2	-7,6	-9,4	-6,2	-6,3	-6,1	-5,0	-4,9	-12,0	-7,8	-7,6	-6,4
S4	-6,9	-6,5	-5,1	-11,6	-9,0	-8,7	-7,6	-6,6	-6,1	-7,3	-6,3	-5,5	-11,6
Total	-7,9	-7,2	-6,8	-10,2	-7,4	-7,3	-6,8	-5,8	-5,4	-8,9	-7,1	-7,2	-9,7

Table L.22: Scenario comparison table excluding subsidy and delta OPEX

Totals			**Average per BPA alternative**	
Average	-7,5		Solo-E	-8,7
St.deviation	1,3		PRDS	-6,9
Minimum	-10,2	Option 3	BPST	-6,7
Maximum	-5,4	Option 8		

Table L.23: Summary of totals table L.22

From tables L.22 and L.23 it can be derived that especially option 3 is not a viable option. Therefore it is not expected that PCX will invest in gas boilers only. Furthermore mainly options 7 and 8 perform very well under various circumstances. In these options the BPA produces steam and the rest is being produced by bio boilers.

Comparison scenarios on system profits including subsidy and OPEX (in million €)

	Options												
	0	1	2	3	4	5	6	7	8	9	10	11	12
2017	-6,1	0,6	-0,6	-9,1	-0,4	-0,7	-0,7	3,5	3,8	-7,1	0,1	-1,3	-9,6
2025	-8,4	-4,9	-6,0	-11,1	-5,7	-5,8	1,9	0,9	1,5	-8,9	-4,6	-6,4	-3,3
S1	-9,7	-6,7	-6,0	-11,9	-7,8	-8,1	-1,8	-1,1	-1,2	-10,6	-7,1	-6,8	-11,3
S2	-7,2	-3,8	-3,2	-9,7	-3,1	-3,2	2,1	1,2	2,0	-8,0	-3,3	-3,2	3,0
S3	-8,9	-5,8	-5,5	-9,7	-4,0	-4,4	0,6	-0,3	0,1	-12,0	-5,4	-5,5	1,9
S4	-6,9	-4,1	-3,0	-11,9	-6,8	-6,9	0,8	1,4	1,6	-7,3	-3,9	-3,4	-8,7
Total	-7,9	-4,1	-4,0	-10,6	-4,6	-4,9	0,5	0,9	1,3	-9,0	-4,0	-4,4	-4,7

Table L.24: Scenario comparison table including subsidy and delta OPEX

Totals			Average per BPA alternative	
Average	-4,3		Solo-E	-6,3
St.deviation	3,5		PRDS	-3,0
Minimum	-10,6	Option 3	BPST	-3,0
Maximum	1,3	Option 8		

Table L.25: Summary of totals table L.24

It can be seen in the tables above that including subsidy and delta OPEX, option 3 still performs worst and options 7 and 8 still perform best. Reason for this is that in options 7 and 8 large amounts of subsidy are granted to steam production on biomass. Options 1 and 2 perform reasonably well. On average the PRDS option performs best overall of the three BPA alternatives.

Comparison scenarios on system profits including OPEX (in million €)

	Options												
	0	1	2	3	4	5	6	7	8	9	10	11	12
2017	-6,1	-6,0	-6,7	-9,1	-7,0	-6,8	-9,4	-7,6	-7,2	-7,1	-6,4	-7,4	-14,0
2025	-8,4	-7,4	-8,2	-11,1	-8,1	-8,1	-6,7	-5,8	-5,5	-8,9	-7,1	-8,7	-10,2
S1	-9,7	-9,2	-8,2	-11,9	-10,2	-10,4	-10,1	-9,1	-9,0	-10,6	-9,6	-9,1	-14,0
S2	-7,2	-6,3	-5,5	-9,7	-5,5	-5,4	-4,6	-3,6	-3,2	-8,0	-5,7	-5,5	-5,4
S3	-8,9	-8,3	-7,7	-9,7	-6,5	-6,6	-6,1	-5,1	-5,0	-12,0	-7,9	-7,7	-6,4
S4	-6,9	-6,5	-5,2	-11,9	-9,3	-9,2	-7,6	-6,6	-6,2	-7,3	-6,4	-5,6	-11,6
Total	-7,9	-7,3	-6,9	-10,6	-7,8	-7,7	-7,4	-6,3	-6,0	-9,0	-7,2	-7,3	-10,2

Table L.26: Scenario comparison table including delta OPEX

Totals			Average per BPA alternative	
Average	-7,8		Solo-E	-9,0
St.deviation	1,3		PRDS	-7,1
Minimum	-10,6	Option 3	BPST	-7,0
Maximum	-6,0	Option 8		

Table L.27: Summary of totals table L.26

Lastly it will be checked that if no or much lower subsidies will be granted than expected, whether the top performers of the other two tables still perform well. From the table above it can be derived that if no subsidy will be granted, still the bio boiler options would perform well. Reason for this is that investment cost have been paid off in three years and are therefore not included in the tables for the year 2025. Furthermore it can be seen that even if no subsidies are granted, option 1 and 2 provide the system good results. Also options 10, 11 and perform well if subsidies are not taken into account.

M. European Emission Trading Scheme

M.1 Introduction to ETS

On January 1st of 2005 the European Union implemented a multinational emission trading scheme, the European Union's Emissions Trading Scheme (EU ETS). Organized in phases, it puts a cap on total allowed emissions. Offering a fixed supply of emission allowances, rights to emit, the system wants to take advantage of the simple economic idea that if the prices are high enough the demand will decline (Jandl, 2009). This means that a price has to be paid for approximately half the carbon dioxide (CO2) emissions originating from a region of the world that accounts for about 20 per cent of global GDP and 17 per cent of the world's energy-related CO2 emissions. Despite the long time that it took for some of the twenty-five member states of the European Union (EU) to allocate emissions permits—or allowances—and to implement the electronic registries that would enable trading, a quantitative limit on CO2 emissions was imposed and since then, a market price has been paid for CO2 emissions by virtually all stationery, industrial, and electricity-generating installations within the EU (Ellerman & Buchner, 2007).

M.2 Implications for PCX

< *information not attached due to confidentiality reasons*>

N. List of interviews

In this appendix an overview will be given of all interviews that have been held to collect the important information. However some information that has been included in the text was derived by short questions to the involved project members. Therefore of some in-text citations, no interview material is available.

The list of interviews and the content of the interviews is as follows:

PERSON INTERVIEWED	DATE	CONTENT
MANAGER DEVELOPMENT BPA *ECA*	05/03/2014	Problem definition Stakeholder environment Background BPA Current subsidy negotiations Introduction to ETS III
INVESTMENT ANALYST BPA MANAGER DEVELOPMENT BPA *ECA*	17/03/2014	Project proposal discussion Importance of action committee area site Y
PROJECT DEVELOPER BIOMASS *ECA*	21/03/2014	Discussion project proposal Stakeholder relations in site Y
SYSTEM ENGINEER BPA *ECA*	25/03/2014	Steam alternatives BPA Assumptions flexible operation in steam system site Y and BPA
MANAGER DEVELOPMENT BPA *ECA*	25/04/2014	Position of PCX in site Y Discussion of model options Brainstorm on collection of data
AREA MANAGER SITE Y *ECA*	28/04/2014	Stakeholder relations in CP
SYSTEM ENGINEER BPA *ECA*	01/05/2014	Technical specifications steam production with BPA Discussion internal document about implications steam supply by BPA
PROJECT DEVELOPER BIOMASS *ECA*	09/05/2014	Estimation of steam demand in site Y on the basis of stakeholder management
COMPLIANCE AND STAKEHOLDER MANAGEMER *ECA*	12/05/2014	Estimation of steam demand in site Y based on ETS III Explanation internal document about ETS III
BUSINESS MANAGER PRODUCTION SITE Y *SITE Y AUTHORITY COMPANY*	16/05/2014	Background of action committee area site Y Positioning of YAC in steam production site Y Future developments plans for site Y Support in construction steam network Steam production estimations
INVESTMENT ANALYST BPA *ECA*	28/05/2014	Discussion about common assumptions for simulation model
MANAGER DEVELOPMENT BPA SYSTEM ENGINEER BPA PLANT MANAGER CHP *ECA*	26/06/2014	Data validation session simulation model
INVESTMENT ANALYST BPA *ECA*	27/06/2014	Operational validation session simulation model
PROJECT DEVELOPER BIOMASS *ECA*	11/07/2014	Assumptions for annuity calculations
INVESTMENT ANALYST BPA *ECA*	weekly	A weekly discussion about the modelling progress was held. During these sessions the latest progression and corresponding questions were discussed. These discussions have not been recorded, but did lead to important insights.

Table N.1: Interviews for data collection and problem understanding

O. List of internal documents

In this appendix an overview will be given of all internal documents that have been consulted to collect important information.

The list of internal documents and the content of the interviews is as follows:

AUTHOR	DATE	CONTENT
COMPLIANCE AND STAKEHOLDER MANAGER *ECA*	07/01/2013	➢ Estimation benefits for PCX participation of BPA in ETS III
CONSULTANT OIL & ENERGY *CONSULTANCY COMPANY*	05/03/2014	➢ Technical and financial specification of steam production alternatives BPA
PROJECT DEVELOPER BIOMASS *ECA*	21/02/2008	➢ Technical specifications CHPX
WASTE INCINERATOR COMPANY SITE Y AND PCB	02/2010	➢ Contract conditions steam supply from waste incinerator to PCB
INVESTMENT ANALYST BPA *ECA*	24/04/2014	➢ Price series for electricity and natural gas
INVESTMENT ANALYST BPA *ECA*	26/11/2012	➢ Basic mass and heat balance CHPX 1 in unfired operation
PROJECT COORDINATOR *PCX*	19/03/2014	➢ Technical assumptions intake BPA steam by PCX
MANAGER; PELLET, O&G AND BIOGRATE COMBUSTION *BIO BOILER COMPANY*	02/09/2013	➢ Email contact between ECA and bio boiler company ➢ Quota for a biomass boiler
MANAGER MARKETING & SALES *GAS BOILER COMPANY*	03/03/2008	➢ Email contact between ECA and gas boiler company ➢ Quota for a gas boiler
PROJECT DEVELOPER BIOMASS *ECA*	26/06/2007	➢ Estimated amount of steam consumed by companies in site Y in period 2005-2008
PROJECT DEVELOPER BIOMASS *ECA*	12/05/2014	➢ Integration of product flows in site Y ➢ Recent developments in site Y

Table O.1: List of intern documents used for data collection